World Energy Outlook 2022

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Today, the world is in the midst of the first truly global energy crisis, with impacts that will be felt for years to come. Russia's unprovoked invasion of Ukraine in February has had far-reaching impacts on the global energy system, disrupting supply and demand patterns and fracturing long-standing trading relationships.

The crisis is affecting all countries, but at the International Energy Agency (IEA), we are particularly concerned about the effect it is having on the people who can least afford it. One of the striking findings in this year's *World Energy Outlook (WEO)* is that the combination of the Covid pandemic and the current energy crisis means that 70 million people who recently gained access to electricity will likely lose the ability to afford that access – and 100 million people may no longer be able to cook with clean fuels, returning to unhealthy and unsafe means of cooking. That is a global tragedy. And it is not only an energy crisis with which we are dealing: many countries also face a food security crisis and increasingly visible impacts of climate change.

As the world faces this unprecedented energy shock and the other overlapping crises, we need to be clear on how we got here and where we need to go. The analysis in this *Outlook* is particularly important to shed light on these questions and to dispel some of the mistaken and misleading ideas that have arisen about this energy crisis.

For example, there is a mistaken idea that this is somehow a clean energy crisis. That is simply not true. The world is struggling with too little clean energy, not too much. Faster clean energy transitions would have helped to moderate the impact of this crisis, and they represent the best way out of it. When people misleadingly blame climate and clean energy for today's crisis, what they are doing – whether they mean to or not – is shifting attention away from the real cause: Russia's invasion of Ukraine.

Another mistaken idea is that today's crisis is a huge setback for efforts to tackle climate change. The analysis in this *Outlook* shows that, in fact, this can be a historic turning point towards a cleaner and more secure energy system thanks to the unprecedented response from governments around the world, including the Inflation Reduction Act in the United States, the Fit for 55 package and REPowerEU in the European Union, Japan's Green Transformation (GX) programme, Korea's aim to increase the share of nuclear and renewables in its energy mix, and ambitious clean energy targets in China and India.

At the same time, I am worried that today's major global energy and climate challenges increase the risk of geopolitical fractures and new international dividing lines – especially between advanced economies and many emerging and developing economies. Unity and solidarity need to be the hallmarks of our response to today's crisis. That is the case for Europe during what promise to be tough winters not only this year but also next. And it is true globally.

This *WEO* underscores that successful energy transitions must be fair and inclusive, offering a helping hand to those in need and ensuring the benefits of the new energy economy are shared widely. Even as countries struggle to manage the brutal shocks from the crisis, the last thing we should do is turn inwards and away from supporting each other. Instead, we need to work together to build trust.

The IEA is committed to continuing to play a central role in this by helping governments to define the actions that are needed to enable the world to confront our shared energy and climate challenges together. In this, we are guided by the IEA's world class energy modelling and analysis – underpinned by unparalleled data – that is exemplified by the *World Energy Outlook*. For this, I would like to warmly thank the excellent IEA team that has worked skilfully and tirelessly under the outstanding leadership of my colleagues Laura Cozzi and Tim Gould to produce another essential and timely *Outlook* that I hope will help decision-makers globally to navigate the current crisis and move the world towards a more secure and sustainable future.

Dr Fatih Birol
Executive Director
International Energy Agency

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Jacob Teter, Leonardo Paoli, Elizabeth Connelly and Ekta Bibra contributed to the analysis on transport. Chiara Delmastro and Martin Husek contributed to the analysis on buildings. Stavroula Evangelopoulou, Francesco Pavan, Amalia Pizarro and Amar Bhardwaj contributed to the analysis on hydrogen. Praveen Bains contributed to the analysis on biofuels. Mathilde Huismans contributed to data science.

Other key contributors from across the IEA were: Ali Al-Saffar, Heymi Bahar, Chiara D'Adamo, Carlos Fernández Alvarez, David Fischer, Inhoi Heo, Jinsun Lim, Luca Lo Re, Rebecca McKimm, Jeremy Moorhouse, Kristine Petrosyan, Gabriel Saive and Talya Vatman.

Valuable comments and feedback were provided by other senior management and numerous other colleagues within the IEA. In particular, Mary Warlick, Keisuke Sadamori, Nick Johnstone, Amos Bromhead, Toril Bosoni, Joel Couse, Paolo Frankl, Brian Motherway, Aad Van Bohemen, Rebecca Gaghen, An Fengquan, Sara Moarif, Hiro Sakaguchi and Jacob Messing.

Thanks go to the IEA's Communications and Digital Office for their help in producing the report and website materials, particularly to Jad Mouawad, Fabien Barau, Curtis Brainard, Adrien Chorlet, Jon Custer, Claire Dehouck, Astrid Dumond, Tanya Dyhin, Merve Erdem, Grace Gordon, Barbara Moure, Jethro Mullen, Isabelle Nonain-Semelin, Julie Puech, Clara Vallois, Gregory Viscusi and Therese Walsh. Ivo Letra and Ben McCulloch provided essential support to the production process. IEA's Office of the Legal Counsel, Office of Management and Administration and Energy Data Centre provided assistance throughout the preparation of the report.

Valuable input to the analysis was provided by: David Wilkinson (independent consultant). Valuable input to the modelling on air pollution and associated health impacts was provided by Peter Rafaj, Gregor Kiesewetter, Wolfgang Schöpp, Chris Heyes, Pallav Purohit, Laura Warnecke, Adriana Gomez-Sanabria and Zbigniew Klimont (International Institute for Applied Systems Analysis). Valuable input to the modelling and analysis of greenhouse gas emissions from land use and bioenergy production was provided by Nicklas Forsell, Andrey Lessa-Derci-Augustynczik, Pekka Lauri, Mykola Gusti, Zuelclady Araujo Gutierrez and Petr Havlík (International Institute for Applied Systems Analysis).

The work could not have been achieved without the support and co-operation provided by many government bodies, organisations and companies worldwide, notably: Enel; Eni; European Union (Global Public Goods and Challenges Programme); Hitachi Energy; Iberdrola; Jupiter Intelligence; Ministry of Economy, Trade and Industry, Japan; Ministry of Economic Affairs and Climate Policy, the Netherlands; The Research Institute of Innovative Technology for the Earth, Japan; Shell; Swiss Federal Office of Energy; and Toshiba.

The IEA Clean Energy Transitions Programme (CETP), particularly through the contributions of the Agence Française de Développement, Italy, Japan, the Netherlands, Sweden and the United Kingdom supported this analysis.

Thanks also go to the IEA Energy Business Council, IEA Coal Industry Advisory Board, IEA Energy Efficiency Industry Advisory Board and the IEA Renewable Industry Advisory Board.

Peer reviewers

Many senior government officials and international experts provided input and reviewed preliminary drafts of the report. Their comments and suggestions were of great value. They include:

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Peter Bach	Danish Energy Agency
Shan Baoguo	State Grid Energy Research Institute, China
Manuel Baritaud	European Investment Bank
Paul Baruya	World Coal Association
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Sohbet Karbuz	Mediterranean Observatory for Energy
Rafael Kawecki	Siemens Energy
Michael Kelly	World LPG Association
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Jim Krane	Baker Institute for Public Policy
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Russia's invasion of Ukraine has sparked a global energy crisis

The world is in the midst of its first global energy crisis – a shock of unprecedented breadth and complexity. Pressures in markets predated Russia's invasion of Ukraine, but Russia's actions have turned a rapid economic recovery from the pandemic – which strained all manner of global supply chains, including energy – into full-blown energy turmoil. Russia has been by far the world's largest exporter of fossil fuels, but its curtailments of natural gas supply to Europe and European sanctions on imports of oil and coal from Russia are severing one of the main arteries of global energy trade. All fuels are affected, but gas markets are the epicentre as Russia seeks leverage by exposing consumers to higher energy bills and supply shortages.

Prices for spot purchases of natural gas have reached levels never seen before, regularly exceeding the equivalent of USD 250 for a barrel of oil. Coal prices have also hit record levels, while oil rose well above USD 100 per barrel in mid-2022 before falling back. High gas and coal prices account for 90% of the upward pressure on electricity costs around the world. To offset shortfalls in Russian gas supply, Europe is set to import an extra 50 billion cubic metres (bcm) of liquefied natural gas (LNG) in 2022 compared with the previous year. This has been eased by lower demand from China, where gas use was held back by lockdowns and subdued economic growth, but higher European LNG demand has diverted gas away from other importers in Asia.

The crisis has stoked inflationary pressures and created a looming risk of recession, as well as a huge USD 2 trillion windfall for fossil fuel producers above their 2021 net income. Higher energy prices are also increasing food insecurity in many developing economies, with the heaviest burden falling on poorer households where a larger share of income is spent on energy and food. Some 75 million people who recently gained access to electricity are likely to lose the ability to pay for it, meaning that for the first time since we started tracking it, the total number of people worldwide without electricity access has started to rise. And almost 100 million people may be pushed back into reliance on firewood for cooking instead of cleaner, healthier solutions.

Faced with energy shortfalls and high prices, governments have so far committed well over USD 500 billion, mainly in advanced economies, to shield consumers from the immediate impacts. They have rushed to try and secure alternative fuel supplies and ensure adequate gas storage. Other short-term actions have included increasing oil- and coal-fired electricity generation, extending the lifetimes of some nuclear power plants, and accelerating the flow of new renewables projects. Demand-side measures have generally received less attention, but greater efficiency is an essential part of the short- and longer-term response.

Is the crisis a boost, or a setback, for energy transitions?

With energy markets remaining extremely vulnerable, today's energy shock is a reminder of the fragility and unsustainability of our current energy system. A key question for policy makers, and for this *Outlook*, is whether the crisis will be a setback for clean energy transitions or will catalyse faster action. Climate policies and net zero commitments were blamed in some quarters for contributing to the run-up in energy prices, but there is scant evidence for this. In the most affected regions, higher shares of renewables were correlated with lower electricity prices, and more efficient homes and electrified heat have provided an important buffer for some – but far from enough – consumers.

Times of crisis put the spotlight on governments, and on how they react. Alongside short-term measures, many governments are now taking longer-term steps: some seeking to increase or diversify oil and gas supply; many looking to accelerate structural change. The three scenarios explored in this *World Energy Outlook* (WEO) are differentiated primarily by the assumptions made on government policies. The **Stated Policies Scenario (STEPS)** shows the trajectory implied by today's policy settings. The **Announced Pledges Scenario (APS)** assumes that all aspirational targets announced by governments are met on time and in full, including their long-term net zero and energy access goals. The **Net Zero Emissions by 2050 (NZE) Scenario** maps out a way to achieve a 1.5 °C stabilisation in the rise in global average temperatures, alongside universal access to modern energy by 2030.

Policy responses are fast-tracking the emergence of a clean energy economy

New policies in major energy markets help propel annual clean energy investment to more than USD 2 trillion by 2030 in the STEPS, a rise of more than 50% from today. Clean energy becomes a huge opportunity for growth and jobs, and a major arena for international economic competition. By 2030, thanks in large part to the US Inflation Reduction Act, annual solar and wind capacity additions in the United States grow two-and-a-half-times over today's levels, while electric car sales are seven times larger. New targets continue to spur the massive build-out of clean energy in China, meaning that its coal and oil consumption both peak before the end of this decade. Faster deployment of renewables and efficiency improvements in the European Union bring down EU natural gas and oil demand by 20% this decade, and coal demand by 50%, a push given additional urgency by the need to find new sources of economic and industrial advantage beyond Russian gas. Japan's Green Transformation (GX) programme provides a major funding boost for technologies including nuclear, low-emissions hydrogen and ammonia, while Korea is also looking to increase the share of nuclear and renewables in its energy mix. India makes further progress towards its domestic renewable capacity target of 500 gigawatts (GW) in 2030, and renewables meet nearly two-thirds of the country's rapidly rising demand for electricity.

As markets rebalance, renewables, supported by nuclear power, see sustained gains; the upside for coal from today's crisis is temporary. The increase in renewable electricity generation is sufficiently fast to outpace growth in total electricity generation, driving down the contribution of fossil fuels for power. The crisis briefly pushes up utilisation rates for existing coal-fired assets, but does not bring higher investment in new ones. Strengthened policies, a subdued economic outlook and high near-term prices combine to moderate overall energy demand growth. Increases come primarily from India, Southeast Asia, Africa and the Middle East. However, the rise in China's energy use, which has been such an important driver for global energy trends over the past two decades, slows and then halts altogether before 2030 as China shifts to a more services-orientated economy.

International energy trade undergoes a profound reorientation in the 2020s as countries adjust to the rupture of Russia-Europe flows, which is assumed to be permanent. Not all Russian flows displaced from Europe find a new home in other markets, bringing down Russian production and global supply. Crude oil and product markets, especially diesel, face a turbulent period as EU bans on Russian imports kick in. Natural gas takes longer to adjust. The upcoming northern hemisphere winter promises to be a perilous moment for gas markets and a testing time for EU solidarity – and the winter of 2023-24 could be even tougher. Major new additions to LNG supply – mainly from North America, Qatar and Africa – arrive only around the mid-2020s. Competition for available cargoes is fierce in the meantime as Chinese import demand picks up again.

Today's stronger policy settings bring a fossil fuel peak into view

For the first time, a *WEO* scenario based on prevailing policy settings has global demand for each of the fossil fuels exhibiting a peak or plateau. In the STEPS, coal use falls back within the next few years, natural gas demand reaches a plateau by the end of the decade, and rising sales of electric vehicles (EVs) mean that oil demand levels off in the mid-2030s before ebbing slightly to mid-century. Total demand for fossil fuels declines steadily from the mid-2020s by around 2 exajoules per year on average to 2050, an annual reduction roughly equivalent to the lifetime output of a large oil field.

Global fossil fuel use has risen alongside GDP since the start of the Industrial Revolution in the 18th century: putting this rise into reverse while continuing to expand the global economy will be a pivotal moment in energy history. The share of fossil fuels in the global energy mix has been stubbornly high, at around 80%, for decades. By 2030 in the STEPS, this share falls below 75%, and to just above 60% by 2050. A high point for global energy-related CO_2 emissions is reached in the STEPS in 2025, at 37 billion tonnes (Gt) per year, and they fall back to 32 Gt by 2050. This would be associated with a rise of around 2.5 °C in global average temperatures by 2100. This is a better outcome than projected a few years ago: renewed policy momentum and technology gains made since 2015 have shaved around 1 °C off the long-term temperature rise. However, a reduction of only 13% in annual CO_2 emissions to 2050 in the STEPS is far from enough to avoid severe impacts from a changing climate.

Full achievement of all climate pledges would move the world towards safer ground, but there is still a large gap between today's ambitions and a 1.5 °C stabilisation. In the APS, a near-term peak in annual emissions is followed by a faster decline to 12 Gt by 2050. This is a bigger reduction than in the *WEO-2021* APS, reflecting the additional pledges that have been made over the past year, notably by India and Indonesia. If implemented on time and in full, these additional national commitments – as well as sectoral commitments for specific industries and company targets (considered for the first time in this year's APS) – keep the temperature rise in the APS in 2100 at around 1.7 °C. However, it is easier to make pledges than to implement them and, even if they are achieved, there is still considerably further to go to align with the NZE Scenario, which achieves the 1.5 °C outcome by reducing annual emissions to 23 Gt by 2030 and to net zero by 2050.

Led by clean electricity, some sectors are poised for a faster transformation

The world is in a critical decade for delivering a more secure, sustainable and affordable energy system – the potential for faster progress is enormous if strong action is taken immediately. Investments in clean electricity and electrification, along with expanded and modernised grids, offer clear and cost-effective opportunities to cut emissions more rapidly while bringing electricity costs down from their current highs. Today's growth rates for deployment of solar PV, wind, EVs and batteries, if maintained, would lead to a much faster transformation than projected in the STEPS, although this would require supportive policies not just in the leading markets for these technologies but across the world. By 2030, if countries deliver on their climate pledges, every second car sold in the European Union, China and the United States is electric.

Supply chains for some key technologies – including batteries, solar PV and electrolysers – are expanding at rates that support higher global ambition. If all announced manufacturing expansion plans for solar PV see the light of day, manufacturing capacity would exceed the deployment levels in the APS in 2030 by around 75% and approach the levels required in the NZE Scenario. In the case of electrolysers for hydrogen production, the potential excess capacity of all announced projects relative to APS deployment in 2030 is around 50%. In the EV sector, the expansion of battery manufacturing capacity reflects the shift underway in the automotive industry, which at times has moved faster than governments in setting targets for electrified mobility. These clean energy supply chains are a huge source of employment growth, with clean energy jobs already exceeding those in fossil fuels worldwide and projected to grow from around 33 million today to almost 55 million in 2030 in the APS.

Efficiency and clean fuels get a competitive boost

Today's high energy prices underscore the benefits of greater energy efficiency and are prompting behavioural and technology changes in some countries to reduce energy use. Efficiency measures can have dramatic effects – today's light bulbs are at least four times more efficient than those on sale two decades ago – but much more remains to be done. Demand for cooling needs to be a particularly focus for policy makers, as it makes the second-largest contribution to the overall rise in global electricity demand over the coming decades (after EVs). Many air conditioners used today are subject only to weak efficiency standards and one-fifth of electricity demand for cooling in emerging and developing economies is not covered by any standards at all. In the STEPS, cooling demand in emerging and developing economies rises by 2 800 terawatt-hours to 2050, which is the equivalent of adding another European Union to today's global electricity demand. This growth is reduced by half in the APS because of tighter efficiency standards and better building design and insulation – and by half again in the NZE Scenario.

Concerns about fuel prices, energy security and emissions – bolstered by stronger policy support – are brightening the prospects for many low-emissions fuels. Investment in low-emissions gases is set to rise sharply in the coming years. In the APS, global low-emissions hydrogen production rises from very low levels today to reach over 30 million tonnes (Mt) per year in 2030, equivalent to over 100 bcm of natural gas (although not all low-emissions hydrogen would replace natural gas). Much of this is produced close to the point of use, but there is growing momentum behind international trade in hydrogen and hydrogen-based fuels. Projects representing a potential 12 Mt of export capacity are in various stages of planning, although these are more numerous and more advanced than corresponding projects to underpin import infrastructure and demand. Carbon capture, utilisation and storage projects are also advancing more rapidly than before, spurred by greater policy support to aid industrial decarbonisation, to produce low- or lower-emissions fuels, and to allow for direct air capture projects that remove carbon from the atmosphere.

But rapid transitions ultimately depend on investment

A huge increase in energy investment is essential to reduce the risks of future price spikes and volatility, and to get on track for net zero emissions by 2050. From USD 1.3 trillion today, clean energy investment rises above USD 2 trillion by 2030 in the STEPS, but it would have to be above USD 4 trillion by the same date in the NZE Scenario, highlighting the need to attract new investors to the energy sector. Governments should take the lead and provide strong strategic direction, but the investments required are far beyond the reaches of public finance. It is vital to harness the vast resources of markets and incentivise private actors to play their part. Today, for every USD 1 spent globally on fossil fuels, USD 1.5 is spent on clean energy technologies. By 2030, in the NZE Scenario, every USD 1 spent on fossil fuels is outmatched by USD 5 on clean energy supply and another USD 4 on efficiency and end-uses.

Shortfalls in clean energy investment are largest in emerging and developing economies, a worrying signal given their rapid projected growth in demand for energy services. If China is excluded, then the amount being invested in clean energy each year in emerging and developing economies has remained flat since the Paris Agreement was concluded in 2015. The cost of capital for a solar PV plant in 2021 in key emerging economies was between two- and three-times higher than in advanced economies and China. Today's rising borrowing costs could exacerbate the financing challenges facing such projects, despite their favourable underlying costs. A renewed international effort is needed to step up climate finance and tackle the various economy-wide or project-specific risks that deter investors. There is immense value in broad national transition strategies such as the Just Energy Transition Partnerships with Indonesia, South Africa and other countries, that integrate international support and ambitious national policy actions while also providing safeguards for energy security and the social consequences of change.

The speed at which investors react to broad and credible transition frameworks depends in practice on a host of more granular issues. Supply chains are fragile, and infrastructure and skilled labour are not always available. Permitting provisions and deadlines are often complex and time-consuming. Clear procedures for project approval, supported by adequate administrative capacity, are vital to accelerate the flow of viable, investable projects – both for clean energy supply as well as for efficiency and electrification. Our analysis finds that permitting and construction of a single overhead electricity transmission line can take up to 13 years, with some of the longest lead times in advanced economies. Developing new deposits of critical minerals has historically taken over 16 years on average, with 12 years spent lining up all aspects of permitting and financing and 4-5 years for construction.

What if transitions don't pick up?

If clean energy investment does not accelerate as in the NZE Scenario then higher investment in oil and gas would be needed to avoid further fuel price volatility, but this would also mean putting the 1.5 °C goal in jeopardy. In the STEPS, an average of almost USD 650 billion per year is spent on upstream oil and natural gas investment to 2030, a rise of more than 50% compared with recent years. This investment comes with risks, both commercial and environmental, and cannot be taken for granted. Despite huge windfalls this year, some Middle East producers are the only part of the upstream industry investing more today than prior to the Covid-19 pandemic. Amid concerns about cost inflation, capital discipline rather than production growth has become the default setting for the US shale industry, meaning that some of the wind has gone from the sails of the main source of recent global oil and gas growth.

Immediate shortfalls in fossil fuel production from Russia will need to be replaced by production elsewhere – even in a world working towards net zero emissions by 2050. The most suitable near-term substitutes are projects with short lead times that bring oil and gas to market quickly, as well as capturing some of the 260 bcm of gas that is wasted each year through flaring and methane leaks to the atmosphere. But lasting solutions to today's crisis lie in reducing fossil fuel demand. Many financial organisations have set goals and plans to scale down investment in fossil fuels. Much more emphasis is needed on goals and plans for scaling up investment in clean energy transitions, and on what governments can do to incentivise this.

Russia loses out in the reshuffling of international trade

Russia's invasion of Ukraine is prompting a wholesale reorientation of global energy trade, leaving Russia with a much-diminished position. All Russia's trade ties with Europe based on fossil fuels had ultimately been undercut in our previous scenarios by Europe's net zero ambitions, but Russia's ability to deliver at relatively low cost meant that it lost ground only gradually. Now the rupture has come with a speed that few imagined possible. In this *Outlook*, more Russian resources are drawn eastwards to Asian markets, but Russia is unsuccessful in finding markets for all of the flows that previously went to Europe. In 2025, Russia's oil production is 2 million barrels a day lower than in the *WEO-2021* and gas production is down by 200 bcm. Longer-term prospects are weakened by uncertainties over demand, as well as restricted access to international capital and technologies to develop more challenging fields and LNG projects. Russian fossil fuel exports never return – in any of our scenarios – to the levels seen in 2021, and its share of internationally traded oil and gas falls by half by 2030 in the STEPS.

Russia's reorientation to Asian markets is particularly challenging in the case of natural gas, as the market opportunity for large-scale additional deliveries to China is limited. Russia is targeting new pipeline links to China, notably the large-capacity Power of Siberia-2 pipeline through Mongolia. However, our demand projections for China raise considerable doubts about the viability of another large-scale gas link with Russia, once the existing Power of Siberia line ramps up to full capacity. In the STEPS, China's gas demand growth slows to 2% per year between 2021 and 2030, compared with an average growth rate of 12% per year since 2010, reflecting a policy preference for renewables and electrification over gas use for power and heat. Chinese importers have been actively contracting for new long-term LNG supplies, and China already has adequate contracted supply to meet projected demand in the STEPS until well into the 2030s.

Were the 2010s the "golden age of gas"?

One of the effects of Russia's actions is that the era of rapid growth in natural gas demand draws to a close. In the STEPS, the scenario that sees the highest gas consumption, global demand rises by less than 5% between 2021 and 2030 and then remains flat at around 4 400 bcm through to 2050. The outlook for gas is dampened by higher near-term prices; more rapid deployment of heat pumps and other efficiency measures; higher renewables deployment and a faster uptake of other flexibility options in the power sector; and, in some cases, reliance on coal for slightly longer. The Inflation Reduction Act cuts projected US natural gas demand in 2030 in the STEPS by more than 40 bcm compared with last year's projections, freeing up gas for export. Stronger climate policies accelerate Europe's structural shift away from gas. New supply brings prices down by the mid-2020s, and LNG becomes even more important to overall gas security. But momentum behind natural gas growth in developing economies has slowed, notably in South and Southeast Asia, putting a dent in the credentials of gas as a transition fuel. Most of the downward revision to gas demand to 2030 in this year's STEPS is due to a faster switch to clean energy, although around one-quarter is because gas loses out to coal and oil.

A focus on affordable, secure transitions based on resilient supply chains

A new energy security paradigm is needed to maintain reliability and affordability while reducing emissions. This *Outlook* includes ten principles that can help guide policy makers through the period when declining fossil fuel and expanding clean energy systems co-exist. During energy transitions, both systems are required to function well in order to deliver the energy services needed by consumers, even as their respective contributions change over time. Maintaining electricity security in tomorrow's power systems calls for new tools, more flexible approaches and mechanisms to ensure adequate capacities. Power generators will need to be more responsive, consumers will need to be more connected and adaptable, and grid infrastructure will need to be strengthened and digitalised. Inclusive, people-centred approaches are essential to allow vulnerable communities to manage the upfront costs of cleaner technologies and ensure that the benefits of transitions are felt widely across societies. Even as transitions reduce fossil fuel use, there are parts of the fossil fuel system that remain critical to energy security, such as gas-fired power for peak electricity needs, or refineries to supply residual users of transport fuels. Unplanned or premature retirement of this infrastructure could have negative consequences for energy security.

As the world moves on from today's energy crisis, it needs to avoid new vulnerabilities arising from high and volatile critical mineral prices or highly concentrated clean energy supply chains. If not adequately addressed, these issues could delay energy transitions or make them more costly. Demand for critical minerals for clean energy technologies is set to rise sharply, more than doubling from today's level by 2030 in the APS. Copper sees the largest increase in terms of absolute volumes, but other critical minerals experience much faster rates of demand growth, notably silicon and silver for solar PV, rare earth elements for wind turbine motors and lithium for batteries. Continued technology innovation and recycling are vital options to ease strains on critical minerals markets. High reliance on individual countries such as China for critical mineral supplies and for many clean technology supply chains is a risk for transitions, but so too are diversification options that close off the benefits of trade.

The energy crisis promises to be a historic turning point towards a cleaner and more secure energy system

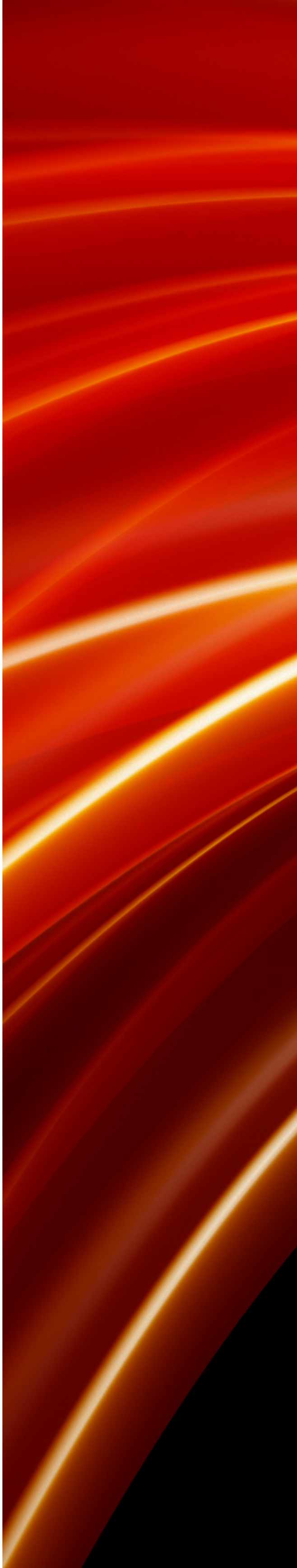
Energy markets and policies have changed as a result of Russia's invasion of Ukraine, not just for the time being, but for decades to come. The environmental case for clean energy needed no reinforcement, but the economic arguments in favour of cost-competitive and affordable clean technologies are now stronger – and so too is the energy security case. This alignment of economic, climate and security priorities has already started to move the dial towards a better outcome for the world's people and for the planet. Much more remains to be done, and as these efforts gather momentum, it is essential to bring everyone on board, especially at a time when geopolitical fractures on energy and climate are all the more visible. This means redoubling efforts to ensure that a broad coalition of countries has a stake in the new energy economy. The journey to a more secure and sustainable energy system may not be a smooth one. But today's crisis makes it crystal clear why we need to press ahead.

PART A
OVERVIEW AND CONTEXT

Part A of the World Energy Outlook provides the starting point for this year's energy projections and gives an overview of some of the key findings.

Chapter 1 explores the causes of today's global energy crisis and the consequences. It provides projections for energy markets and energy security through three scenarios and examines what those outlooks imply for energy-related emissions and achievement of the world's sustainable development goals.

Chapter 2 examines the various forces that are impacting the energy sector today and the policy responses, and assesses the implications for our Outlook in 2022. It also details the basis of each of the three main scenarios and how and why they differ.



Overview and key findings

Global energy crisis: causes and implications

SUMMARY

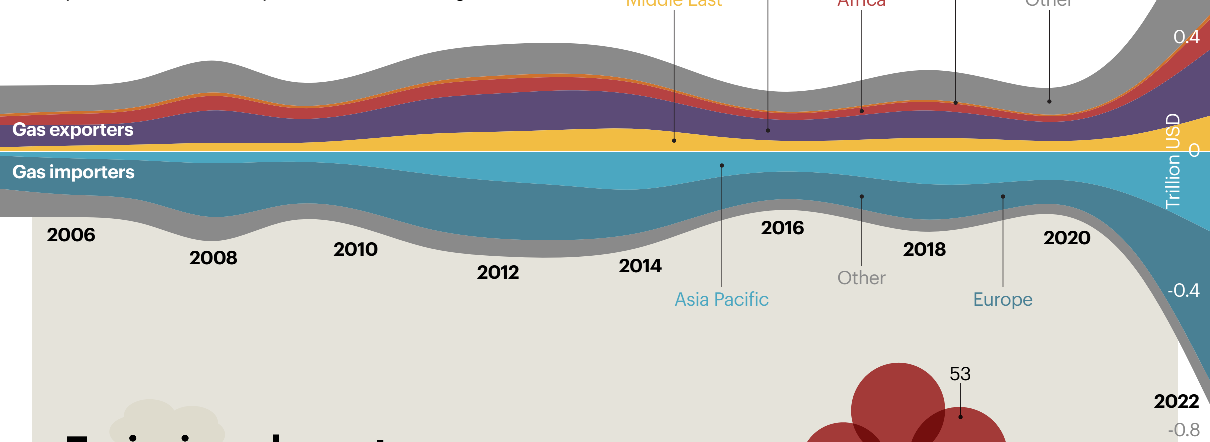
- The global energy crisis sparked by Russia's invasion of Ukraine is having far-reaching implications for households, businesses and entire economies, prompting short-term responses from governments as well as a deeper debate about the ways to reduce the risk of future disruptions and promote energy security. This is a global crisis, but Europe is the main theatre in which it is playing out, and natural gas is centre stage – especially during the coming northern hemisphere winter.
- High energy prices are causing a huge transfer of wealth from consumers to producers, back to the levels seen in 2014 for oil, but entirely unprecedented for natural gas. High fuel prices account for 90% of the rise in the average costs of electricity generation worldwide, natural gas alone for more than 50%. The costs of renewables and carbon dioxide have played only a marginal role, underscoring that this is a crisis where energy transitions are the solution, rather than the problem.
- Price and economic pressures mean that the number of people without access to modern energy is rising for the first time in a decade. Around 75 million people who recently gained access to electricity are likely to lose the ability to pay for it, and 100 million people may revert to the use of traditional biomass for cooking.
- There remain huge uncertainties over how this energy crisis will evolve and for how long fossil fuel prices will remain elevated, and the risks of further energy disruption and geopolitical fragmentation are high. In all our scenarios, price pressures and a dim near-term outlook for the global economy feed through into lower energy demand than in last year's *Outlook*.
- The crisis provides a short-term boost to demand for oil and coal as consumers scramble for alternatives to high priced gas. But the lasting gains from the crisis accrue to low-emissions sources, mainly renewables, but also nuclear in some cases, alongside faster progress with efficiency and electrification, e.g. electric vehicles.
- In the Stated Policies Scenario (STEPS), global energy demand growth of around 1% per year to 2030 is met in aggregate almost entirely by renewables. Emerging market and developing economies, such as India, see increases across a broader range of fuels and technologies, while the only sources to show growth in advanced economies to 2030 are low-emissions.
- The cost advantages of mature clean energy technologies and the prospects for new ones, such as low-emissions hydrogen, are boosted by the Inflation Reduction Act in the United States, Europe's increased push for clean energy, and other major new policies. The result is to turbo-charge the emerging global clean energy economy.
- The STEPS in this *Outlook* is the first *World Energy Outlook (WEO)* scenario based on prevailing policy settings that sees a definitive peak in global demand for fossil fuels.

Coal demand peaks in the next few years, natural gas demand reaches a plateau by the end of the decade, and oil demand reaches a high point in the mid-2030s before falling slightly. From 80% today – a level that has been constant for decades – the share of fossil fuels in the global energy mix falls to less than 75% by 2030 and to just above 60% by mid-century. In the Announced Pledges Scenario (APS), the drive to meet climate pledges in full sends demand for all the fossil fuels into decline by 2030.

- With the loss of its largest export market in Europe, Russia faces the prospect of a much-diminished role in international energy affairs. 2021 proves to be a high-water mark for Russian export flows. Its share of internationally traded gas, which stood at 30% in 2021, falls to 15% by 2030 in the STEPS and to 10% in the APS. Importers in China have been actively contracting for liquefied natural gas, and there is no room in China's projected gas balance for another large-scale pipeline from Russia.
- Energy-related CO_2 emissions rebounded to 36.6 Gt in 2021, the largest ever annual rise in emissions. In the STEPS, they reach a plateau around 37 Gt before falling slowly to 32 Gt in 2050, a trajectory that would lead to a 2.5 °C rise in global average temperatures by 2100. This is around 1 °C lower than implied by the baseline trajectory prior to the Paris Agreement, indicating the progress that has been made since then. But much more needs to be done. In the APS, emissions peak in the mid-2020s and fall to 12 Gt in 2050, resulting in a projected global median temperature rise in 2100 of 1.7 °C. In the Net Zero Emissions by 2050 (NZE) Scenario, CO_2 emissions fall to 23 Gt in 2030 and to zero in 2050, a trajectory consistent with limiting the temperature increase to less than 1.5 °C in 2100.
- Planned increases in global clean energy manufacturing capacity provide a leading indicator of the potential for rapid increases in deployment. In the case of heat pumps, current and planned manufacturing capacity is below the deployment levels projected in the APS. But announced global manufacturing capacity for electrolysers and solar PV modules in 2030 is sufficient not only to reach APS deployment levels but to go beyond them.
- One point common to each scenario is the rising share of electricity in global final energy consumption. From 20% today, this increases in each scenario, reaching more than 50% by mid-century in the NZE Scenario. This is associated with a huge overall increase in global electricity demand – with the bulk of this growth coming from emerging market and developing economies – and the need for constant vigilance from policy makers to a range of risks to electricity security, in particular the ever increasing need for flexible operation of power systems.
- The world has not been investing enough in energy in recent years, a fact that left the energy system much more vulnerable to the sort of shocks seen in 2022. A smooth and secure energy transition will require a major uptick in clean energy investment flows. Getting on track for the NZE Scenario will require a tripling in spending on clean energy and infrastructure to 2030, alongside a shift towards much higher investment in emerging market and developing economies.

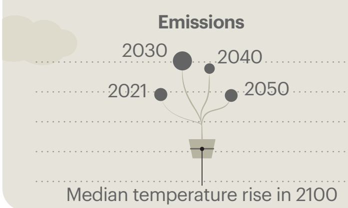
Huge transfers from consumers to producers:

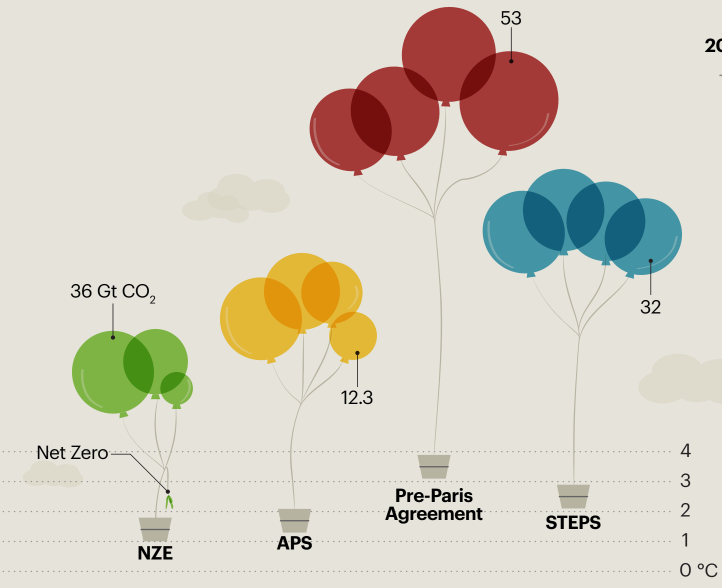
Oil has been expensive before, but there is no precedent for the import bills for natural gas in 2022.



Emissions have to come down

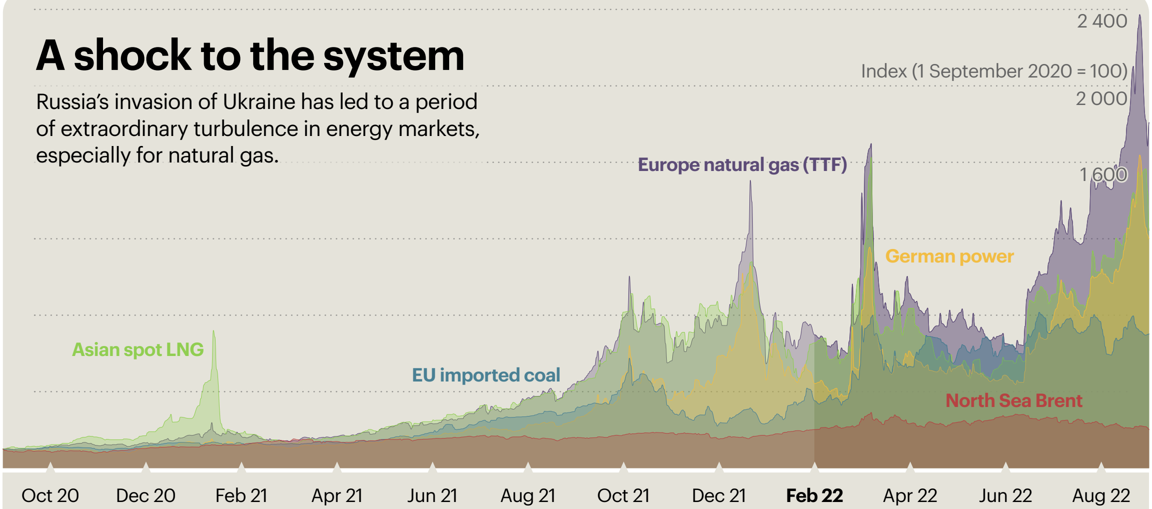
Policy and technology changes since the Paris Agreement in 2015 have reduced the projected temperature rise, but there's still a long way to go to cap global warming at 1.5 °C.





A shock to the system

Russia's invasion of Ukraine has led to a period of extraordinary turbulence in energy markets, especially for natural gas.



1.1 Introduction

Each energy crisis has echoes of the past, and the acute strains on markets today are drawing comparison with the most severe energy disruptions in modern energy history, most notably the oil shocks of the 1970s. Then, as now, there were strong geopolitical drivers for the rise in prices, which led to high inflation and economic damage. Then, as now, the crises brought to the surface some underlying fragilities and dependencies in the energy system. Then, as now, high prices created strong economic incentives to act, and those incentives were reinforced by considerations of economic and energy security.

But today's global energy crisis is significantly broader and more complex than those that came before. The shocks in the 1970s were about oil, and the task facing policy makers was relatively clear (if not necessarily simple to implement): reduce dependence on oil, especially oil imports. By contrast, the energy crisis today has multiple dimensions: natural gas, but also oil, coal, electricity, food security and climate. Therefore, the solutions are similarly all encompassing. Ultimately what is required is not just to diversify away from a single energy commodity, but to change the nature of the energy system itself, and to do so while maintaining the affordable, secure provision of energy services.

This *Outlook* explores how this change might play out, and what pitfalls and opportunities may be encountered along the way. Each scenario is based on a different vision of how policy makers might respond to today's crisis. In the **Stated Policies Scenario** (STEPS), we explore how the energy system evolves if we retain current policy settings. These include the latest policy measures adopted by governments around the world, such as the Inflation Reduction Act in the United States, but do not assume that aspirational or economy-wide targets are met unless they are backed up with detail on how they are to be achieved.

In the **Announced Pledges Scenario** (APS), governments get the benefit of the doubt. In this scenario, their targets are achieved on time and in full, whether they relate to climate change, energy systems or national pledges in other areas such as energy access. Trends in this scenario reveal the extent of the world's collective ambition, as it stands today, to tackle climate change and meet other sustainable development goals. Only in the **Net Zero Emissions by 2050** (NZE) **Scenario**, do we work back from specific goals – the main one in this case being to cap global warming to 1.5 °C – and show how they can be achieved.

Each scenario meets current energy security and climate challenges in different ways and to different extents, but the starting point for today's decision makers is fundamentally different from that facing their counterparts in the 1970s. The climate and environmental challenges are much more acute, due to a half-century of rising emissions. But the clean technology choices available today are also much more mature and cost competitive, providing options for much more efficient energy use, cleaner energy production and generation, and new kinds of storage. As a result, many of the component parts of a new type of energy system are clearly visible. The question is how effectively and quickly they can be deployed alongside traditional technologies, and then in place of them.

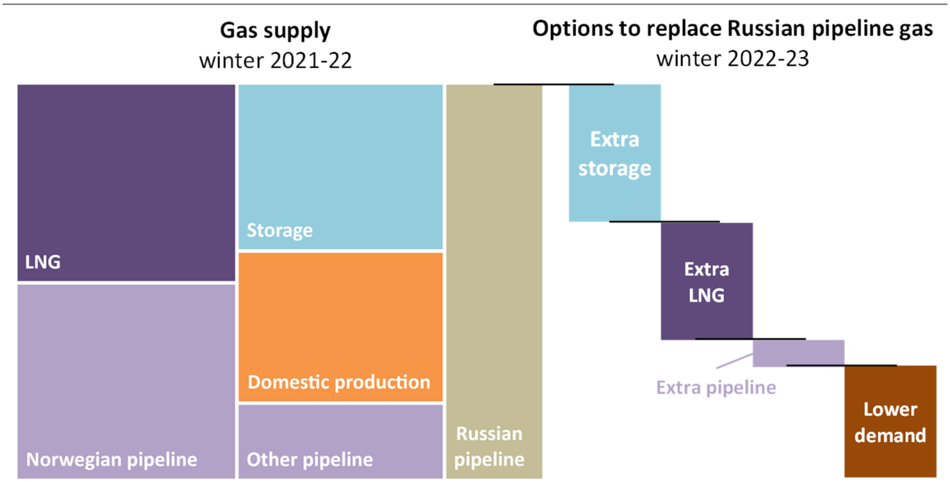
1.2 Causes of the crisis and immediate consequences

1.2.1 Causes of the crisis

The world is facing a global energy crisis of unprecedented depth and complexity. This is having far-reaching implications for many households, businesses and entire economies, prompting a range of short-term responses from governments as well as a deeper debate about the ways to avoid such disruptions in the future. Pressures on markets predated the Russian Federation's (hereinafter Russia) invasion of Ukraine, but its actions have tipped what was a strong recovery from the pandemic – strong enough to strain weakened supply chains and production capacity – into full-blown turmoil in energy markets, causing severe damage to the global economy.

This is a global crisis, but Europe is the main theatre in which it is playing out, and natural gas is centre stage. Russia is seeking to gain political leverage by withholding gas supplies and exposing consumers to higher energy bills and supply shortages over the winter heating season. As of September 2022, Russia's gas deliveries to the European Union are down by 80% compared to where they have been in recent years. This has naturally created significant pressure on European and global gas balances. Due to demand for heating, European gas demand is roughly twice as high during the winter months as during the summer, and is met by a combination of domestic production (which has been in decline), imports by pipeline and liquefied natural gas (LNG), and withdrawals from storage (Figure 1.1).

Figure 1.1 ▷ European Union and United Kingdom winter natural gas supply and options to compensate for a cut in Russian pipeline gas



Russian pipeline imports met 20% of gas demand in the European Union in winter 2021-22; managing without this gas requires alternative imports, use of storage and lower demand

EU gas storage facilities were more than 90% full in early October 2022, a considerable achievement given the cuts to Russian supply over the course of the year. In combination with lower demand and continued strong inflows from non-Russian sources, this opens a narrow but potentially safe pathway for Europe through the northern hemisphere winter months, albeit at highly elevated prices, on condition that the weather does not turn too cold. However, the balances for 2023-2024 look more challenging.

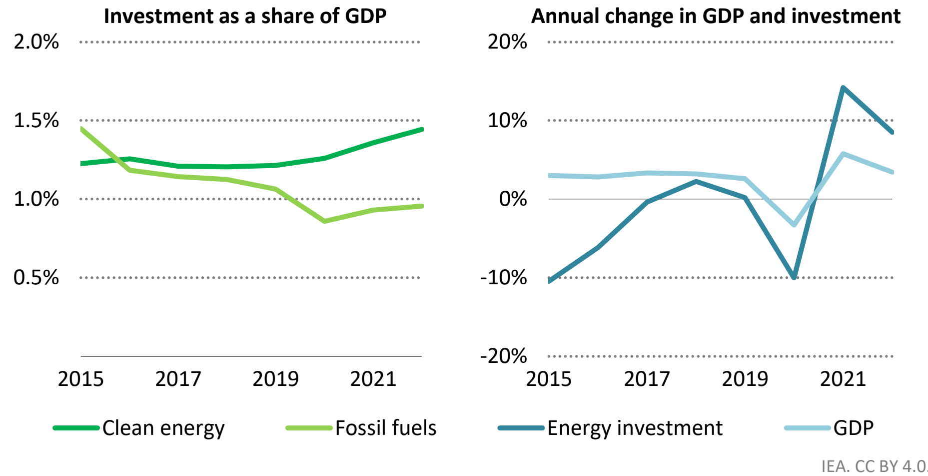
There are many strands to the energy relationship between Russia and Europe. Russia has acted to sever the gas relationship. The European Union has halted coal imports from Russia, meaning that coal deliveries from Europe's largest external supplier fell to zero as of August 2022. For the moment, Russian oil production and exports remain close to pre-war levels, despite some countries such as the United States and the United Kingdom imposing immediate restrictions on oil trade. Some reorientation of trade flows has already taken place, with lower flows of oil from Russia to the European Union and North America offset by higher exports to other markets, notably India, China and Türkiye. But the major changes lie ahead: Russia exported 2.6 million barrels per day (mb/d) of oil to the European Union in September 2022, and most of these exports will come to an end when an EU ban on seaborne crude oil imports from Russia enters into force in December 2022 and on a ban on oil products from Russia (which are mainly middle distillates) takes effect in February 2023.

The proximate cause of the crisis was Russia's invasion of Ukraine, but pressure on markets was visible before February 2022. The main reason was the speed of the economic rebound from the pandemic-induced slump in 2020; this stretched all manner of supply chains, including those in fuel supply. There were also weather-related factors, a higher incidence of outages to supply – often related to maintenance postponed from 2020 as a result of the pandemic – and what the IEA was calling "artificial tightness" in markets. In natural gas markets, this stemmed in large part from Gazprom's sluggishness in re-filling its European gas storage in the third- quarter of 2021, which in retrospect has to be seen in the context of Russia's invasion of Ukraine some months later and the pressure subsequently applied to Europe by cutting off gas supplies.

The key underlying imbalance, which had been some years in the making, relates to investment (Figure 1.2). This has been a recurrent theme in IEA analysis in the *World Energy Outlook* and *World Energy Investment* series. For five years after the conclusion of the Paris Agreement, the amount of investment going into energy transitions remained flat at around USD 1 trillion per year. Since clean energy technology costs continued to decline during this period, this was enough to generate year-on-year increases in deployment. But it remained far short of the amounts needed to support a thoroughgoing transformation of the energy system. Only in the last two years, 2021 and 2022, did clean energy spending see a notable uptick.

The other side of the investment coin is spending on fossil fuels. This dropped rapidly after the fall of the oil price in 2014-15, reflecting lower revenues and investor frustration at the poor returns that oil and gas companies were generating. In the absence of a much-needed acceleration to energy transitions to curb fossil fuel demand, the declines in oil and gas investment in the second-half of the 2010s presented a risk to market balances in the 2020s. In the *WEO-2016* Executive Summary, for example, we said that "if new project approvals remain low for a third year in a row in 2017, then it becomes increasingly unlikely that demand (as projected in our then New Policies Scenario) and supply can be matched in the early 2020s without the start of a new boom/bust cycle for the industry". Natural gas markets also faced the "risk of a hard landing" (IEA, 2016).

Figure 1.2 ▷ Historical energy investment and GDP trends



Energy investment was subdued from 2015 to 2020; fossil fuel investment dropped after the 2014-2015 oil price fall and clean energy spending did not start to pick up until recently

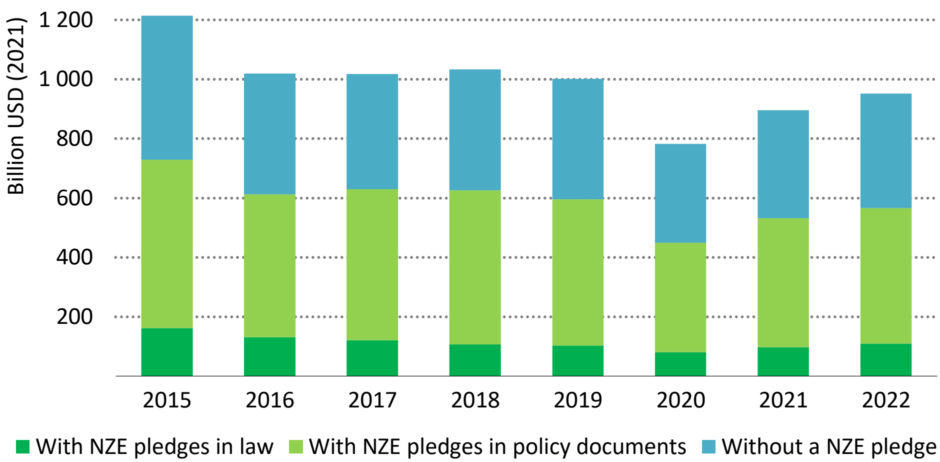
Acceleration in new approvals failed to materialise, however, at least in part because uncertainty over long-term demand led the industry to shy away from large capital-intensive projects. Even today, despite higher prices and huge windfall products for the oil and gas industry in 2022, upstream spending is the only significant segment of the investment picture that remains below pre-Covid levels.

The other underlying issue that has contributed to the crisis is Europe's continued high level of reliance on Russian energy. In 2021, one-out-of-five units of primary energy consumed in the European Union came from Russia. This reliance on Russia had long been identified as a strategic weakness, especially after the annexation of Crimea in 2014, and some infrastructure was built to diversify sources of imports, but Russian flows remained high. In the case of natural gas, Russia's share of European gas demand actually rose from 30% on average in 2005-10 to reach 40% in 2015-20.

Climate policies and net zero emissions commitments were blamed in some quarters for contributing to the run-up in prices, but it is difficult to argue that they played a role. More rapid deployment of clean energy sources and technologies in practice would have helped to protect consumers and mitigate some of the upward pressure on fuel prices. It would also have mitigated the post-pandemic rebound in energy-related carbon dioxide (CO_2) emissions which reached 36.6 gigatonnes (Gt) in 2021. The annual increase of 1.9 Gt was the largest in history, offsetting the previous year's pandemic-induced decline.

Moreover, there is scant evidence to support the notion that net zero emissions pledges have stifled traditional investments in supply, as these pledges are not yet correlated with changes in fossil fuel spending. Most net zero emissions pledges are recent, and many have yet to be translated into specific plans and policy measures. Our analysis of fossil fuel investment in countries with net zero emissions pledges (68 countries plus the European Union) shows that they are at a similar level to where they were in 2016, and that changes in investment levels in those countries in recent years are not noticeably different from those that have taken place in countries without net zero emissions pledges (Figure 1.3).

Figure 1.3 ▷ Fossil fuel investment in countries with and without net zero emissions pledges, 2015-22



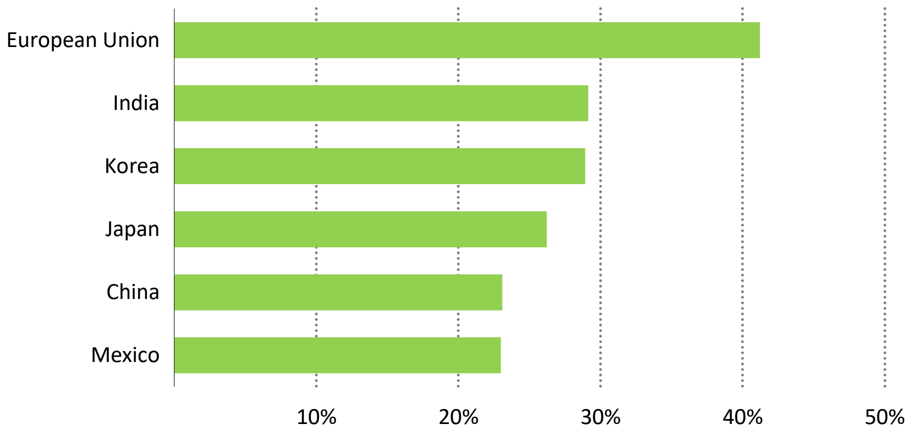
There are, as yet, few signs that net zero emissions pledges are correlated with lower global spending on fossil fuels

Notes: NZE = net zero emissions. Investment is based on countries where investment occurs rather than where it originates. Status of NZE pledges as of 2022.

1.2.2 Immediate consequences

The most visible consequence of the crisis was an explosion in energy prices. While oil prices above USD 100/barrel have been seen before, there is no precedent for the price levels seen in 2022 for natural gas, with prices at Europe's Title Transfer Facility (TTF) hub regularly exceeding USD 50 per million British thermal units (MBtu), the equivalent of more than USD 200/barrel. High fuel prices were the main reason for upward pressure on global electricity prices, in our estimation accounting for 90% of the rise in the average costs of electricity generation worldwide (natural gas alone for more than 50%). The costs of capital recovery added only about 5% to the price pressures, as the electricity sector continues to shift towards relatively capital-intensive technologies like solar PV and wind. The remaining 5% increase in costs was due to higher costs for maintenance and those related to CO_2 prices in several markets.

Figure 1.4 ▷ Year-on-year increase in average power generation costs by selected country and region, 2022



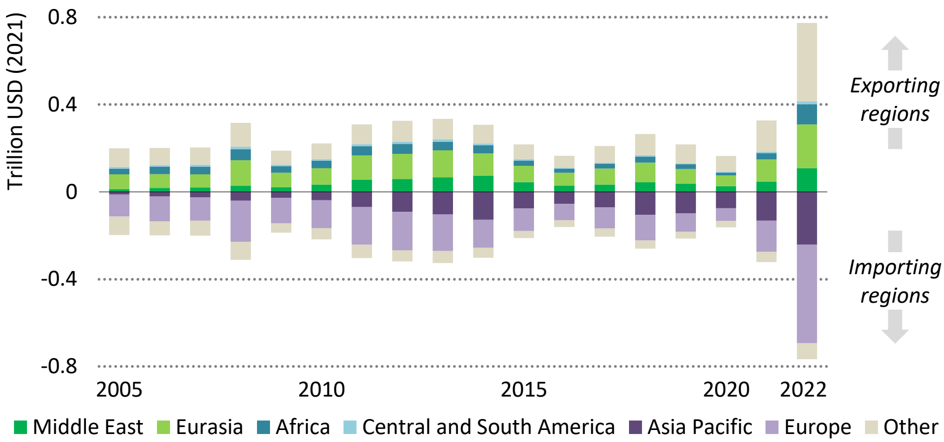
Increases in power generation costs were driven by higher fuel prices and have been particularly sharp in gas-importing countries and regions

The high cost of natural gas-fired power – typically the marginal source of generation – was the main factor behind a huge rise in EU wholesale electricity prices, with trends also abetted by higher coal, oil and CO_2 prices, reduced availability of nuclear power and a poor year for hydropower. Wholesale electricity prices in the European Union tripled in the first-half of 2022, well above the 40% increase in the underlying average costs of generation (Figure 1.4). This divergence, which produced huge excess revenues for some market participants, sparked a vigorous debate over the EU electricity market design and whether gas and electricity prices should somehow be de-linked.

The ripple effects of higher natural gas prices in Europe were felt around the world. One of the most immediate consequences of Russia's curtailment of gas deliveries was a sharp increase in European demand for LNG imports: in the first eight months of 2022, net LNG imports in Europe rose by two-thirds (by 45 billion cubic metres [bcm]) compared with the same period a year earlier. It fell mainly on Asia to balance the market; Asian LNG demand has fallen year-on-year in 2022 for the first time since 2015. Relatively weak demand in the

People's Republic of China (herein after China), due to slower economic growth and Covid-related lockdowns, has been a factor in easing market balances (the same is true for oil), although this raises questions about what lies ahead when demand in China starts to pick up. Elsewhere, high prices and shortfalls in supply have led to significant hardship for developing countries that rely on LNG.

Figure 1.5 ▹ Value of natural gas trade, 2005-2022

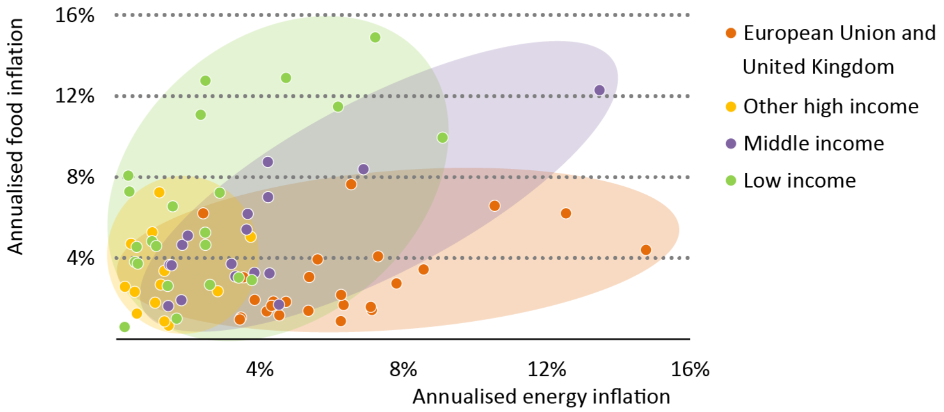


There is no precedent for the huge increase in payments for traded gas in 2022

One effect of the current high energy prices is a huge transfer of wealth from consumers to producers. The sums involved are large but not entirely unprecedented for oil, being similar to the amounts paid during the early 2010s, and prior to the decline in the oil price in late 2014. But they are extraordinary for natural gas (Figure 1.5). Natural gas is typically the junior partner in terms of revenue for hydrocarbon exporters, with the value of international trade in gas averaging around 20% of the total value of traded oil and gas between 2010 and 2021. This percentage is now set to increase to 40% in 2022.

The energy crisis is fuelling inflationary pressures, increasing food insecurity and squeezing household budgets, especially in poor households where a relatively high percentage of income is spent on energy and food. The effects of higher natural gas and electricity prices have been felt acutely across much of Europe. Elsewhere in the world, the consequences have varied according to the type of economy, but they are clearly negative in overall terms: the International Monetary Fund cut its expectations of global growth for 2022 from 4.9% in October 2021 to 3.2% in its October update (IMF, 2022a). Overall, low income countries are particularly exposed to higher food prices, to which higher energy and fertiliser costs contribute (Figure 1.6). The crisis has also been a further setback for efforts to improve energy access (Box 1.1).

Figure 1.6 ▷ Contributions of energy and food to inflation in selected countries, 2022



Energy is behind many of the inflationary impacts of the crisis in Europe, but higher food prices – to which energy contributes – are the main driver in many low income countries

Source: IEA analysis based on IMF (2022b).

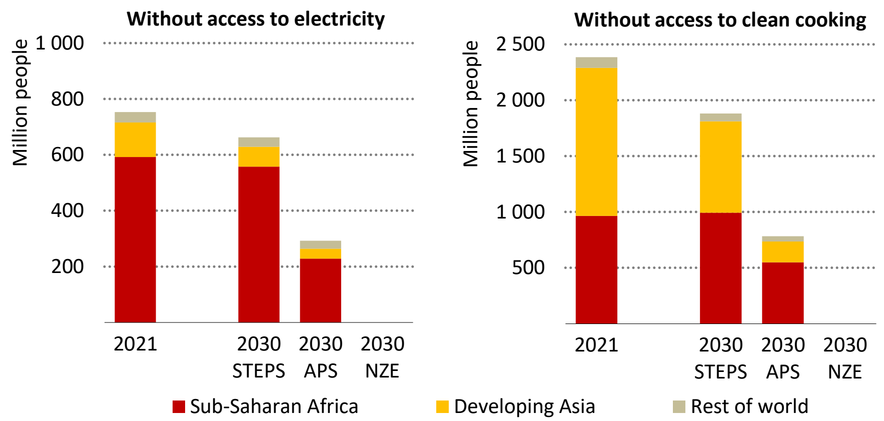
Box 1.1 ▷ Getting energy access back on track

Due to the combination of the pandemic and the current energy crisis, the IEA estimates that 75 million people that recently gained access to electricity are likely to lose the ability to pay for it, and that 100 million people that have gained access to cooking with clean fuels may forgo it on cost grounds, returning instead to the use of traditional biomass.

Getting the world on track for universal access to electricity and clean cooking will require dedicated additional effort from a wide range of national and international actors. Only half of the 113 countries without universal access to electricity have targets to increase access, and fewer than half of those aim to reach universal access by 2030. An even smaller number, e.g. Côte d'Ivoire, Kenya, Senegal, Rwanda and Myanmar, have comprehensive national electrification strategies in place. The achievement of national targets – as modelled in the APS – is therefore not enough to achieve full universal access to electricity by 2030 (the aim of Sustainable Development Goal 7). The NZE Scenario, by contrast, builds in achievement of the 2030 target (Figure 1.7).

The gap between the Sustainable Development Goal 7 (SDG 7) target and current policy ambitions is even wider in the case of clean cooking fuels. Some 128 countries currently lack universal access to clean cooking, but only 39 of them have clean cooking targets, and fewer than half of these are targeting universal access by 2030. China and Indonesia are close to being on track to achieve their targets but in many other countries there is a need to raise the current level of ambition and to improve implementation. As with access to electricity, universal access to clean cooking by 2030 is built into the NZE Scenario.

Figure 1.7 ▷ Number of people without access to electricity and clean cooking by scenario, 2021 and 2030



Well-formulated national strategies and international support are vital to regain momentum on improving energy access after Covid-19 and today's high energy prices

Notes: Sub-Saharan Africa excludes South Africa. STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Short-term policy responses to the crisis have been focused on affordability and security of supply, with mitigating measures that can be implemented quickly at a premium, even when they are expensive or come at the cost of temporarily higher emissions. One response has been to seek to protect consumers from some or all of the increase in prices, with massive interventions in particular to shield vulnerable consumers. Since September 2021, the IEA has tracked around USD 550 billion in government interventions, mostly in Europe, to shield consumers from the worst effects of the price spikes, with a large amount of additional support also under consideration in several countries. There have been measures to allow for higher coal-fired generation, to extend the lifetime of some nuclear power plants and to accelerate the flow of new renewable projects. Demand-side measures have generally received less attention, but there have been initiatives to encourage and incentivise cuts in energy use: at the European Union level, these include a voluntary 15% reduction in natural gas demand as well as a mandatory reduction target of 5% of electricity use in peak hours (demand which is typically met by gas-fired generation). There have also been various interventions to cap the revenues paid for cheaper sources of generation, which would otherwise be making huge gains because of the price-setting role of gas-fired plants, alongside temporary additional taxes on the profits of oil and gas companies, with the proceeds used to help ease the pressure on household and company energy bills.

Alongside these short-term measures, some governments have taken steps that will play out over the longer term. Some of these seek to increase oil and gas supply, via announcements of new incentives or licensing rounds,[1] or through support for new infrastructure, in particular new LNG terminals in Europe to facilitate the supply of non-Russian gas. But most of the new policy initiatives aim to accelerate the structural transformation of the energy sector. The European Union is raising its renewables and energy efficiency targets and putting significant resources behind achieving them. The adoption of the Inflation Reduction Act in the United States gives a boost to an array of clean energy technologies through the provision of USD 370 billion for energy security and climate change investments, with the potential to mobilise far larger sums from the private sector. The Japanese government is seeking to restart and build more nuclear plants and expand other low-emissions technologies with its Green Transformation (GX) plan. China continues to break records for investments in renewables and to add huge numbers of electric vehicles (EVs) to its stock each year. India has taken a key step towards establishing a carbon market and boosting the energy efficiency of buildings and appliances.

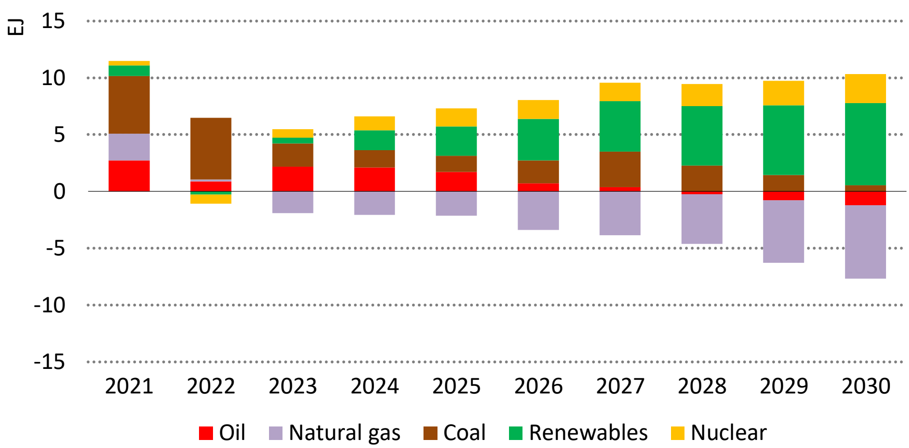
There remain huge uncertainties over how this energy crisis will evolve. The biggest concern is the war in Ukraine – how it will progress, when and how it might end. Others relate to the possibility of further escalation in prices, the severity of the 2022-23 winter, the extent to which Russian export flows can be redirected to other markets, and the way that high prices influence consumer behaviour or social attitudes towards clean energy transitions. But the current energy shock has already had a seismic effect, providing a vivid reminder – if one was needed – of the importance of energy security and diversity. In so doing, it has highlighted the fragility and unsustainability of many aspects of our current energy system and the wider risks that this poses for our economies and well-being. And it has played out against a backdrop of increasingly visible vulnerabilities and impacts from a changing climate. Times of crisis put the spotlight on governments, and the scenarios that we include in the *World Energy Outlook* are differentiated primarily by how policy makers respond.

[1] The typical lead times for upstream projects are considerable. Our analysis shows that for conventional upstream projects that have started production since 2010, it took on average around six years from the award of an exploration licence to discovery; nine years from discovery to project approval; and just over four years from approval to first production.

1.3 Outlook for energy markets and security

Today's high energy prices and gloomy economic outlook lead to lower energy demand growth in the STEPS and APS, both in the near term and out to 2030, than in the *WEO-2021* (IEA, 2021a). Faced with market uncertainty and high prices, consumers are forgoing purchases and industry is scaling back production. Despite a strong economic rebound from the pandemic in 2021, the assumed rate of average annual GDP growth for the rest of the decade has been revised down slightly to 3.3% (see Chapter 2). Energy demand rises more slowly in both the STEPS and APS as a result, and the mixture of fuels used to meet this demand growth changes substantially from previous projections (Figure 1.8).

Figure 1.8 ▷ Difference in total energy supply in the *WEO-2022* STEPS relative to the *WEO-2021* STEPS



Gas demand is markedly lower than in last year's STEPS while low-emissions sources – led by renewables – see even greater growth. The upside for coal proves short-lived.

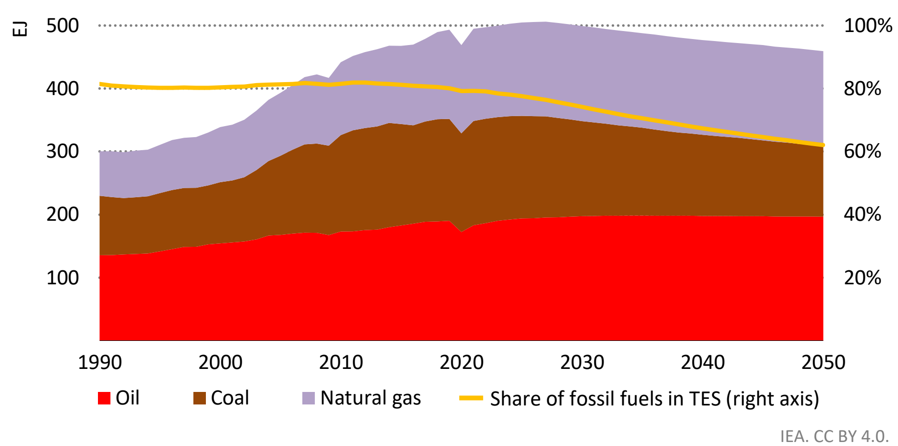
Notes: EJ = exajoule. Positive numbers indicate total energy supply is higher in the STEPS in this *Outlook* than in the *WEO-2021* STEPS.

The trends to 2030 in the STEPS are consistent with a world that is grappling with a host of near-term vulnerabilities, concerned about the high cost of imported fuels but also about climate change, and aware of the opportunities afforded by cost-effective clean energy technologies. Natural gas prices remain at very high levels by historical standards until the middle of the decade, causing gas to lose ground as new natural gas power plant constructions slows, with countries opting for other sources to maintain system adequacy and flexibility while accelerating renewables. Trade flows undergo a profound reorientation as importing regions tend to prioritise domestic resources where possible in an attempt to ensure reliable supplies of energy and limit exposure to volatile international markets, and as the implications of Europe's shift away from Russian imports reverberate around the system. Overall, energy security concerns reinforce the rise of low-emissions sources and efficiency: energy demand growth of almost 1% a year to 2030 is largely met by renewables. For the first time, the STEPS in this *Outlook* shows a noticeable peak in overall fossil fuel consumption within this decade (Box 1.2). However, while showing distinct signs of change, the trends in the STEPS do not yet amount to a paradigm shift.

Box 1.2 ▷ Era of fossil fuel growth may soon be over

The Stated Policies Scenario in this *Outlook* is the first *WEO* scenario based on prevailing policy settings that sees global demand for each of the fossil fuels exhibit a peak or plateau. Coal demand peaks within the next few years, natural gas demand reaches a plateau by the end of the decade, and oil demand reaches a high point in the mid-2030s before falling. The result is that total demand for fossil fuels declines steadily from the mid-2020s by around 2 exajoules (EJ) (equivalent to 1 million barrels of oil equivalent per day [mboe/d]) every year on average to 2050 (Figure 1.9).

Figure 1.9 ▷ Fossil fuel demand in the STEPS, 1990-2050



Total fossil fuel use sees a definitive peak for the first time in this year's STEPS. The share of fossil fuels in the energy mix falls to around 60% in 2050, a clear break from past trends

Note: EJ = exajoule; TES = total energy supply.

Changes in fossil fuel use have broadly followed changes in GDP for decades, and global fossil fuel demand has remained at around 80% of total demand for decades. The 2022 STEPS projections are now putting the world on a path towards a significant break with these trends within a few years. By 2030, fossil fuels account for less than three-quarters of total energy supply, and by 2050 their share falls to just above 60%. These trends are emblematic of a shift in the energy landscape since the Paris Agreement. In the *WEO-2015*, for example, the scenario equivalent to the STEPS (then called the New Policies Scenario) saw a steady rise in demand for each of the fossil fuels to 2040, and total fossil fuel use in 2040 was projected to be nearly 20% larger than in 2040 in this year's STEPS projections (IEA, 2015). The biggest single change since then has been in the power sector: the STEPS in this *Outlook* sees a much higher level of renewables deployment to 2030 and beyond than its predecessor scenario did in 2015, and this comes at the expense of coal and natural gas.

The APS builds on these trends, but assumes that governments, companies and citizens take further measures to ensure that the response to these trends is consistent with long-term climate goals. These have collectively become more ambitious since the *WEO-2021* as a result of new pledges and targets announced since then, notably in India and Indonesia. In the APS, global energy demand is set to increase by 0.2% per year to 2030, compared with 0.8% per year in the STEPS, reflecting more active measures in the APS to curb demand through energy efficiency gains. There is also a much more dramatic shift in favour of low-emissions sources of energy. The NZE Scenario maps out a complete and even more rapid transformation which is consistent with a path to net zero CO_2 emissions from energy and industrial processes by 2050.

The rate at which the energy efficiency of different economies improves is a crucial variable in our *Outlook*. Between 2017 and 2020, energy intensity has improved on average by 1.3% per year – considerably lower than the 2.1% seen between 2011 and 2016 – and the rate of improvement further slowed to 0.5% in 2021. In the STEPS, energy intensity improves by 2.4% per year from 2021 to 2030; as a result, around 44 EJ (10% of total final consumption) is avoided by 2030. However, this still leaves a great deal of untapped potential: in the APS, energy intensity improves by 3% per year, and even more rapidly in the NZE Scenario.

1.3.1 Trends and vulnerabilities across the energy mix

Electricity

There are many uncertainties in our *Outlook*, but one point which is common to all the scenarios is the rising share of electricity in global final energy consumption. From 20% today, this increases to 22% by 2030 in the STEPS, and 28% in 2050. In the APS, the share rises to 24% in 2030 and 39% in 2050. In the NZE Scenario, the share rises further to 28% by 2030 and 52% by 2050. This is associated with a huge overall increase in global electricity demand over the coming decades – by mid-century, electricity demand is 75% higher than today in the STEPS, 120% higher in APS and 150% in the NZE Scenario. Clean electricity and electrification are absolutely central to the shift to a net zero emissions system.

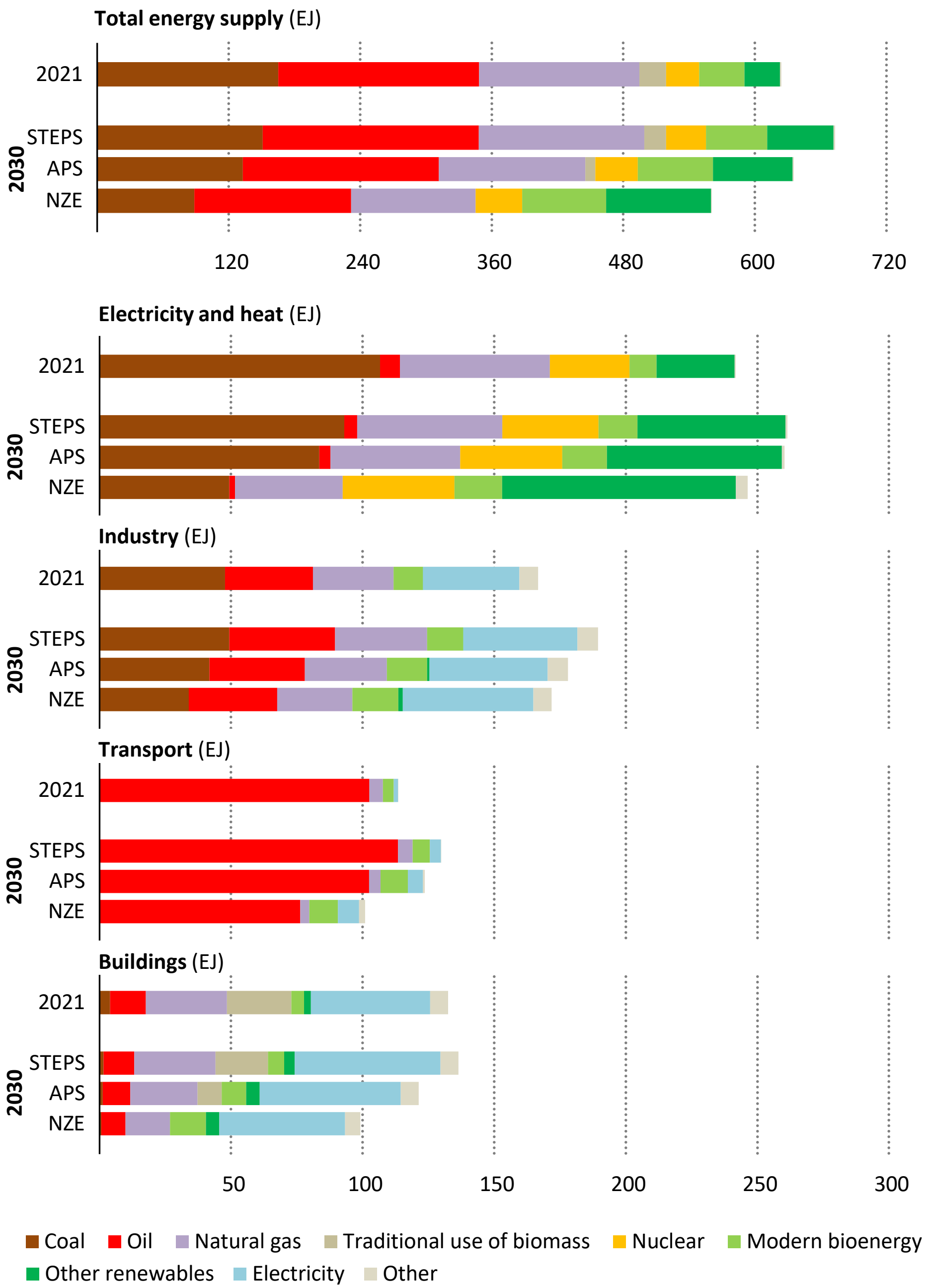
The bulk of the growth comes from emerging market and developing economies, where electricity meets a broad range of residential, commercial and industrial needs. Growing populations, higher incomes and rising temperatures lead to rapidly increasing demand for space cooling, which is one of the biggest contributors to electricity demand growth; an extra 2 800 terawatt-hours (TWh) globally for space cooling to 2050 in emerging market and developing economies in the STEPS is the equivalent of adding another European Union to current global electricity demand. Comparing this demand for space cooling across the scenarios provides a useful illustration of the value of stringent efficiency policies: in the APS, efficiency gains cut the growth in cooling demand by almost half; even more stringent standards for air conditioners in the NZE Scenario, together with better insulation in homes, cut this by half again.

As modern lives and economies become increasingly reliant on electricity, so the reliability and affordability of electricity supply take centre stage in any discussion about energy security, and decarbonisation of electricity supply becomes central in planning for net zero emissions goals. Around 65% of the coal used globally in 2021 and 40% of the natural gas were for power generation. Coal use for electricity generation is rising in many countries, at least temporarily, in response to the energy crisis. The shares of coal and natural gas in power generation are set to decrease to 2030 in each scenario, but to varying degrees (Figure 1.10). The global average carbon intensity of electricity generation is currently 460 grammes of carbon dioxide per kilowatt-hour (g CO_2/kWh), heavily influenced by the amount of coal in the mix. By mid-century, unabated coal falls to 12% of total generation in the STEPS, down from 36% today, helping to reduce the carbon intensity of electricity generation to 160 g CO_2/kWh. This point is reached 20 years earlier in the NZE Scenario, which sees carbon intensity dip below zero by 2050 as negative emissions in the power sector offset residual emissions in industry and transport.

Changing demand patterns and rising shares of solar photovoltaics (PV) and wind in the electricity mix put a premium on power system flexibility as a cornerstone of electricity security. Flexibility needs (measured as the amount the rest of the system needs to adjust on an hourly basis to accommodate demand patterns and the variability of wind and solar output) increase in all scenarios; they double in the APS by 2030, for example, and then nearly double again by 2050. There are four main sources of flexibility in power systems: generation plants, grids, demand-side response and energy storage. For the moment, thermal power plants perform most of the adjustments to match energy demand and supply, but as other forms of flexibility develop and expand, coal and then gas-fired plants see their role as a source of flexibility progressively diminish and eventually disappear. Removing existing sources of flexibility before others are scaled up represents a major risk to electricity security.

Adequate investment to expand and modernise grid infrastructure is a case in point. Our projections in the STEPS see annual investment of USD 770 billion in infrastructure and storage to 2050 as grids increase in length by about 90% over the period. Investment in grids and storage is 30% higher on average in the APS, at close to USD 1 trillion per year. However, there are obstacles that need to be addressed. In practice, the permitting and construction of a single high power overhead line (>400 kilovolts) can take as much as 13 years, depending on the jurisdiction and length of the line, with some of the longest lead times found in advanced economies. Transmission bottlenecks are already creating numerous inefficiencies and risks. For example, authorities in Viet Nam announced in early 2022 that they would not connect any new solar PV or wind project to the grid for the rest of the year, while in Mongolia 12% of the electricity generated in 2021 could not be transported to end-users.

Figure 1.10 ▷ Global energy supply and demand by sector, scenario and fuel



Energy efficiency, electrification and expansion of low-emissions supply are the hallmarks of rapid transitions to 2030

Clean energy supply and critical minerals

Clean energy, including both low-emissions electricity and fuels, is the big growth story of this *Outlook.* The extent of that growth still rests in the hands of policy makers, even where – as in the case of wind and solar – they enjoy large cost advantages over other technologies. But there are signs that the energy crisis is galvanising increased policy support, with the Inflation Reduction Act in the United States being a particularly striking example.

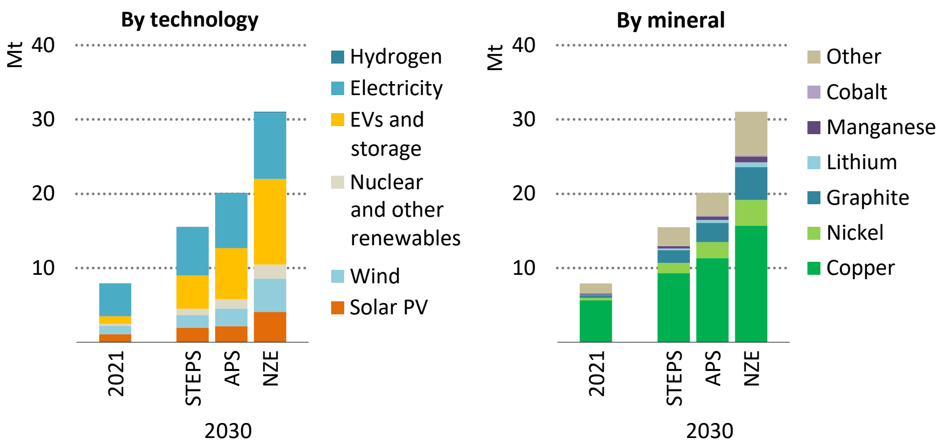
Low-emissions sources now account for around 40% of electricity generation, with 30% coming from renewables and another 10% from nuclear. Deployment of solar PV and wind power accelerates in all scenarios, setting new records every year to 2030: by mid-century their combined share of these two technologies in the electricity mix reaches 45% in the STEPS and 60% in the APS. Within ten years, if countries are taking the necessary action to deliver on their climate pledges, the world will be deploying around 210 gigawatts (GW) of wind capacity each year and 370 GW of solar. The balance of deployment varies by region and country. In the United States and India, for example, solar PV becomes the leading technology. By contrast, the European Union moves towards an electricity system dominated by onshore and offshore wind, with both sources combined accounting for more than 40% of total generation in 2050 in the STEPS and over 50% in the APS and NZE Scenario.

The huge rise in the share of solar PV and wind in total generation in all scenarios fundamentally reshapes the power system and significantly increases the demand for power system flexibility to maintain electricity security. This puts a premium on dispatchable low-emissions technologies, such as hydropower, bioenergy and geothermal. It also encourages new approaches such as the co-firing of ammonia in coal plants and low-emissions hydrogen in natural gas plants, as well as some retrofits of existing power plants with carbon capture, utilisation and storage (CCUS). Regions with high shares of solar PV relative to wind tend to see higher relative levels of battery deployment than regions in which wind predominates, such as China or the European Union, because the short-duration storage that batteries provide is well suited to smooth out the daily cycle of solar PV-based electricity generation. Regions where wind is the leading power generation technology tend to rely on a wider range of sources of flexibility.

Investment in nuclear power is also coming back into favour in some countries. There have been announcements of lifetime extensions for existing reactors, often as part of the response to the current crisis, as well as announcements of new construction, for example in Japan and France. Worldwide, the largest new build nuclear programme is in China as it works towards its goal of carbon neutrality by 2060. There is growing interest in the potential for small modular reactors to contribute to emissions reductions and power system reliability. The share of nuclear in the generation mix remains broadly where it is today – around 10% – in all scenarios.

Critical minerals are a fundamental part of the energy and electricity security landscape. Demand for critical minerals for clean energy technologies is set to rise two to fourfold by 2030 (depending on the scenario) as a result of the expanding deployment of renewables, EVs, battery storage and electricity networks (Figure 1.11). Copper use sees the largest increase in terms of absolute volumes, with current demand of around 6 million tonnes (Mt) per year increasing to 11 Mt by 2030 in the APS and 16 Mt in the NZE Scenario, but other critical minerals experience faster rates of demand growth, notably silver and silicon for solar PV, rare earth elements for wind turbine motors and lithium for batteries. Both the extraction and processing of critical minerals are highly concentrated geographically: unless the need for stronger resilience and diversity in supply chains is addressed, there is a risk that the increasing use and importance of critical minerals could become a bottleneck for clean energy deployment.

Figure 1.11 ▷ Mineral requirements for clean energy technologies by scenario, 2021 and 2030



Mineral requirements for clean energy technologies quadruple to 2030 in the NZE Scenario, with particularly high growth for materials for electric vehicles

Notes: Mt = million tonnes; EVs = electric vehicles. Includes most of the minerals used in various clean energy technologies, but does not include steel and aluminium. See IEA (2021b) for a full list of minerals assessed.

Recycling is an important and – for the moment – underutilised option to reduce critical minerals demand: 95% of solar panel components by mass are recyclable, and the percentage for wind turbines is similar. In the NZE Scenario, annual capacity retirements for solar PV rise from 3 GW in 2030 to 400 GW in 2050, and for wind turbines from 16 GW to 240 GW over the same period. Further policy efforts are needed to boost recycling and ensure that the solar panels and wind turbines reaching the end of their life do not end up in landfills. Other untapped opportunities for reuse and recycling include spent EV batteries, which can retain large amounts of unused energy that no longer meet the standards for use in a vehicle; spent EV batteries typically maintain about 80% of their total usable capacity.

While not increasing at the scale of low-emissions electricity, the prospects for low-emissions fuels are brightening, with biogases and low-emissions hydrogen in particular getting a boost from the current energy crisis. In the APS, global low-emissions hydrogen production rises from very low levels today to reach 30 million tonnes of hydrogen (Mt H_2) per year in 2030. This is equivalent to 100 bcm of natural gas (although not all low-emissions hydrogen would replace natural gas use). More ambitious production targets are also being set in many countries for biogases and biomethane. Efforts to promote the use of hydrogen are concentrated in Europe and the United States, but other countries are also active in this field: Japan, for example, aims for a 20% rate of co-firing imported ammonia at its coal-fired power plants by 2030, and this will require 0.5 Mt H_2 per year.

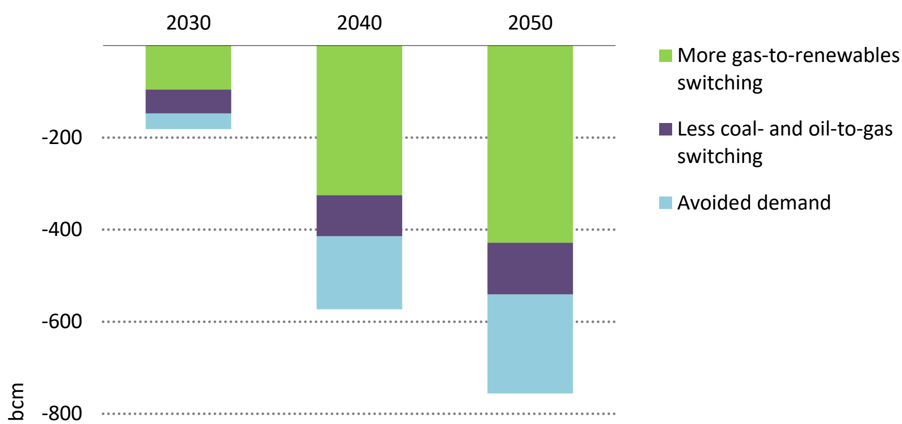
Liquid fuels are deriving less benefit from current market conditions: disruption to food supply chains and high fertiliser prices mean liquid biofuel costs have risen sharply. To avoid conflicts between food production and affordability, there is a general shift in planning for energy transitions away from conventional bioenergy sources towards advanced biofuels, and a particular focus on two inputs: sustainable waste streams that do not require specific land use and dedicated short rotation woody crops grown on cropland, pasture land and marginal lands that are not suited to food crops. In the NZE Scenario, there is no increase in cropland use for bioenergy and no bioenergy crops are grown on existing forested land. Liquid biofuels increase from 2.2 million barrels of oil equivalent per day (mboe/d) in 2021 to 3.4 mboe/d in the STEPS, 5.5 mboe/d in the APS and 5.7 mboe/d in the NZE Scenario in 2030. Aviation and shipping are the largest contributors to the rise in liquid biofuel demand in the APS and NZE Scenario as road transport is increasingly electrified.

Natural gas

The era of rapid growth in natural gas seems to be drawing to a close. In the STEPS, demand rises by less than 5% between 2021 and 2030 and then remains flat at around 4 400 bcm through to 2050. This is about 750 bcm lower in 2050 than in the corresponding scenario in the *WEO-2021* (Figure 1.12). Higher near-term prices, more rapid electrification of heat demand, faster uptake of other flexibility options in the power sector – and in some cases reliance on coal for slightly longer – all dampen the outlook for gas. New policy initiatives also play an important part: for example, the support provided for a variety of clean energy technologies by the US Inflation Reduction Act is a key reason why natural gas demand in the United States is around 250 bcm lower by mid-century, compared with the STEPS in the *WEO-2021*. Russia's invasion of Ukraine and its cuts in gas supply to the European Union also accelerate Europe's structural shift away from natural gas.

In both the STEPS and APS, natural gas prices in importing countries in Europe and Asia remain high over the next few years as Europe's drive to reduce reliance on Russian imports keeps global gas markets tight during a relatively barren period for large new gas export projects. A rebalancing comes later in the 2020s when slower demand growth coincides with new supply projects coming online. But this crisis has undercut momentum behind natural gas expansion in some large potential markets in south and southeast Asia and put a significant dent in the idea of gas as a transition fuel. Globally, around one-quarter of the downward revision to gas demand to 2030 in this year's STEPS is due to less switching from coal and oil to natural gas, but most of it reflects accelerated switching from natural gas to clean energy. In the NZE Scenario, natural gas demand falls further and faster than in the STEPS and APS, declining to 3 300 bcm in 2030 and 1 200 bcm in 2050. Around 1 900 bcm equivalent of low-emissions gases – hydrogen, biogases and synthetic methane – are consumed globally in the NZE Scenario in 2050.

Figure 1.12 ▷ Drivers of change in natural gas demand in the *WEO-2022* STEPS relative to the *WEO-2021* STEPS



Natural gas demand in this year's STEPS is around 750 bcm lower in 2050 than in the WEO-2021, driven mainly by switching from natural gas to renewables

Note: bcm = billion cubic metres.

In all our scenarios, the European Union compensates for the loss of Russian imports with an accelerated transition away from natural gas through a surge in renewable capacity additions and a push to retrofit buildings and install heat pumps, alongside an increased near-term call on non-Russian supply, notably via LNG. Additional annual clean energy investment of some USD 65 billion to 2030 in the APS is more than offset over time by lower natural gas import costs. Meanwhile there are no easy diversification options for the Russian gas traditionally exported to Europe.

The broader gas security landscape is defined by three key questions. First concerns the role of gas in the electricity market. Gas accounted for 23% of global electricity generation in 2021 and this share declines in all scenarios, albeit not as precipitously as that of coal. But declines in the volume of gas consumed for power generation do not imply a commensurate reduction in the value of gas to electricity security: natural gas-fired capacity remains a critical source of power system flexibility in many markets, especially to cover for seasonal variations in demand. Europe's gas storage continues to play a vital role: the share of gas stored to total gas demand in 2030 in the APS is similar to the share in 2021.

Second concerns the level of investment. Gas infrastructure investments are capital intensive and typically pay back over decades; they are therefore vulnerable to uncertainties concerning long-term demand. This has already been a stumbling block for gas diversification efforts in Europe: most potential suppliers are looking for long-term commitments, which European buyers are unwilling to provide because strong near-term needs are unlikely to be sustained into the 2030s. And a similar dilemma may come to Asia. The commercial case for new LNG investments in the APS is undercut by falling import demand in emerging market and developing economies in Asia in the 2040s and beyond. Shortening economic lifetimes to ten years would reduce the risk of new capacity additions turning into stranded assets, but it would also increase the break-even gas price needed to fully recoup investment costs by around 20% on average. A shift to low-emissions hydrogen and hydrogen-based fuels could provide a partial answer to this dilemma, but is unlikely to offer a complete solution.

The third question concerns flexibility of delivery. Around 50% of current global LNG trade, 250 bcm, is flexible in the sense of having its end destination determined cargo-by-cargo by price competition at a late stage: the rest is governed by fixed point-to-point delivery arrangements. The current energy crisis has illustrated this flexibility well, with high prices in Europe incentivising a major influx of cargoes to meet the continent's shortfall in gas, albeit at the expense of gas importers elsewhere, notably among developing countries in Asia. However, while flexibility on the supply side is likely to be underpinned by a further rise in LNG exports from the United States (facilitated by the reductions in domestic demand arising from the Inflation Reduction Act), there are open questions about flexibility on the demand side. The power sector is typically an important provider of flexibility, as utilities often have the ability to switch to other fuels if gas becomes too costly. But the phase-out of coal will reduce this flexibility: as a result, gas demand in Europe in particular is likely to become less responsive to price, and demand-side flexibility is likely to become concentrated in other markets, notably in China.

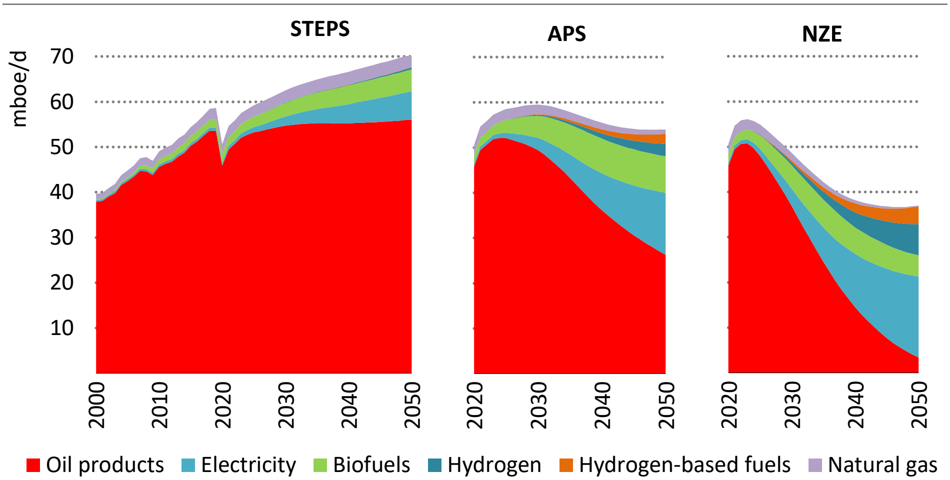
Oil

Oil demand peaks in each scenario in this *Outlook*. In the STEPS, demand reaches a high point in the mid-2030s at 103 mb/d and then declines very gently to 2050. Global gasoline demand peaks in the near term and falls as EVs deploy. Demand in advanced economies declines by 3 mb/d to 2030, mainly because of reductions in road transport, but this is more than offset by increases in emerging market and developing economies where demand rises by 8 mb/d this decade. Globally, the main sectors seeing an increase in the use of oil are aviation and shipping, petrochemicals (where oil is used as feedstock), and heavy trucks, where oil is used as a fuel and not displaced by the rise of EVs in the same way as in other road transport modes. These sectors see a rise in demand of around 16 mb/d between 2021 and 2050, but from the mid-2030s growth in these sectors is more than offset by declining oil use elsewhere, especially in passenger cars, buildings and power generation.

There is no shortage of oil resources worldwide to cover this level of demand in the STEPS to 2050; a key uncertainty for oil security relates to the adequacy of investment. The impact of the Covid-19 pandemic and the low level of investment in recent years mean there are relatively few new resources under development and a dwindling stock of discovered resources in the non-OPEC world available to be developed. New oil resources discovered in 2021 were at their lowest level since the 1930s. Moreover, there are concerns in some quarters in several non-OPEC countries about the commercial wisdom and social acceptability of embarking on significant high upstream capital expenditure. The STEPS sees near-term increases in output in the United States, Guyana and Brazil, among others, but reliance on major resource-holders in the Middle East grows steadily: the share of OPEC countries in global oil production rises from 35% in 2021 to 36% in 2030 and 43% in 2050, implying an increasing degree of market power for that group of producers. Persistent under-production in recent years among this group, relative to the targeted levels, may be a harbinger of the risks that lie ahead.

The outlook for oil is very different in the APS, where stronger policy action leads global oil demand to peak in the mid-2020s before dropping to 93 mb/d in 2030 (similar to the level of demand in 2019). Oil demand in advanced economies falls by 7.5 mb/d between 2021 and 2030 and increases by 4 mb/d in emerging market and developing economies. It is different again in the NZE Scenario, where global oil demand never recovers to its 2019 level and falls by nearly 20 mb/d between 2021 and 2030, led by a sharp decline in oil use in passenger cars (Figure 1.13).

Figure 1.13 ▷ Energy use in transport by scenario, 2000-2050



Transport has long been the bedrock of oil demand, but its role weakens in the APS and NZE Scenario as electricity displaces very large volumes of oil

Note: mboe/d = million barrels of oil equivalent per day.

These two scenarios ease the risks on the supply side that arise in the STEPS, but, despite today's scramble for oil products, they imply severe long-term pressures for refiners. In the APS, more than half of current refining capacity faces the risk of lower utilisation or closure by 2050, and there are few capacity additions after projects currently under construction come online. Those refiners that survive, invest to reduce emissions from refining operations, notably via low-emissions hydrogen, CCUS and efficiency improvements. They also view integration with petrochemical operations as a major strategic priority, given that the use of oil as a petrochemical feedstock is the most durable element of demand. It was the only use of oil that increased in 2020 amid the disruption of the Covid-19 pandemic, and demand remains relatively robust even in very rapid transitions: in the NZE Scenario, oil use for passenger cars falls by 98% between today and 2050, but oil use for petrochemicals falls by only 10%, despite policies to ban or reduce single-use plastics, improve recycling rates and promote alternative feedstocks. This is not to say that these policies have no effects: global average recycling rates for plastics increase from the current level of 17% to 27% in 2050 in the STEPS, 50% in the APS, and 54% in the NZE Scenario.[2] Many refiners are now considering expansion into plastics recycling as another way to secure new revenue streams, alongside areas such as liquid biofuels and low-emissions hydrogen.

Coal

Coal consumption is projected to fall in all scenarios, declining by 10% to 2030 in the STEPS, by 20% in the APS over the same period, and by 45% in the NZE Scenario. In the near term, coal demand increases as the energy crisis leads to some switching away from natural gas because of concerns about high prices and availability. As a result, coal demand in the STEPS is higher in 2030 than in the same scenario in the *WEO-2021*. This increase in demand, however, is relatively short-lived: in the STEPS, coal demand is lower in 2030 than it is today (although not as low as projected in the STEPS in the *WEO-2021)*. By and large, the current crisis pushes up utilisation rates for existing coal-fired assets, but does not bring higher investment in new ones. This amount of additional capacity, however, does prolong the period until global coal-fired capacity peaks (2025 in the STEPS).

In addition to increased demand in the power sector, coal sees a rise in demand in industry in emerging market and developing economies, where it already accounts for 35% of energy used by industry. These trends in power and industry keep coal demand around today's elevated levels to the mid-2020s, but structural decline sets in thereafter. Overall coal consumption shows a more sustained rise only in a few fast growing countries and regions, notably India and Southeast Asia. In India, coal demand in the STEPS does not peak until the early-2030s, when the deployment of renewables in the power sector speeds up; in the APS, this peak occurs in the late 2020s, and the subsequent decline in coal demand is considerably steeper.

[2] Globally, 17% of plastic waste is collected for recycling today although there are large differences between regions: for example, 25% is collected for recycling in Europe and less than 10% in the United States. Recycling rates for plastics are much lower than recycling rates for steel (80%), aluminium (80%) and paper (60%).

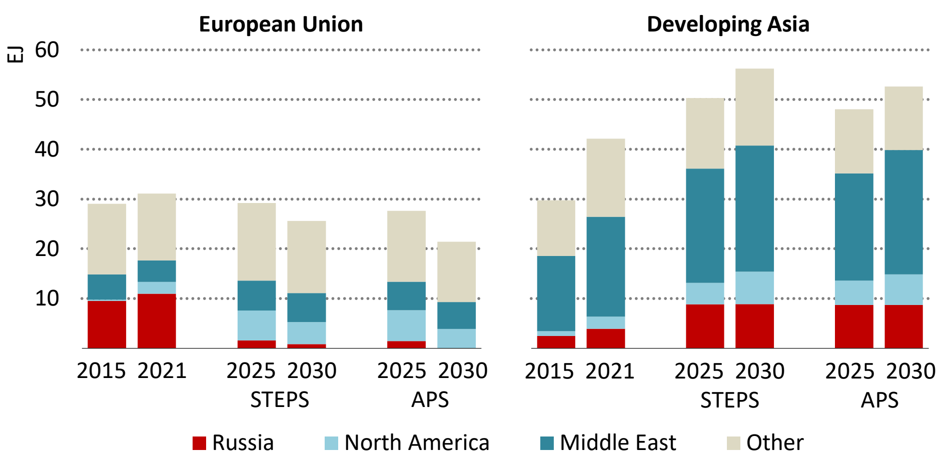
Advanced economies consumed around 1 000 million tonnes of coal equivalent (Mtce) of coal in 2021, accounting for just under 20% of global coal demand (for context, coal demand in China increased by an average of 100 Mtce each year between 2000 and 2020). Three-quarters of advanced economy coal use is in the power sector; in the APS, where countries meet their climate targets, unabated coal generation falls by around 80% to 2030 and is phased out completely by 2040. The NZE Scenario includes an even more ambitious timetable: it sees an end to unabated coal use for electricity generation in advanced economies by 2035 and worldwide by 2040.

Focus: Russia and the reshuffling of global energy trade

The *World Energy Outlook* has long highlighted the prospect of changes in the geography, scale and composition of international energy trade, notably the shift in fossil fuel imports towards Asia, the rising importance of trade in critical minerals and the emergence of trade in hydrogen and hydrogen-based fuels. Some of these changes are now being turbo-charged by Russia's invasion of Ukraine, which has led to the abrupt severance of the large and important inter-regional energy trade relationship between Russia and Europe.

All trade ties with Europe based on fossil fuels are ultimately undercut in our scenarios by the region's net zero emissions ambitions, but Russia's ability to deliver at relatively low cost meant that it lost ground only gradually in previous editions of the *Outlook*. Now the rupture has come with a speed that few imagined possible, and our scenarios assume that there is no way back. This means a major reshuffling of international trade, with inevitable implications for the geopolitics of energy.

Figure 1.14 ▷ Crude oil and natural gas imports to the European Union and emerging market and developing economies in Asia by origin



Russia's oil and gas exports switch focus to developing Asia in the STEPS and APS, but gains in these new markets are less than losses in exports to Europe

Note: EJ = exajoule.

The largest uncertainty regards Russia's ability to find alternative export markets. The prospects vary by fuel, with natural gas presenting Russia with the most difficult dilemma. In our scenarios, Russia attempts to pivot to Asia and other non-European markets, but is unsuccessful in finding markets for all of the flows that previously went to Europe, and it struggles in some cases to develop new resources and infrastructure (Box 1.3). Total Russian export levels are considerably lower than in previous *WEOs*, and Russia never returns – in any of our scenarios – to the export levels that it saw in 2021 (Figure 1.14).

Box 1.3 ⊳ What next for Russian oil and gas?

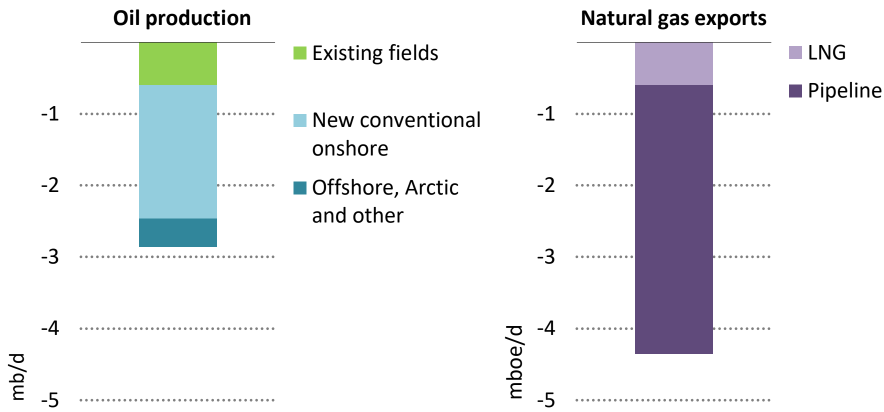
The outlook for Russian oil and gas was marked by uncertainty well before its invasion of Ukraine. Markets for Russian exports were shifting, but infrastructure links were still concentrated in Europe. Future production growth would need to come from more challenging and remote deposits, yet some important upstream technologies were subject to sanctions imposed after the annexation of Crimea in 2014. And oil and gas assets were being concentrated in the hands of a few state-owned champions to the detriment of the private or semi-private players – both domestic and international – that drove much of Russia's oil and gas growth since 2000.

The invasion of Ukraine deepened all of these dilemmas. Major companies, led by Rosneft, had announced increases in investment for 2022, but these are now far from certain. Along with the loss of key European markets, the sanctions put in place by the European Union and United States are considerably tougher now than in 2014. They include wide-ranging restrictions on the ability of international companies to invest in Russia, on the scope for Russian companies to raise finance internationally, and on Russian access to western technology. Russia had attempted to work around the earlier restrictions through a programme of import substitution, which was only partially effective. Some fields are at risk of being shut in – a jolt from which older reservoirs in particular might struggle to recover.

There are many uncertainties about how this plays out, but our projections in the STEPS and APS suggest that the key long-term challenges for Russia are concentrated in the upstream for oil, and in the midstream for gas (the issues are moot in the NZE Scenario, as no new developments are required). A growing share of Russian oil production had been set to come from new production areas, including projects in Eastern Siberia, the Arctic and offshore, as well as other hard-to-recover resources. Risks to the timing and cost of these developments have compounded, and they are amplified by the absence of western companies, technologies and some service providers (Figure 1.15).

Prior to its invasion of Ukraine, Russia planned to use LNG to diversify export flows away from Europe with a stated aim to export 170-200 bcm of LNG per year by 2035, up from around 40 bcm currently. Now this appears a distant prospect without international partners and technologies, especially for liquefaction. Novatek has developed a home-grown liquefaction technology called Arctic Cascade, used for the fourth train of the Yamal LNG project, but implementation was beset by difficulties and delays. Now most of Russia's LNG expansion plans are back on the drawing board.

Figure 1.15 ▷ Changes in Russian oil production and natural gas export in 2035 in the *WEO-2022* STEPS relative to the *WEO-2021* STEPS



Russia's oil and gas outlook has deteriorated since the WEO-2021, it will be tough for it to develop new upstream oil projects and to find alternative markets for gas

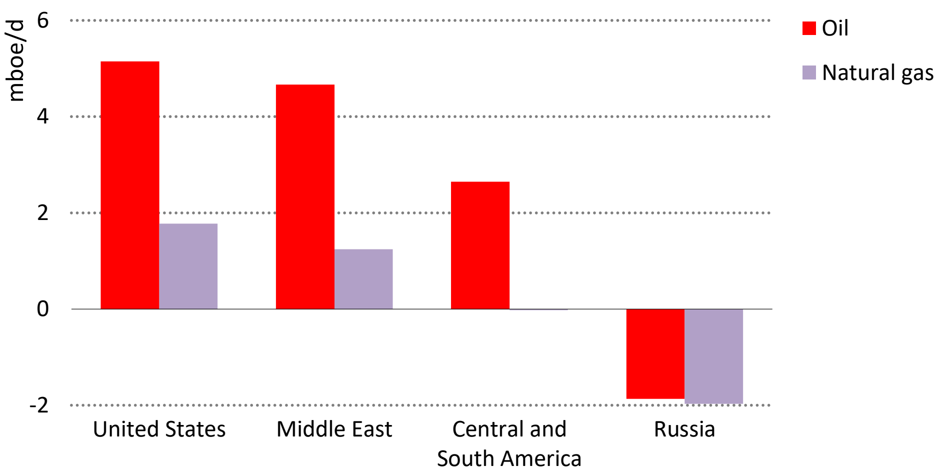
Notes: mb/d = million barrels per day; mboe/d = million barrels of oil equivalent per day; LNG = liquefied natural gas. The figure shows the differences in oil and natural gas production in 2050 between the STEPS in the *WEO-2021* and the same scenario in this *Outlook*.

Over time, more Russian resources are likely to be drawn eastwards to Asian markets. In the case of oil, increased Russian flows to Asia are already visible. For natural gas, the reorientation of flows will require more time to take shape because of the need for major new infrastructure investments if exports are to expand beyond the 38 bcm/year foreseen for the Power of Siberia pipeline. These will require new agreements with partners, some of which have found their confidence in natural gas – and in Russia – shaken by recent events.

For the moment, with no links to alternative markets, much of the natural gas that was intended to flow westwards to Europe has no place to go. As a result, Russia's share of internationally traded gas, which stood at 30% in 2021, falls to 15% by 2030 in the STEPS and to 10% in the APS. Its projected net income from gas sales (revenue minus costs) falls from USD 75 billion in 2021 to less than USD 30 billion in 2030 in the APS.

Russia's share of global fossil fuel exports declines substantially as a result of the current crisis (Figure 1.16). In the case of oil, Russia exported more than 7 mb/d in 2021;[3] this falls by around 25% by 2030 in the STEPS and by 40% to 2050. By the mid-2020s, North America is exporting more oil to global markets than Russia, but the gap left by Russia is mainly filled by higher exports from the Middle East. In coal markets, more than 80% of global exports go to the Pacific Basin in 2030 (up from about 75% in 2021). Russia has plans to switch exports to these markets, but the ability to do so rapidly is constrained by bottlenecks in the rail system.

Figure 1.16 ▷ Change in net trade position of selected oil and gas exporters in the STEPS, 2021-2030



With the loss of its largest export market, Russia faces the prospect of a much-diminished future role in international energy trade

Russia's reorientation to Asian markets is trickiest in the case of natural gas. Russia is discussing the possibility of new pipeline links to China, notably the large capacity Power of Siberia-2 pipeline through Mongolia (also sometimes called Soyuz-Vostok). However, our demand projections for China raise considerable doubt about the viability of another large-scale gas link with Russia. The STEPS is the most favourable scenario for such a pipeline, and in these projections natural gas demand growth in China slows to 2% per year between 2021 and 2030, compared with an average growth rate of 12% per year between 2010 and 2021. Importers in China have been actively contracting for new long-term LNG supplies, and China's most recent five-year plan focusses on boosting domestic production. Alongside the

[3] This represents volumes traded between regions modelled in the *WEO* and does not include intra-regional trade. Oil trade includes both crude oil and oil products.

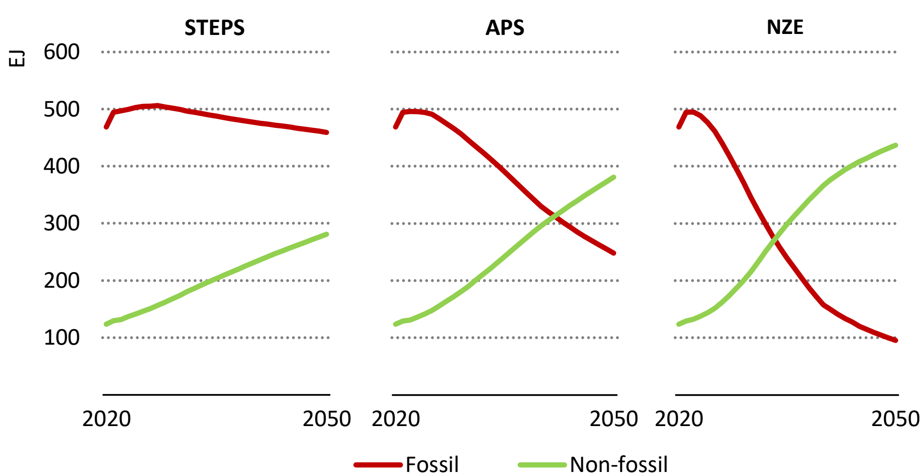
ramp-up of imports through existing pipelines, China's already contracted supplies more than cover its requirements in this scenario until well into the 2030s.

Today's gas security crisis has also boosted momentum behind projects seeking to trade hydrogen and hydrogen-based fuels. However, our tracking of planned projects reveals a significant imbalance: export projects are more numerous and more advanced than those for the corresponding import infrastructure. Of the 12 Mt H_2 per year of proposed exports, only 2 Mt H_2 per year have named potential or agreed off-takers and a further 3 Mt H_2 per year cite export to a specific region. The amount of investment necessary to set up international value chains for hydrogen is enormous. Assets that could deliver 10 Mt H_2 per year to the European Union in 2030 (in line with the REPowerEU Plan) would cost some USD 700-850 billion, a sum that would more than double when financing costs are included.

1.3.2 Is a messy transition unavoidable?

Our scenarios model orderly processes of change in which markets are always in equilibrium, with investment rising and falling in different sectors to allow for a balance of supply and demand. However, today's energy crisis has underscored that, in practice, the future of energy markets is likely to be disjointed, subject to geopolitical friction and prone to regular market imbalances. In particular, the crisis has undercut the trust and collaboration that are essential to ease the journey to a net zero emissions system. A lack of sequencing and co-ordination, both within countries and internationally, would also be very damaging to the prospects for a people-centred process of change.

Figure 1.17 ▻ Fossil and non-fossil energy supply by scenario, 2020-2050



There is an orderly process of change in the global fuel mix in all WEO scenarios, with the main differentiating feature being the rapidity of transition from fossil fuels

Does this make a messy transition unavoidable? In this *Outlook*, we explore approaches that can lessen the scope for volatility and turbulence ahead. These are not related specifically to the current crisis, although many of them are relevant to discussions about how best to cope with it and move beyond it. The ten guidelines below, amplified in Chapter 4, are designed to advance climate, security and affordability objectives in tandem, and require a strong role for governments to manage the process of change – though without giving up the gains that come from well-functioning market mechanisms. Many of them are designed to address specific issues that arise in what has been called the "mid-transition", when carbon-emitting and clean fuels and technologies need to co-exist (Figure 1.17).

- **Synchronise scaling up a range of clean energy technologies with scaling back of fossil fuels.** Many companies and financial organisations have set goals and plans to scale down investment in fossil fuels. Much more emphasis is needed on their goals and plans for the scaling up of investment in clean energy technologies, and on what governments can do to incentivise this. Sequencing is important: continuing investment in fossil fuels is needed to keep supply and demand in balance while energy transitions are in progress, but the extent of this requirement is entirely dependent on the speed at which clean energy investment scales up. In the NZE Scenario, for every USD 1 spent globally on fossil fuels in 2030, more than USD 9 is spent on clean energy (Spotlight).

- **Tackle the demand side and prioritise energy efficiency**. The energy crisis highlights the crucial role of energy efficiency and behavioural measures to help avoid mismatches between demand and supply. Since 2000, efficiency measures have reduced unit energy consumption significantly across various end-uses, but there is much more that can be done. This is especially the case in emerging market and developing economies where energy performance standards for appliances such as air conditioners and refrigerators are often weak and sometimes non-existent. Stock turnover is another major challenge, especially for long-lived assets, for example, over half of the buildings that will be in use in 2050 have already been built. This underlines the case for policies that accelerate the rate of retrofits.

- **Reverse the slide into energy poverty and give poor communities a lift into the new energy economy**. As a result of the pandemic and the energy crisis, 75 million people have lost the ability to pay for extended electricity services and 100 million for clean cooking solutions. In emerging market and developing economies, the poorest households consume nine-times less energy than the wealthiest, but spend a far higher proportion of their income on energy. The least well-off often live in less efficient buildings, utilise older inefficient appliances, and rely on more inefficient means for cooking and heating. Policy interventions are essential to help them cope with the higher upfront costs of clean energy investments (such as efficiency and electrification). If climate policies do not do this, they risk being socially divisive, especially in a high price environment.

- **Collaborate to bring down the cost of capital in emerging market and developing economies.** The cost of capital is a signal of the real and perceived risks associated with investment, and it is higher in many emerging market and developing economies than elsewhere. New investor surveys conducted for the new IEA-hosted Cost of Capital Observatory suggest that the cost of capital for a solar PV plant in 2021 in key emerging economies was between two- and three-times higher than in advanced economies and China. Tackling the various economy-wide or project-specific risks that push up the cost of capital is essential to bring investment to where it is most needed. It would also make a huge difference to the overall costs of transition. A 200 basis point reduction in the cost of capital in all emerging market and developing economies would reduce the cumulative clean energy financing costs to reach net zero emissions by USD 15 trillion through to 2050.

- **Manage the retirement and reuse of existing infrastructure carefully, bearing in mind that some of it will be essential for a secure journey to net zero emissions.** Some parts of the existing fossil fuel infrastructure perform functions that will remain critical for some time, even in very rapid energy transitions. For example, the importance of gas-fired power for electricity security actually *increases* in many countries during energy transitions before falling – especially in systems with significant seasonal variations in demand. In the European Union, peak requirements for natural gas go up through to 2030 even though overall or aggregate demand goes down. Managing the decline in refinery capacity is also important: even in markets where internal combustion engine (ICE) vehicle sales are banned, oil demand for transport does not disappear immediately. Unplanned or premature retirement of this infrastructure will have negative consequences for energy security and for jobs.

- **Tackle the specific risks facing producer economies**. Oil and gas security during transitions will depend on the ability of hydrocarbon-dependent economies to diversify and find other sources of economic advantage. These may well continue to be in the energy sector: many resource-rich countries are investing a part of current windfall oil and gas profits in renewables and low-emissions hydrogen. Potential export earnings from hydrogen are no substitute for those from oil and gas, but low cost renewables, natural gas and CCUS storage potential could provide a durable foundation for attracting investment in energy-intensive industrial sectors.

- **Invest in flexibility – a new watchword for electricity security**. Maintaining electricity security in the power systems of tomorrow calls for new tools and approaches. Power generators will need to be more responsive; consumers will need to be more connected and adaptable, and grid infrastructure will need to be strengthened and digitalised. Higher variability in electricity supply and demand means that the requirement for flexibility quadruples by mid-century in both the APS and the NZE Scenario, underscoring the importance of policies that adequately remunerate the relevant technologies and infrastructure. Battery storage and demand-side response become increasingly important, each providing a quarter of the flexibility needs in 2050 in the APS.

- **Ensure diverse and resilient clean energy supply chains**. High and volatile critical mineral prices and highly concentrated supply chains could delay energy transitions or make them more costly. Demand for critical minerals is set to quadruple by 2050 in both the APS and the NZE Scenario. At 2021 prices, the value of the minerals used in clean energy technologies increases more than fivefold, reaching USD 400 billion by 2050 in these scenarios. Minimising this risk requires action to scale up and diversify supplies alongside recycling and other measures to moderate demand growth. Technological innovation has already shown its ability to relieve some of the pressure on primary supplies: newer low cobalt EV batteries contain 75–90% less cobalt than earlier generations of batteries, although they use twice as much nickel.
- **Foster the climate resilience of energy infrastructure**. The growing frequency and intensity of extreme weather events presents major risks to the security of energy supplies. IEA analysis of the risks facing four illustrative assets shows that the potential financial impact from flooding could amount to 0.3-1.2% of their total asset value in 2050, and in one case would be four-times higher than this without flood defences in place. Governments need to anticipate the risks and ensure that energy systems have the ability to absorb and recover from adverse climate impacts.
- **Provide strategic direction and address market failures, but do not dismantle markets.** The energy crisis has been accompanied by large-scale interventions from governments, often to protect different types of consumers from price spikes and to ensure energy security. Governments are also taking on increasingly expansive roles to drive and accelerate transitions. However, transitions are unlikely to be efficient if they are managed on a top-down basis alone. Governments need to harness the vast resources of markets and incentivise private actors to play their part. Around 70% of the investments required in transitions are likely to need to come from private sources. This means correcting for market failures – including via support for innovation and by the phase out of harmful fossil fuel subsidies – and providing the policy signals and public finance that can catalyse private investment.

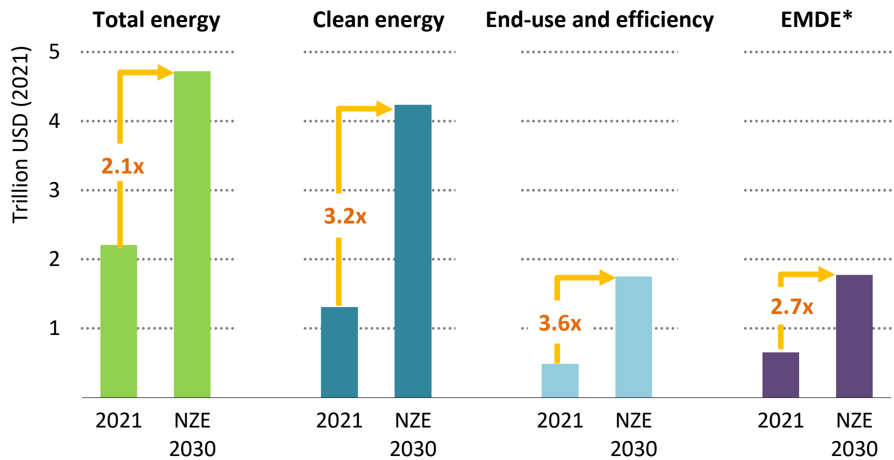
S P O T L I G H T

Can the world right its investment imbalances?

Clean energy investment has picked up in recent years, but is still well short of the levels required to provide lasting solutions to today's energy crisis. In the absence of accelerated clean energy transitions, spending on traditional fuels is also insufficient to keep the current system operating effectively. Something has to change in order to avoid an energy-starved world characterised by continued price volatility.

IEA analysis has repeatedly highlighted that a surge in spending to boost deployment of clean energy technologies and infrastructure provides the way forward, and that this needs to happen quickly or global energy markets will face a turbulent and volatile period ahead. However, the task ahead is sometimes mischaracterised and oversimplified as a reallocation of *existing* flows from "dirty" to "clean". In practice, comparing current energy investment flows with what will be required in the NZE Scenario in 2030 highlights at least four inter-related tasks (Figure 1.18). None of these can be considered in isolation without risking new imbalances and market volatility. Reductions in fossil fuel investment are a consequence of these changes.

Figure 1.18 ▷ Energy investment in the NZE Scenario, 2021 and 2030



There are multiple imbalances in current investment flows that need to be addressed in order to meet rising demand for energy services while reducing emissions

* Excludes China.

Note: EMDE = emerging market and developing economies; NZE = NZE Scenario.

- **Attract more investors to energy.** There is not enough capital flowing to the energy sector. It would need to double over the coming decade to get the world on track for a 1.5 °C stabilisation in global average temperatures. This means tapping new sources of finance, beyond those already engaged.
- **Scale up a range of clean technologies and infrastructure.** The increase in global investment needs to be concentrated across multiple clean technologies, including renewable generation, efficiency improvements, clean fuels and CCUS, as well as the required infrastructure in the form of expanded and modernised grids and storage. Total clean energy investment increases threefold between 2021 and 2030 and nine-times more energy investment flows to clean energy than to fossil fuels in 2030.

- **Do not underweight the demand side.** The transformation of the energy sector requires a rebalancing towards demand and end-use sectors to spur much higher efficiency and electrification.
- **Create a low-emissions pathway for developing economies.** With the exception of China, investment levels are lagging most significantly in emerging market and developing economies. Meeting rising demand for energy services in a sustainable way will only be possible if development models are able to bypass the high carbon choices that other economies have pursued in the past.

The scale of additional investment required means that most of it will need to come from private sources, but public financial institutions play crucial roles to bring forward investment in areas where private players do not yet see the right balance of risk and reward. A clear and unified focus on energy transitions among the international development banks, alongside larger climate finance commitments from advanced economies, is critical to support transitions across the developing world.

1.4 Outlook for energy transitions

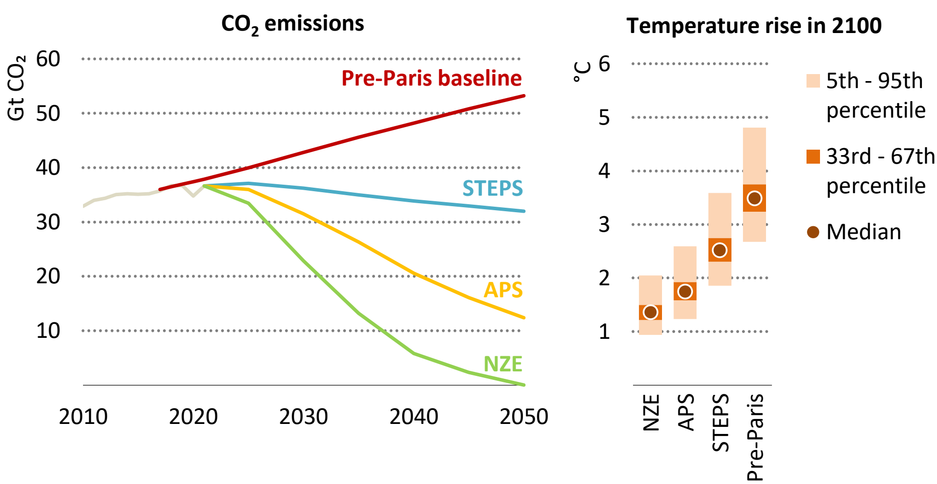
Energy-related and industrial process CO_2 emissions rebounded by 1.9 Gt in 2021 – the largest ever annual rise in emissions – with global CO_2 emissions in 2021 totalling 36.6 Gt. In the STEPS, CO_2 emissions reach a plateau in the mid-2020s at 37 Gt and thereafter fall slowly to 32 Gt by 2050 (Figure 1.19). This decline represents a break in the close historical relationship between growth in GDP and growth in emissions. It highlights the progress made since the Paris Agreement in 2015. Prior to that, the trajectory based on current policies was for CO_2 emissions to rise to more than 50 Gt by 2050. This would have led to a median global average surface temperature rise of around 3.5 °C by 2100.[4] The STEPS indicates a trajectory that would lead to a 2.5 °C temperature rise in 2100. In other words, the changes in policies and technologies made since 2015 have already reduced the projected long-term temperature rise by around 1 °C by 2100. However, the STEPS trajectory is not an adequate answer to the challenge of climate change; it would not be enough to avoid severe impacts from a warming planet.

In the **APS**, CO_2 emissions peak in the mid-2020s and fall to around 12 Gt in 2050. This is a bigger emissions reduction than in the *WEO-2021*, reflecting the new or updated Nationally Determined Contributions (NDCs) and announced net zero emissions pledges that have been made over the last year, the most significant of which was India's announcement of a 2070 net zero emissions target (Figure 1.20). These additional commitments help to reduce the gap in 2030 between energy-related CO_2 emissions in the APS and the NZE Scenario by 2.1 Gt. There are large differences in emissions trajectories between regions, CO_2 emissions

[4] Energy-related non-CO_2 emissions, including methane and nitrogen dioxide, are modelled in detail for all scenarios; non-energy-related greenhouse gas emissions are assumed to move in line with the overall emissions reduction efforts of each scenario.

in 2030 decline by 40% in advanced economies but by only 5% in emerging market and developing economies. The projected global median temperature rise in 2100 is about 1.7 °C. This gets close to achieving the goal of the Paris Agreement to limit the temperature rise to "well below 2 °C", and it marks the first time that collective government targets and pledges have been sufficient, if delivered in full and on time, to hold global warming to below 2 °C. However, as the IPCC has underlined, warming of close to 2 °C would still entail strong negative impacts for societies around the world (IPCC, 2022b).

Figure 1.19 ▷ Energy-related and process CO_2 emissions, 2010-2050 and temperature rise in 2100 by scenario



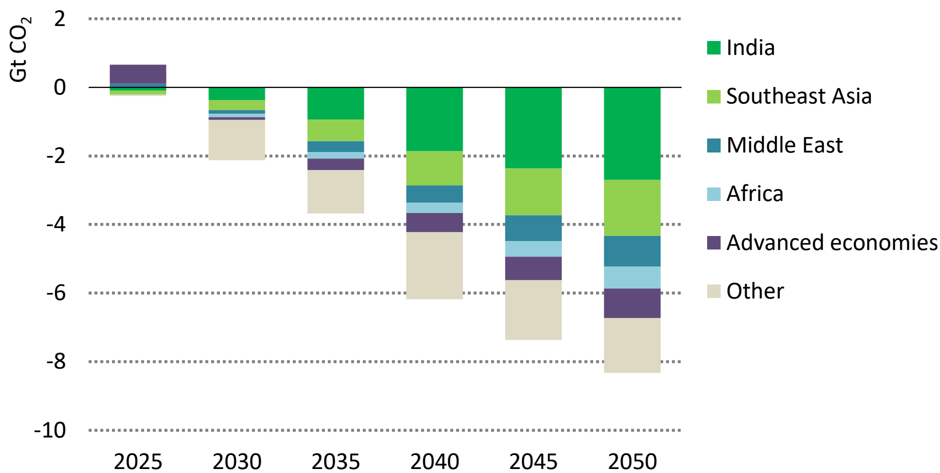
Policy and technology advances since 2015 have shaved 1 °C off the temperature rise in 2100 but stated policies still lead to a temperature rise well above the Paris Agreement goals

Notes: Pre-Paris trajectory is based on the Current Policies Scenario from the *WEO-2015* (IEA, 2015). Temperature rise estimates are relative to 1850-1900 and match the IPCC Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014 (IPCC, 2022a).

In the **NZE Scenario**, CO_2 emissions decline to 23 Gt in 2030 and to zero in 2050, plus there is a 75% reduction in energy-related methane emissions to 2030. The global temperature rise peaks below 1.6 °C around 2040, before dropping to around 1.4 °C in 2100. As a result, the NZE Scenario falls within the group of scenarios categorised by the IPCC as a "no or low overshoot" scenario, and aligns with the goal, agreed again in Glasgow at COP26 in 2021, to "pursue efforts to limit the temperature increase to 1.5 °C" (IPCC, 2022b).

Access to clean energy is one of the key indicators of sustainable development tracked in our scenarios along with energy-related emissions. The outlook for the future varies widely by scenario. Only in the NZE Scenario is universal access to both electricity and clean cooking achieved by 2030. Air quality is another critical indicator of well-being. Outcomes are strongly correlated with the strength of climate action (Box 1.4).

Figure 1.20 ▷ Change in CO_2 emissions in the 2022 APS relative to the *WEO-2021* APS, 2025-2050



Emissions in 2050 in this year's APS are 8 Gt CO_2 lower than last year's Outlook, mainly due to the net zero emissions pledges made by India and in Southeast Asia

Box 1.4 ▷ Air pollution and its negative impacts on human health

Polluted air causes at least 19 000 excess deaths a day around the world.[5] It also entails significant direct economic costs, such as those related to the provision of healthcare, as well as indirect economic costs, such as those arising from labour productivity losses or crop damage. Air pollutant emissions decline in each of the scenarios, but the trajectories vary considerably.

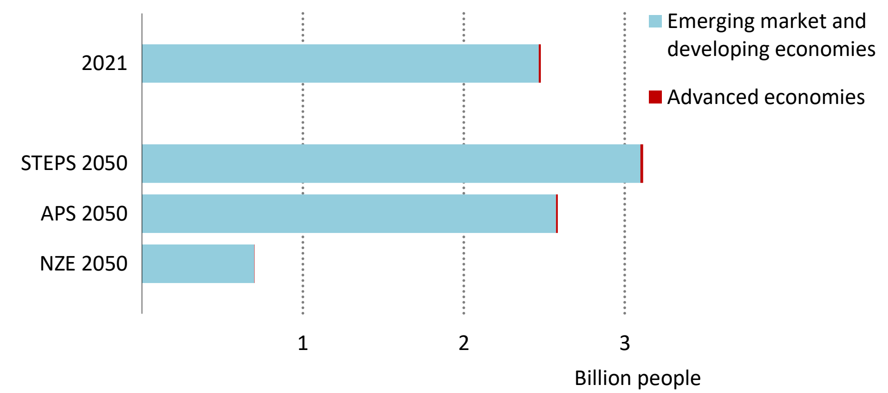
In the STEPS, vehicle emissions standards, reduced coal use and a lower level of reliance on fuelwood and other solid biomass for heating and cooking help to bring about a modest decline in air pollutant emissions from current levels. However, the overall effects of polluted air on public health continue to worsen through to 2050 – especially in Asia – because of population growth and urbanisation and because of the time lag between exposure to pollution and health problems and premature death.

The health impacts of air pollution continue to rise through to 2050 in the APS, despite the achievement of all announced emissions reductions goals. This is because fossil fuel use in many emerging market and developing economies does not dramatically decline until after 2030, leaving many exposed to high levels of pollution during this decade. The

[5] In 2021, indoor air pollution caused an estimated 3.6 million premature deaths, while outdoor air pollution caused 4.2 million.

SDG 7 goal of universal access to clean cooking by 2030 is not achieved in this scenario, which has a similar effect. Only in the NZE Scenario do we see a major difference in outcomes, with nearly two billion fewer people breathing heavily polluted air in 2050 than today (Figure 1.21).

Figure 1.21 ⊳ Population exposed to heavily polluted air, 2021 and 2050



IEA. CC BY 4.0.

The APS sees a lower number of people breathing heavily polluted air than in the STEPS but only in the NZE Scenario does the number in 2050 fall below current levels

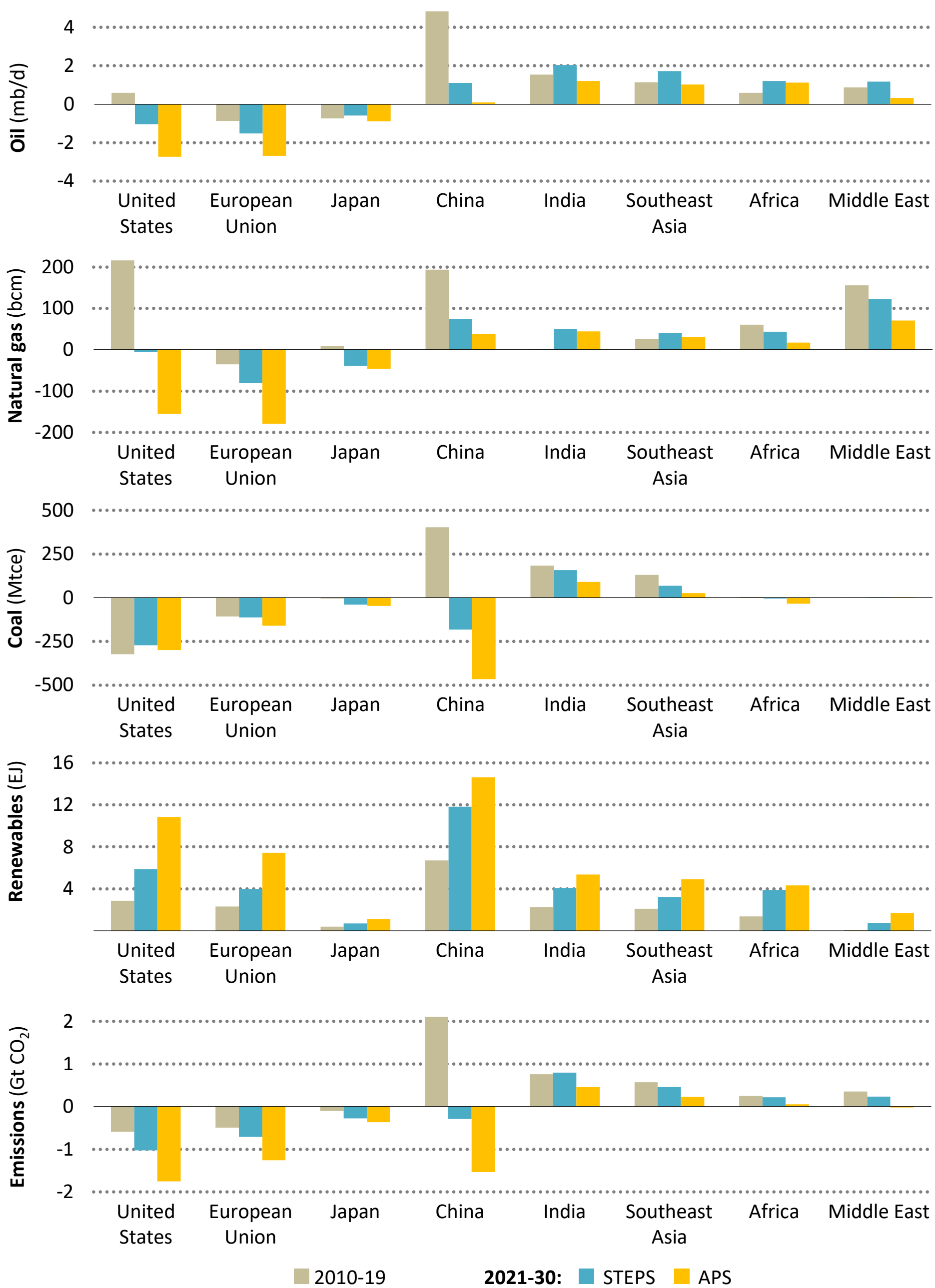
Note: Heavily polluted air = $PM_{2.5}$ concentrations ≥ 35 microgrammes per cubic metre.

1.4.1 Selected country and regional trends

United States

The Inflation Reduction Act and the Bipartisan Infrastructure Act catalyse a sharp rise in the pace of energy transitions in the United States compared with the *WEO-2021* (Box 1.5). Strong growth in renewables means that coal demand falls by three-quarters to 2030 (Figure 1.22). Gas-fired generation peaks before 2030: overall natural gas demand ends the decade just under the level it reached in 2021, allowing for increased exports of LNG. Oil demand falls by 1 mb/d by 2030 from nearly 18 mb/d today, largely due to an increase in EV sales (30% of car sales in 2030) and fuel economy improvements. Policy changes also provide support for lifetime extensions for the ageing fleet of nuclear power plants. The STEPS projections are consistent with a nearly 40% reduction in US energy-related CO_2 emissions to 2030 relative to 2005 levels. In the APS, the United States achieves its stated ambition of net zero emissions from the electricity sector around 2035 through faster deployment of renewables, CCUS, hydrogen and ammonia, and an expansion of nuclear power including development of small modular reactors. Sales of EVs rise more quickly than in the STEPS, and EVs account for one-out-of-two cars sold by 2030.

Figure 1.22 ⊳ **Energy demand growth by region and scenario, 2021-30**



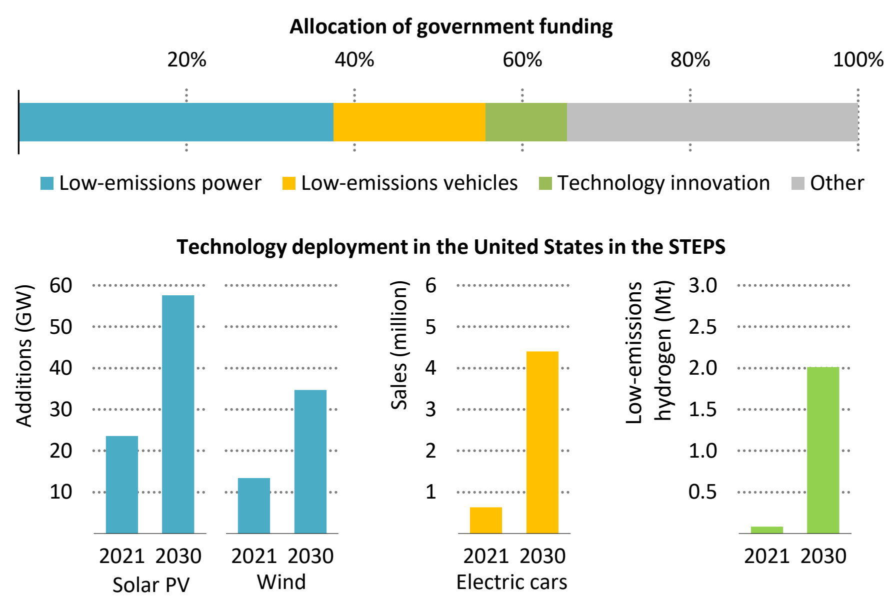
Fast growing regions see energy demand met by a range of fuels and technologies, while growth in advanced economies is met exclusively by low-emissions sources

Box 1.5 ▷ The Inflation Reduction Act: a major landmark in US transitions

The US Inflation Reduction Act commits nearly USD 370 billion to energy security and climate change provisions, more than one-third of all government spending earmarked for clean energy in recovery packages since the outbreak of the Covid-19 pandemic in 2020. This comes on top of an additional USD 190 billion for clean energy and mass transit in the Infrastructure Investment and Jobs Act, adopted in November 2021.

Together, these bolster efforts to reduce greenhouse gas emissions in the United States, resulting in around 40% less CO_2 emissions in 2030 in the STEPS relative to 2005 levels. The largest impact of the Inflation Reduction Act is in the electricity sector, where CO_2 emissions in 2030 are almost 50% lower than today, due to tax credits accelerating the deployment of solar PV and wind, combined with support for nuclear lifetime extensions and batteries. Tax credits for electric cars help lift annual sales from 0.6 million today (5% of car sales), to nearly 4.5 million in 2030 (30% of sales). Technologies that aid emissions reductions in hard-to-abate industrial sectors, such as CCUS and low-emissions hydrogen, all are eligible for substantial tax credits, which lay the foundations for strong growth.

Figure 1.23 ▷ Government funding in the US Inflation Reduction Act and Infrastructure Investment and Jobs Act and technology deployment in the STEPS in the United States, 2021-30



Recent US legislation provides nearly USD 560 billion for clean energy, significantly boosting clean power, electric cars, and low-emissions hydrogen

These incentives mobilise substantial additional private investment. With the tax credits, the levelised cost for new solar PV and wind in the United States would be lower than new renewable projects in all other regions in the STEPS. When stacked with the low-emissions hydrogen production tax credits, hydrogen produced using solar PV or wind could cover upfront investment within the first year of investment when secured against the future tax credit revenues. Direct air capture projects, if capturing the full tax benefits, could be in a similar situation by the end of this decade. This removes many critical barriers for these industries and their off-takers, and is set to move these new technologies rapidly along the learning curve towards larger scale commercial deployment. Higher incentives are available for projects and consumers using goods manufactured in the United States, which coupled with tax credits for investors, is set to provide a major boost to clean energy manufacturing in the United States.

Overall, the Inflation Reduction Act leads to a strong uptick of new clean energy projects in the STEPS. In the power sector, annual solar and wind capacity additions expand 2.5-times over current levels by 2030, while electric car sales expand around seven-fold (Figure 1.23). These trends, along with other efficiency policies and efforts to reduce methane emissions, increase the availability and value proposition of US oil and gas exports, which help to substitute for lower exports from Russia.

European Union

Higher coal use during the energy crisis proves temporary as energy transitions gather pace. In the STEPS, strengthened policy targets and frameworks, high fossil fuel prices and the drive to reduce import dependency on Russia mean that the European Union sees demand for coal fall by around half by 2030, and demand for natural gas and for oil by almost a fifth each. Deployment of wind and solar PV gains further momentum and they respectively account for almost for 30% and 15% of electricity generation by 2030 in the STEPS, up from 13% and 5% in 2021. In end-use sectors, reductions in natural gas use in buildings and industry and the uptake of EVs in road transport contribute the majority of the reductions in fossil fuel use.

In the APS, targets in the Fit for 55 package are largely met – and in some cases exceeded – to fulfil the NDC objective to reduce greenhouse gas (GHG) emissions by 55% by 2030 relative to 1990. This means CO_2 emissions decline by around 45% relative to 2021 levels in the APS, compared to 26% in the STEPS. Rapid renewables deployment, efficiency gains and electrification drive a faster reduction of natural gas use in the power and buildings sectors than in the STEPS, as well as lower demand for oil. The European Union moves towards an electricity system dominated by wind, with onshore and offshore sources together accounting for just over 40% of total generation in 2050 in the STEPS and 50% in the APS.

Japan

Japan sees a 1% annual reduction in total energy supply to 2030 in the STEPS, in line with its new Strategic Energy Plan approved in October 2021. This plan foresees restarting nuclear reactors that are offline and lifting both the shares of nuclear and renewables to allow for a significant reduction in reliance on coal- and gas-fired plants. Japan is also seeking to retrofit coal plants to co-fire with ammonia; it is the only country deploying this technology at significant scale in the STEPS.

In the APS, a 36% decrease in emissions from 2021 to 2030 is achieved via further electrification of industry and transport, and acceleration of energy efficiency improvements, for example through building materials standards for new construction. Additional policy impetus comes from the new Energy Efficient Technological Strategies and strengthening its Top Runner programme. Further decarbonisation of the power sector in the APS reflects the new Green Transformation initiative, which would make large-scale funding available to various low-emissions technologies, reinforce the effort to revive nuclear reactors and introduce measures to support manufacturers of nuclear technology.

China

Growth in energy demand in China has been a major driver for all manner of energy trends over the past two decades, yet it slows in the STEPS and stalls before 2030, with emissions peaking around the same time (in line with its NDC and national targets). Renewables account for nearly 45% of electricity generation in 2030 and account for the majority of the electricity demand growth, helping unabated coal use to peak before 2030 in alignment with government targets. Oil demand also peaks in the second-half of this decade, reaching a similar level of demand as the United States in 2030 at just under 17 mb/d (with a population four-times larger) before declining. This peak and decline reflect rising EV sales, and China remains the world's largest EV market.

In the APS, the peak in emissions occurs slightly earlier and at a lower level as China accelerates action to achieve carbon neutrality before 2060. Electrification via low-emissions sources is central to its emissions reduction efforts: total generation in 2050 rises by two-thirds in the STEPS and nearly doubles in the APS. The share of low-emissions technologies exceeds 75% in the STEPS and 90% in the APS, up from 34% today. The world's largest new build nuclear programme means an expanding role: new projects add more than 120 GW of nuclear capacity in the STEPS, and 160 GW in the APS, on top of the 50 GW in operation today.

India

India becomes the world's most populous country by 2025 and, combined with the twin forces of urbanisation and industrialisation, this underpins rapid growth in energy demand, which rises by more than 3% per year in the STEPS from 2021 to 2030. It sees the largest increase in energy demand of any country. Even though India continues to make great strides with renewables deployment and efficiency policies, the sheer scale of its development means that the combined import bill for fossil fuels doubles over the next two decades in the STEPS, with oil by far the largest component. This points to continued risks to energy security.

Coal generation is projected to continue to expand in absolute terms in the STEPS, peaking around 2030, though its share of electricity generation falls from just below 75% to 55% over this period. Government programmes, such as the Gati Shakti National Master Plan and the Self-Reliant India scheme, and strong economics underpin robust growth in renewables and electric mobility, notably for two/three-wheelers. Renewables meet more than 60% of the growth in demand for power, and account for 35% of the electricity mix by 2030: solar PV alone accounts for more than 15%. However, coal still meets a third of overall energy demand growth by 2030, and oil, mainly for transport, another quarter. In the APS, more rapid progress in deploying low-emissions alternatives in power, industry and transport sectors in particular puts India on a trajectory in line with its goal of net zero emissions by 2070.

Southeast Asia

Southeast Asia is also projected to see a rapid rise in energy demand, with annual average growth of more than 3% from 2021 to 2030 in the STEPS. This is met by increases in all fuels and technologies, led by oil. Coal continues to dominate in the electricity sector, its share declining only slightly from 42% today to 39% by 2030 in the STEPS. With the implementation in full of announced pledges – notably Indonesia's goal to halt unabated coal generation by the 2050s – coal use in the power sector falls by more than half by 2050 in the APS, and renewables quickly become the largest source of electricity generation. Electricity use extends to new end-use sectors, driven by targets to halt sales of ICE vehicles in Thailand by 2035 and in Singapore by 2040, and the aim of Indonesia to achieve 2 million electric cars on the road by 2030.

Africa

The global energy crisis has been a setback for many African countries, with the partial exception of energy exporters. High energy prices have contributed to rising costs for basic foodstuffs both directly (cost of energy for agricultural equipment) and indirectly (through higher natural gas input costs for nitrogen fertilisers). In the STEPS, low cost renewable power, including solar PV, hydro and geothermal, adds substantially to the energy supply over the coming decades, and renewables provide one-third of total generation by 2030. Growth in oil in transport and for liquefied petroleum gas (LPG) for cooking push demand to over 5 mb/d by 2030; natural gas, supported by new discoveries, fuels the expanding steel, cement, water desalination and fertiliser industries.

Middle East

Natural gas meets more than 60% of energy demand growth in the Middle East to 2030 in the STEPS, much of which is due to an increase in the use of natural gas in water desalination plants. Gas demand remains relatively resilient in the APS, with a small but increasing share used for hydrogen production. Renewables meet half of rising power demand, thanks to some of the lowest cost solar in the world and an increasing policy focus on diversifying the energy sector and the broader economy. With large hydrocarbon reserves and renewables potential, many Middle East countries are also exploring the potential for hydrogen production and trade, with Europe and Japan the main potential buyers.

1.4.2 Keeping the door to 1.5 °C open

Today's policy settings fall short of what is needed during a critical decade to deliver the collective emissions reductions contained in the NDCs, and even further short of what is required to align with a 1.5 °C stabilisation in global average temperatures. In 2030, CO_2 emissions in the APS are around 5 Gt CO_2 lower than in the STEPS, but nearly 9 Gt CO_2 higher than in the NZE Scenario. The gap between the APS and the NZE Scenario to 2030 is nearly twice as large as the gap between the STEPS and the APS, highlighting the need not only to implement existing pledges but also to raise the overall level of ambition.

Closing the gap between the STEPS and the APS trajectories, and then with the NZE Scenario, will depend on the world's ability to scale up resilient clean energy supply chains, which has clear implications for the need for investment in traditional elements of supply. This overview chapter concludes with a review of our findings on these critically important and highly interdependent questions.

Priority measures to close the gap with the NZE Scenario to 2030

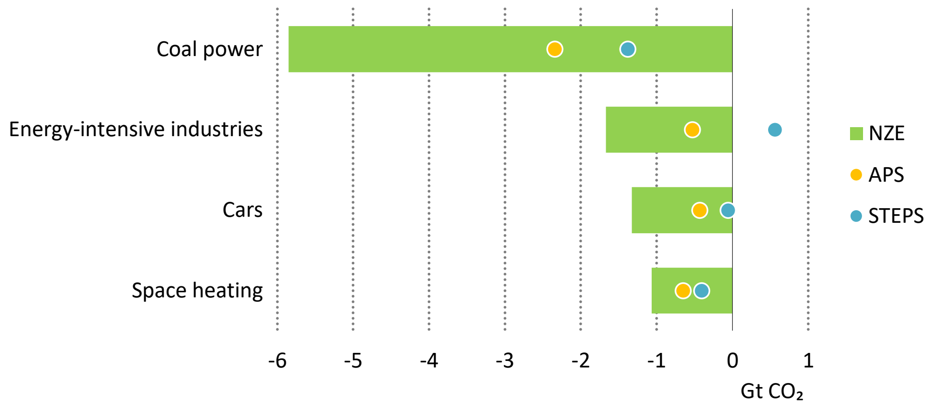
What are the key policy measures and instruments that will be required this decade to implement existing pledges and close the gap between the STEPS and the APS trajectories, and then with the NZE Scenario?

The most rapid changes and the largest emissions reductions this decade will need to come from the electricity sector, and in particular from a rapid expansion of **clean electricity** generation and a consequent decline in emissions from coal (Figure 1.24).[6] The early decarbonisation of electricity supply is a critical element to energy transitions, since clean electricity not only cuts power sector emissions but also helps bring about emissions reductions in end-use sectors as they increasingly look to electricity to meet demand for energy services. As a result, electricity becomes the "new oil" in terms of its dominant role in final energy consumption. Unlike oil, however, it plays a role in all end-use sectors and also drives huge improvements in the overall efficiency of the energy system. By 2050, electricity provides two-thirds of the useful energy enjoyed by consumers, much higher than its share in final consumption (slightly more than one-half).

Despite its position in the vanguard of energy transitions, the electricity sector emitted 13 Gt CO_2 in 2021, more than one-third of global energy-related CO_2 emissions. Electricity sector CO_2 emissions peak in the coming years in each scenario and are followed by steep reductions. Additional pledges and announcements over the past year have helped close the projected gap in emissions between the APS and NZE Scenario, especially in advanced economies where the full implementation of country pledges would now bring the outlook close to that of the NZE Scenario. However, there remains a huge amount to be done to completely close this gap, particularly in emerging market and developing economies.

[6] In November 2022, the IEA will release *Coal in Net Zero Transitions: Strategies for rapid, secure and people-centred change*.

Figure 1.24 ▷ **CO_2 emissions reductions in selected sectors, 2021-2030**



Reducing emissions from coal-fired power, energy intensive industries, cars and space heating accounts for three-quarters of total emissions reductions to 2030 in the NZE Scenario

The reduction in emissions from coal-fired power generation call for a dramatic acceleration in deployment of low-emissions sources, mainly renewables, supported by measures to expand and modernise grids and to incentivise investment in various forms of flexibility, including energy storage. There is no way to tackle climate change effectively without a surge in investment in clean power and infrastructure that significantly reduces coal-fired generation. If the existing fleet of coal-fired power plants were to operate as they have in recent years for the next 50 years, this alone would take up two-thirds of the remaining CO_2 budget consistent with limiting the global average temperature increase to 1.5 °C.

Despite the huge investment required, the rapid replacement of fossil fuel generation by renewables, principally solar PV and wind, helps to reduce electricity costs as well as emissions. In the NZE Scenario, electricity costs come down from their current high levels by the middle of the decade, and total electricity supply costs per unit of electricity generation are then broadly stable to 2030. After 2030 they start to reduce: by 2050 the average cost of electricity is around 10% below the level seen in 2021.

Two other critical strategies to close the gap with climate objectives are **energy efficiency** improvements and **electrification** of end-uses. Efficiency improvements, combined with more robust materials efficiency and behaviour change, are fundamental in the NZE Scenario to facilitate a much faster rise in the share of low-emissions electricity supply. In 2030, energy savings from these measures as well as behavioural changes amount to around 110 EJ, equivalent to total final energy consumption of China today. As a result, total energy supply declines by 10% over the coming decade in the NZE Scenario even as the global economy grows by nearly a third. This contrasts with a 2% increase in total energy supply over the same period in the APS and a near 10% rise in the STEPS.

Expanding electrification and the widespread deployment of efficiency and energy savings enable the **buildings** sector to almost halve its emissions in the NZE Scenario by 2030, despite the continued expansion of floor area and appliance ownership driven mainly by emerging market and developing economies. The switch from traditional biomass to more efficient cook stoves and fuels is also an important driver of overall trends. Electricity becomes the principal source of energy for decarbonised heating: homes using electricity for heating rise from 20% today to 30% in 2030 and to more than 50% in 2050, with high efficiency heat pumps becoming the primary technology choice.

Emissions trends in the **transport** sector are determined by how quickly oil can be displaced; at present it accounts for 90% of energy use in transport. Both passenger and freight activity are set to more than double by 2050, underpinned by higher mobility demand needs in the developing world as economies and populations expand and living standards rise. Reductions in emissions of around one-quarter to 2030 in the NZE Scenario are driven by increased electrification, efficiency improvements and behaviour change.

Electric vehicles offer the most cost-effective low-emissions technology in most segments in both the short and long term, and they come to dominate road transport. By 2030, 60% of all new car sales are electric in the NZE Scenario (compared with 35% in the APS and 25% in the STEPS). The electrification of heavy freight segments proceeds more slowly, while emerging market and developing economies initially focus on the electrification of two/three-wheelers and urban buses. Over the longer term, the blending and direct use of low-emissions fuels such as biofuels, hydrogen and hydrogen-based fuels increases significantly, especially in aviation and shipping, and for long-haul road freight.

The outlook for energy use in **industry** is shaped by continuing growth in demand for industrial materials. In the STEPS, world output of crude steel increases by around 10% by 2030, and around 30% by 2050, driven by India, Southeast Asia and Africa. Global output of cement also expands as Africa and India continue the process of urbanisation and industrialisation. A much stronger focus on more efficient use of materials tempers this growth in the NZE Scenario, but it is not enough to prevent an overall increase in demand for industrial materials.

Nonetheless, the industry sector sees a reduction of nearly a quarter in overall emissions by 2030 in the NZE Scenario. Widespread implementation of more stringent efficiency standards and policies encouraging fuel switching are the key measures to generate these reductions in the near term. Some technologies required for the transition of energy-intensive industrial branches are not yet commercially available.

Progress in some areas therefore depends on the further development of key technologies. This underscores the importance of enhanced public support for **innovation** and demonstration projects in the 2020s so that these technologies can be deployed at scale in the 2030s and beyond. Between 2031 and 2040, the speed of emissions reductions in the industry and transport sectors accelerates to almost 10% per year in the NZE Scenario, as electrification, low-emissions fuels and CCUS technologies start to make more significant inroads into the existing stock of assets.

In addition to rapid cuts in CO_2, the NZE Scenario entails a steep fall in other energy-related greenhouse gases. For example, energy-related **methane** emissions drop by 75% from 125 Mt in 2021 to 30 Mt in 2030, on track for less than 10 Mt in 2050. Some of this occurs because of the overall reduction in fossil fuel consumption, but most of it comes from a huge increase in the deployment of emissions reduction measures and technologies across the oil, natural gas and coal supply chains. These measures lead to the elimination of all technically avoidable methane emissions by 2030. Reducing methane leaks and a rapid phase out in all non-emergency flaring would bring a double dividend: relief for very tight gas markets and reduced greenhouse gas emissions.

Scaling up clean energy supply chains

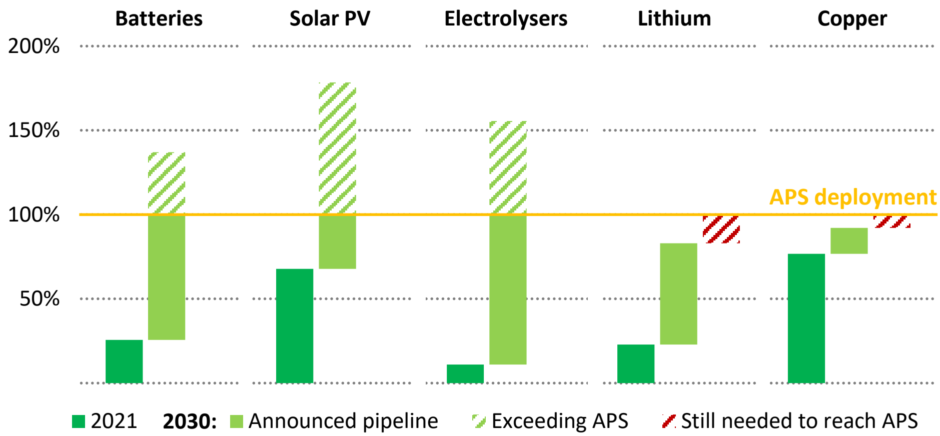
Accelerating clean energy transitions requires large increases in the global manufacturing capacity of clean energy technologies and in related inputs such as critical minerals. Meeting this industrial challenge is essential to reduce emissions in line with climate goals, plus it will create jobs in the companies and countries that are positioned to take advantage of the market opportunities (Box 1.6).

Current deployment trends for key clean energy technologies show some encouraging signs. Renewables-based electricity generation rose by a record 500 TWh in 2021 to reach an all-time high and it looks set to mark a new record in 2022. Electric car sales reached a record 6.6 million in 2021, more than double the sales in 2020, and sales in 2022 are indicating particularly strong growth, led by China, United States and European Union.

Planned increases in global clean energy manufacturing capacity for key technologies provide a crucial leading indicator of the way that things could evolve (Figure 1.25). There are some technologies where a lack of manufacturing capacity risks becoming a bottleneck. For example, current and planned manufacturing capacity for heat pumps is below the levels projected in the APS. There are also some encouraging signs. Increasing confidence in future demand, boosted by measures such as the US Inflation Reduction Act that encourage investment in more resilient and diversified supply chains, means that companies and countries are scaling up clean energy manufacturing capacity.

For some technologies, announced capacity increases exceed the required manufacturing capacity in 2030 in the APS. For example, if all announced expansions of electrolyser manufacturing capacity see the light of day, it would lead to global manufacturing capacity around 50% higher by 2030 than projected in the APS. In the case of solar PV, the potential excess capacity if all announced projects are implemented relative to APS levels would be even larger, at 80%. This provides important comfort to policy makers that their collective ambitions are not only aligned with global supply chains, but that even more robust ambition would be possible.

Figure 1.25 ▷ Announced manufacturing capacity for selected energy technologies relative to deployment in the APS, 2021 and 2030



Announced increases in manufacturing capacity for key technologies, including solar PV, electrolysers and batteries, would exceed projected deployment in 2030 in the APS

Note: Shows annual production capacity in 2030 relative to the level of demand projected in the APS in 2030.

This optimistic message, however, needs to be tempered with caveats. First, it is far from guaranteed that all of the announced projects will come to fruition. For example, if we exclude more speculative announcements such as those without a clear start date from the calculation for electrolysers, then the announced manufacturing capacity for 2030 would fall short of the needs in the APS. Therefore, it is critical that policy continues to play a supportive role to help turn these ambitions into reality.

Second, the finding that in some instances announced supply capacity exceeds our projections for 2030 demand in the APS is also a risk to markets and suppliers. In some cases, policy makers need to do more to ensure that demand actually materialises. For example, in the case of solar PV, policy action is essential to address local barriers to uptake, including those relating to land acquisition, permitting, provision of timely grid connections and secure integration of the variable resource into electricity systems.

Third, not all parts of any given supply chain are developing new capacity at the same rate. For example, even though announced projects and potential new projects would see lithium supply capacity expand three-and-a-half-times to 2030, this is still not sufficient to meet APS needs. The smooth growth of clean technology supply chains requires co-ordination and sequencing across all parts of the value chain, from inputs to manufacturing capacity through to demand. Good data on projects, capacities and project timelines together with credible commitments to future levels of deployment are essential to limit future volatility.

Fourth, today's clean technology supply chains are very concentrated geographically. China accounts for 75% of the world's production capacity for battery cells, and as much as 97% of global capacity for wafer manufacturing for PV cells (14% of global wafer production in 2021 was at a single factory in China). This industrial capacity has been instrumental to bring down costs worldwide, giving much-needed momentum to clean energy transitions, but the current level of geographical concentration also poses potential challenges that governments need to address. Maintaining the economic efficiency benefits of trade while diversifying supply chains will be critical to ensure that clean energy transitions are both secure and cost effective.

In addition, even if the projected growth of clean technology supply chains is encouraging when measured against the benchmarks set by the APS, it is still insufficient to bring the world into line with the trajectory in the NZE Scenario. None of the clean energy technologies or critical minerals shown in Figure 1.25 currently have an announced supply capacity sufficient to meet the massive ramp-up needed in the NZE Scenario by 2030, although batteries and solar PV get close (see Chapter 3, Box 3.6).

Box 1.6 ▷ Energy job growth: opportunity or bottleneck?

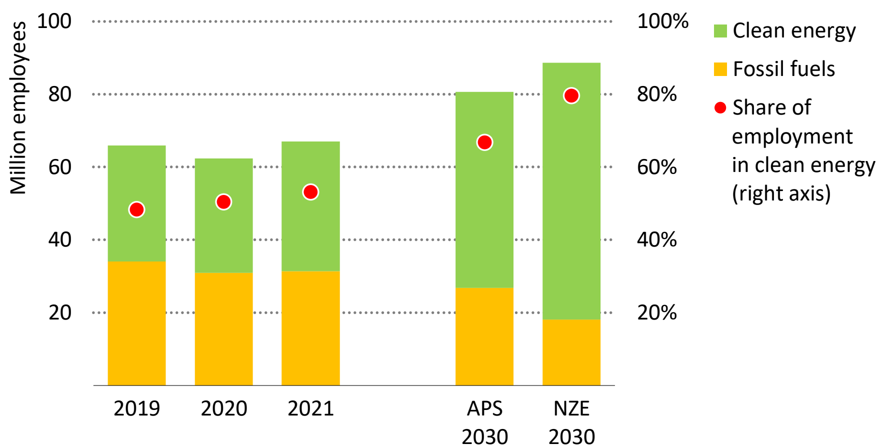
Energy transitions are already starting to transform the landscape for energy employment, with more than 50% of the energy workforce now employed in clean energy (IEA, 2022). The development of new energy-related projects, including the manufacture of their components, is the largest driver of energy employment, accounting for over 60% of energy-related jobs. The energy sector, which is not clearly defined by industrial codes, includes workers from several industrial sectors. Their work includes constructing new power generation facilities and transmission lines, carrying out efficiency retrofits, installing heat pumps, completing new oil and gas wells, and designing and constructing infrastructure.

In the NZE Scenario, total energy investment more than doubles to 2030, driving up the demand for skilled workers across the energy sector. Energy employment expands to almost 90 million in 2030 from around 65 million today (Figure 1.26). Job growth in the APS is less dramatic, but energy employment still reaches 80 million in 2030. In all scenarios, the number of new jobs created outweighs the number of those lost in fossil fuel industries, although the jobs that are created may not be in the same places as those that are lost, and the required skills in many cases will be different.

Recent legislative and policy measures, such as the US Inflation Reduction Act, Make in India and Japan's Green Transformation (GX), include provisions to support the development of local clean energy manufacturing. There is a strong case for bolstering such provisions with strategic and proactive labour policies to ensure that their ambitions are not hampered by a shortage of skilled workers.

The energy sector demands, as a whole, far more skilled workers than economy-wide averages – around 45% of energy workers today are in high skilled occupations, compared to only one-quarter economy-wide. This share is even higher for jobs in energy research and development, and the number of such jobs is set to expand rapidly to 2030 and beyond. Establishing market strength in clean energy technologies is likely to be significantly helped by tailored training and certification, an area where businesses should work in close collaboration with ministries of energy, labour and education.

Figure 1.26 ⊳ Global employment in fossil fuels and clean energy



Clean energy employment makes up just over half of the energy workforce today and this share rises significantly in both the APS and the NZE Scenario

In order to attract workers, including those moving from other parts of the energy sector, firms will need to take account of various factors. Energy sector wages typically have a premium relative to economy-wide average wages, though established industries such as nuclear, oil and gas typically offer the highest wages, which may make it challenging to attract workers to new clean energy industries. Newer industries, such as solar, often do not have the same labour protections and union representation as established fossil fuel industries, especially in emerging market and developing economies.

The percentage of women in the energy workforce is consistently low when compared to economy-wide averages: it averages 15% in traditional energy sectors compared to 39% in the economy as a whole. As the energy workforce expands, there will be opportunities to address these long-standing imbalances.

Implications for investment in oil and gas

Our scenarios project widely different outlooks for oil and gas demand, and therefore also for the investments that are required. If demand increases in the future or remains at a consistently high level – as in the STEPS – new upstream conventional projects are required to meet this demand and to offset declines in production from existing fields. New upstream projects are needed in the APS as well; even though global demand soon peaks and starts to fall, the reduction in demand is slower than the rate at which production from existing fields declines.

In the IEA's Net Zero by 2050 Roadmap, first published in 2021 (IEA, 2021a), a huge surge in clean energy investment led to a large projected drop in oil and gas consumption. The trajectory of falling demand matched the declines in supply that would be seen with continued investment in existing sources of supply but without any need for the approval of new long lead time upstream conventional projects.

However, over the year since the 2021 Roadmap was published, oil and gas demand has risen and additional oil and gas (and coal) projects have received final investment decisions; all the new investments in fossil fuel infrastructure not included in the 2021 NZE Scenario would result in 25 Gt of emissions if operated to the end of their lifetime (around 5% of the remaining carbon budget for 1.5 °C). Russia's invasion of Ukraine adds an additional dimension to this outlook, as it could now lead to a substantial and prolonged reduction in Russian energy supplies.

Against this backdrop, does the 2021 finding that no new oil and gas fields are needed along the journey to net zero by mid-century still hold for the updated NZE Scenario in this year's *Outlook*? There are two dimensions to this question, which need to be treated separately. First, how can countries replace the immediate shortfalls in fossil fuel supply from Russia? And second, have circumstances changed in a way that could justify approvals of new oil and gas fields, even in a world working towards net zero emissions by 2050?

On the first question, the immediate shortfalls in Russian fossil fuel production need to be replaced in part by production elsewhere, in any scenario. The size of the shortfall depends in large part on the strength of actions taken to reduce demand. But new conventional oil and gas field approvals taken today would not help to meet these immediate needs, as the lead times for large new supply projects mean that they take many years to start producing meaningful volumes.

The more suitable options are investments with shorter lead times and quicker payback periods. These include, for example, extending production from existing fields, tight oil and shale gas (which can be brought to market quickly), and making use of natural gas that is currently flared and vented. Some new infrastructure may also be needed to facilitate the diversification of supply away from Russia. For example, many European countries are looking to install LNG import terminals and, with careful investment planning, there are opportunities for these to facilitate future imports of hydrogen or hydrogen-based fuels.

On the second question, it is worth taking a step back and considering the sort of world the NZE Scenario is describing. As the 2021 Roadmap underlined, this is a world that is united in its determination to achieve the 1.5 °C goal, and that is working consistently and cooperatively towards that goal. In the words of the 2021 Summary for Policymakers: "the unwavering policy focus on climate change in the net zero pathway results in a sharp decline in fossil fuel demand, meaning that the focus for oil and gas producers switches entirely to output – and emissions reductions – from the operation of existing assets."

The NZE Scenario in this *Outlook* relies on a similar vision of the future to that in the 2021 Roadmap. And, as a result it remains the case that – with the steep reductions in fossil fuel demand in the NZE Scenario in this *Outlook* – fossil fuel demand can be met through continued investment in existing assets and already approved projects, but without any new long lead time upstream conventional projects.

Meeting this condition, though, comes with consequences that countries need to consider carefully, especially in a world marked by geopolitical tensions. One crucial aspect – already highlighted in the 2021 Roadmap, and even more visible in this year's update – is the increased reliance over time on a smaller concentration of suppliers. In the case of oil, the updated NZE Scenario requires higher near-term production from members of OPEC than before to keep markets in balance, and a continuing high level of reliance on this production to meet remaining oil demand through to 2050. In the NZE Scenario, the share of oil supply coming from OPEC members rises from 35% in 2021 to 52% in 2050. Even though the oil market is much smaller in 2050 than today, the share of OPEC by then would be higher than at any point in the history of oil markets. It cannot be taken for granted that importers will be comfortable with such a concentration in supply.

In the case of natural gas, the reduction in Russian supply to Europe in this year's NZE Scenario is accompanied by lower projected gas use, as higher prices curb the cost effectiveness of gas helping to displace coal. But Europe is still left in a precarious situation. In last year's NZE Scenario, Europe's declining gas import needs were met in large part by contracted gas supply from Russia. In this year's scenario, Europe relies on natural gas becoming available from elsewhere in the world. This includes gas that has already been contracted to Asian importers – notably in China – that is surplus to their requirements as these countries undertake efforts to cut emissions. In this case, Europe may want greater certainty over its gas import requirements by concluding new gas supply arrangements, even as it redoubles its efforts to reduce reliance on all fossil fuels.

The possibility of additional oil and gas projects, beyond the levels of supply needed in the NZE Scenario, comes with some important caveats and qualifications:

- Discussion of the supply and investment aspects of the transition should not distract from the need for a massive surge in investment in renewables, energy efficiency and other clean energy technologies. This is the necessary condition that needs to be met in order to reduce and then remove the need for new field developments.
- Any emissions coming from new projects would need to be compensated by even more robust emissions reductions in the latter years of our projections to achieve net zero emissions by 2050; they do not come for free in climate terms. This would make the later stages of the transition even more challenging, and creates the clear risk that this target moves out of reach. No one should imagine that Russia's invasion can justify a wave of new oil and gas infrastructure in a world that wants to reach net zero emissions by 2050.

- Any new developments that do go ahead would have to prioritise low-emissions technologies across the full supply chain from extraction, processing and transport to end-use. This means minimising methane leaks and other upstream and midstream emissions, and integrating the use of CCUS or of non-combustion uses of the hydrocarbons. For new LNG liquefaction facilities, projects would likely need to have a much shorter lifetime for delivering natural gas than is traditionally the case. This could mean shortening the period of capital recovery, making the delivered gas more expensive, and planning from the outset how to extend emissions reductions across the whole value chain, for example by moving to delivery of low-emissions gases.
- If the world is successful in bringing down fossil demand quickly enough to reach net zero emissions by 2050; any new projects would face major commercial risks. The countries or companies choosing to undertake them need to recognise that these developments may fail to recover their upfront costs. They would also need to plan and justify for how global production levels will be further reduced in the future in a successful transition to net zero emissions by mid-century.

It is understandable why some countries and companies are looking to move ahead with the exploration and approval of large longer-term supply projects. But the higher emissions that these projects imply have consequences for our efforts to meet a 1.5 °C, and it is imperative that decision makers today make the additional burden on future generations as light as possible. There are many ways to respond to the immediate energy crisis that can pave the way both to a more secure and a cleaner future. That is where the lasting solutions lie.

Setting the scene

Context and scenario design

SUMMARY

- The recovery in global energy consumption that followed the pandemic-induced drop in 2020 ended prematurely with Russia's invasion of Ukraine in early 2022, plunging global energy markets into turmoil, stoking inflationary pressures and slowing economic growth. The strains on markets did not begin with Russia's invasion of Ukraine, but they have been sharply exacerbated by it. This has led to volatility and steep spikes in energy prices, particularly for natural gas in European markets, and the menace of further disruption to supply looms large. Amid this turmoil, growth in renewables has held up well.
- The crisis has shattered energy relationships with Russia built on the assumption of trust and secure supplies, and led to a reappraisal of energy security needs in many countries. This is leading to a recasting of the energy trade and investment landscape in profound ways. It has already prompted a host of measures aimed at strengthening energy security, including support to build domestic production capability in key sectors.
- One key question is whether today's crisis will lead to acceleration in energy transitions, or whether a combination of economic turmoil and short-term policy choices will slow momentum. On the one hand, high fossil fuel prices and record levels of emissions offer strong reasons to move away from reliance on these fuels or to use them more efficiently. On the other, energy security concerns may spur renewed investments in fossil fuel supply and infrastructure. This *Outlook* considers the implications of different policy choices.
- Today's energy crisis shares some parallels with the 1970s oil price shocks, but there are also important differences. The crises in the 1970s were concentrated in oil markets and the global economy was much more dependent on oil than it is today. However, the intensity of use of other fossil fuels has not declined to the same extent; for natural gas it has risen in many cases. The global nature of the current crisis, its spread across all fossil fuels and the knock-on effects on electricity prices are all warning signs of broader economic impacts.
- Governments made a host of commitments to sustainability in the run-up to the COP26 meeting in Glasgow in 2021, and these remain the bedrock for many energy strategies. In some cases, these ambitions have now been reinforced by new measures seeking to reinforce long-term energy security and accelerate energy transitions, including the US Inflation Reduction Act and the REPowerEU Plan. The total amount of government spending committed to clean energy transitions since the start of the pandemic amounts to USD 1.1 trillion.

- Near-term borrowing costs are likely to rise as monetary policy tightens in many countries. This could disadvantage some clean energy projects for which financing costs play a major role in levelised costs. Nonetheless, clean technologies remain the most cost-efficient option for new power generation in many countries, even before taking account of the exceptionally high prices seen in 2022 for coal and gas.
- This *Outlook* explores three scenarios – fully updated – that provide a framework for thinking about the future of energy and exploring the implications of various policy choices, investment trends and technology dynamics. The scenarios, which should not be considered as IEA forecasts, are:
  - **Stated Policies Scenario**, which looks not at what governments say they will achieve, but at what they are actually doing to achieve the targets and objectives they have set out, and assesses where this leads the energy sector.
  - **Announced Pledges Scenario,** which examines where all current announced energy and climate commitments – including net zero emissions pledges as well as commitments in areas such as energy access – would take the energy sector if implemented in full and on time.
  - **Net Zero Emissions by 2050 Scenario**, which maps out a way to achieve a 1.5 °C stabilisation in global average temperature and meet key energy-related UN Sustainable Development Goals.
- Rising demand for energy services to 2040 is underpinned by economic growth, which is lower to 2030 than in last year's *Outlook* but which averages 2.8% per year through to 2050. The world's population rises from 7.8 billion people in 2021 to 9.7 billion in 2050, an increase of almost one-quarter. These economic and demographic assumptions are kept constant across the various scenarios, while energy and climate policies, technology costs and prices vary.
- Cost pressures are being felt across the energy sector from persistent strains on supply chains and from higher prices for critical minerals and essential construction materials such as cement and steel. We expect recent rises in clean technology costs to be temporary, and to recede in the face of the forces of innovation and improvements in manufacturing and installation processes. Current trends are, however, prompting governments to pay closer attention to the resilience and diversity of clean energy supply chains, which cannot be taken for granted.
- Today's exceptionally high fossil fuel prices are projected to ease as economies slow and markets rebalance, although natural gas markets remain tight for several years as Europe competes for available LNG cargoes to compensate for curtailed Russian supply. The speed of adjustment and the longer-term price trajectories differ by scenario, depending on the strength of policy action to curb demand.

Russia's invasion of Ukraine is reshaping the energy world

Energy markets

High and volatile energy prices are hurting households and businesses, shifting the choice of fuels and setting back progress towards achieving universal access to energy.

Energy policy

Short-term responses have focused on securing available supply and protecting consumers, but many governments in the US, EU and elsewhere have adopted new policies that give a major boost to investments in clean energy and efficiency.

Energy trade

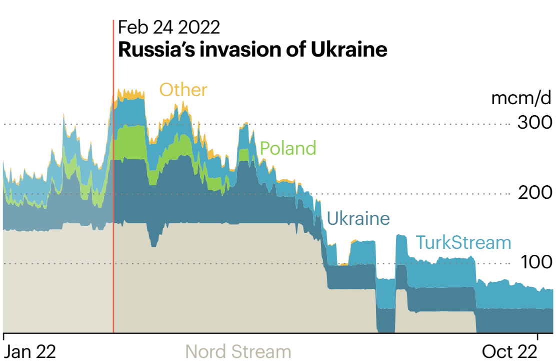
European sanctions on coal and oil imports and Gazprom's decisions to cut gas supply are triggering a profound reshuffling of trade flows around the world.

Economic impacts

High fossil fuel prices are stoking inflationary pressures; the combination of falling real incomes and rising prices is creating a looming risk of global recession.

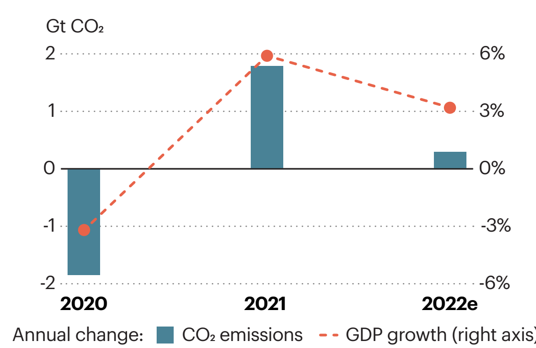
Russia has cut its natural gas pipeline flows...

...to the European Union by around 80% since invading Ukraine.



CO_2 emissions from global fossil fuel combustion...

...saw a record rise in 2021, but a strong expansion of renewables and electric vehicles is expected to dampen growth in 2022.



2.1 Introduction

The world is in the middle of a global energy crisis of unprecedented depth and complexity. Europe is at the centre of this crisis, but it is having major implications for markets, policies and economies worldwide. As so often is the case, the poorest and most vulnerable are likely to suffer most. The strains did not begin with Russia's invasion of Ukraine, but they have been sharply exacerbated by it. Extraordinarily high prices are sparking a reappraisal of energy policies and priorities. The Europe-Russia energy relationship lies in tatters, calling into question the viability of decades of fossil fuel infrastructure and investment decisions built on this foundation. A profound reorientation of international energy trade is underway, bringing new market risks even as it addresses longstanding vulnerabilities.

Many of the contours of this new world are not yet fully defined, but there is no going back to the way things were. And we know from past energy crises that the process of adjustment is unlikely to be a smooth one. That adjustment will also be taking place in the context of commitments made by governments to clean energy transitions. A central theme of this *World Energy Outlook 2022* is how the levers of technological change and innovation, trade and investment and behavioural shifts might drive a secure transition towards a net zero emissions energy system, while minimising the potential risks and trade-offs between various policy objectives.

This chapter sets the scene. It starts with an exploration of how the crisis has not just upended energy markets but also soured the economic outlook, before considering the underlying forces bearing on today's energy sector, the policy responses and what it all means for our starting point in 2022. Europe's scramble to reduce reliance on Russian fossil fuel imports takes centre stage, but the repercussions of Russia's invasion of Ukraine are being felt much more broadly across a deeply interconnected global energy system.

The chapter concludes by introducing the scenarios used in this *Outlook*, explaining how and why they differ from each other, setting out the macroeconomic and demographic assumptions that underpin them as well as the outlook for energy and carbon prices and energy technology development. The three scenarios are:

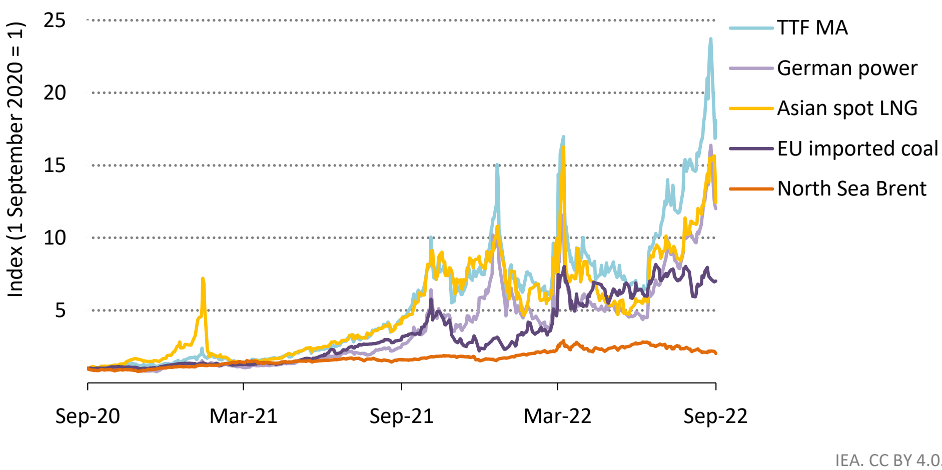
- **Stated Policies Scenario** (STEPS), which maps out a trajectory that reflects current policy settings, based on a detailed sector-by-sector assessment of what policies are actually in place or are under development by governments around the world.
- **Announced Pledges Scenario** (APS), which assumes that all long-term emissions and energy access targets, including net zero commitments, will be met on time and in full, even where policies are not yet in place to deliver them.
- **Net Zero Emissions by 2050** (NZE) **Scenario**, which sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, updating the landmark IEA analysis first published in 2021. While the first two scenarios are exploratory, the NZE Scenario is normative, as it is designed to achieve the stated objective and shows a pathway to that goal.

2.2 Background to the global energy crisis

The historic plunge in global energy consumption in the early months of the Covid-19 crisis in 2020 drove the prices of many fossil fuels to their lowest levels in decades. However, the price rebounds since mid-2021 have been brutally quick (Figure 2.1). Oil prices that briefly moved into negative territory in 2020 have been back around or above USD 100/barrel. Coal prices have reached record levels. Spot natural gas prices in Europe have regularly been above USD 50 per million British thermal units (MBtu), more than double the crude oil price on an energy-equivalent basis. Tight gas and coal markets have fed through into exceptionally high electricity prices in many markets. The global energy crisis has hurt households, industries and entire economies around the world, with the poorest and most vulnerable suffering particular hardship.

2

Figure 2.1 ▷ Evolution in selected energy price indicators since September 2020



This has been a period of extraordinary turbulence in energy markets, intensified by Russia's invasion of Ukraine in February 2022

Note: TTF MA = Title Transfer Facility month-ahead prices; LNG = liquefied natural gas; Brent = Brent crude oil benchmark.

Sources: IEA analysis based on Argus Media (2022); ICIS (2022); BNEF (2022).

2.2.1 Initial signs of strain

There was no single cause behind the initial rise in prices in 2021, prior to Russia's invasion of Ukraine. Many factors played a part, chief among them being:

- **The rapidity of the economic recovery from the pandemic-induced recession**. This strained many elements of global supply chains, including those in the energy sector. In 2021, demand for all the fossil fuels grew by at least 5%.

- **The impact of weather-related events on demand and electricity generation trends**. These events include droughts that curtailed hydropower output in Brazil and elsewhere (resulting in a more than threefold year-on-year increase in Brazil's liquefied natural gas [LNG] imports), heat waves that reduced nuclear power availability in France and elsewhere, lower than average wind speeds that affected wind generation in Europe, and Hurricane Ida's interruption of US offshore production.
- **Planned and unplanned outages to supply**. Covid lockdowns in 2020 pushed some maintenance work into 2021, which weighed on supply just when demand was recovering. Flooding in Australia in early 2022 temporarily interrupted coal production, and a month-long coal export ban in Indonesia tightened trading conditions, sending prices much higher. Natural gas markets were meanwhile affected by unplanned outages at LNG liquefaction plants, unforeseen repair works and a variety of project delays.
- **The stance of major suppliers**. The most notable example was Russia's Gazprom, which reduced its short-term sales and did not replenish its own storage sites in Europe to the levels seen in previous years or otherwise increase natural gas availability. This amplified the market reaction when a cold spell hit Europe in December 2021.
- **Underlying investment dynamics**. Governments have not been pursuing strong enough policies to generate a much-needed increase in clean energy investment. In the absence of such a surge in energy efficiency improvements and clean energy deployment, investment in the fossil fuels sector has also been falling short of what is required to meet rising demand. Investment in upstream oil and gas halved between 2014 and 2021, due primarily to two commodity price collapses in 2014-15 and in 2020.

Climate policies were blamed in some quarters for contributing to the initial run-up in prices, but it is difficult to argue that they played a significant role. In fact, more rapid deployment of clean energy sources and technologies would have helped to protect consumers and mitigate some of the upward pressure on fuel prices. They would also have mitigated the post-pandemic rebound in energy-related carbon dioxide (CO_2) emissions which reached 36.6 billion tonnes in 2021. The annual increase of 1.9 billion tonnes was the largest in history, offsetting the previous year's pandemic-induced decline.

2.2.2 Russia's invasion of Ukraine

Russia's invasion of Ukraine in February 2022 made the strains in the energy sector far worse. Alongside huge damage to Ukraine's energy sector (Box 2.1), it has had wider implications for energy that will be felt for many years to come. Russia has been by some distance the world's largest exporter of fossil fuels, and a particularly important supplier to Europe: in 2021, one-of-five units of energy consumed in the European Union came from Russia. This reliance on Russia had long been identified as a strategic weakness, and some infrastructure was built to diversify sources of imports, but Russian flows remained high: in the case of natural gas, Russia's share of European gas demand actually rose from 30% on average over 2005-10 to reach 40% in the 2015-20 period.

Box 2.1 ▷ Moving towards a new energy sector in Ukraine

The war in Ukraine has tragically upended the lives of Ukrainians and created huge economic difficulties. There are of course huge uncertainties over the future course of the conflict and its aftermath. However, in the energy sector, as in many others, Russia's invasion is likely to mark a decisive break with the past for Ukraine.

Although diversification efforts have accelerated since 2014, Ukraine has remained largely dependent on Russian sources of energy to meet domestic demand. Russia often used this dependency to its advantage. Russia also sought to reduce Ukraine's importance to European natural gas security by building up alternative pipeline routes to European consumers, after cutting off gas supplies to Ukraine in 2006 and in the winter of 2008-09 over price and pipeline tariff disputes. In 2015, Ukraine decided to stop buying Russian gas and was able to contract what it needed from its western neighbours instead, although these new arrangements still relied in practice on Russian transit volumes for their delivery. In addition, Ukraine continued to depend heavily on Russian and Belarusian oil products, which met roughly 75% of domestic demand.

Ukraine's energy infrastructure has suffered severely since February. The safety of its nuclear facilities is a particular area of concern: nearly half of Ukraine's nuclear generation capacity is located in occupied territory and Zaporizhzhia – the largest nuclear plant in Europe – is very close to the front lines. Nuclear safety should be paramount. On-going military operations raise significant nuclear safety risks.

More broadly, the ability of decision makers to assure power and heat for civilians is being compromised by Russian attacks on critical energy infrastructure and other targets. As of mid-September 2022, 30% of thermal and solar generation and 90% of wind generation capacity had been destroyed or was under Russian occupation, and all oil refining capacity is either offline or has been destroyed. These numbers predate Russia's coordinated missile attacks against Ukraine in October where electricity grid facilities and other energy assets were among the targets. Falling revenues, driven in large part by deteriorating collection rates from utilities, also present a major challenge to the government.

The winter of 2022-23 will be a very difficult one for Ukraine, particularly if gas transit through Ukraine is interrupted. Ukraine has been buying as much gas as it can to fill its underground storage infrastructure, but high prices and fiscal constraints have limited how much can be achieved. Domestic production levels are likely to reach 16-17 billion cubic metres (bcm), barring any attacks on production facilities. Gas demand is likely to be significantly lower than the 27 bcm consumed in 2021 and may even fall to 18 bcm or lower: much depends on how much territory is occupied and how much infrastructure is lost. The government is looking at potential demand-restraint measures such as lowering minimum temperature standards in residential buildings to 16 °C.

In the medium and longer term, Ukraine is looking towards integration with European energy infrastructure. The day before the invasion, Ukraine's transmission service operator, Ukrenergo, decided to disconnect from the Integrated Power System, which linked Ukraine's power system to that of Russia and Belarus, and to do a test run in "island mode". The system ended up running in this mode for 21 days until it was synchronised with the European Union's ENTSO-E power system.

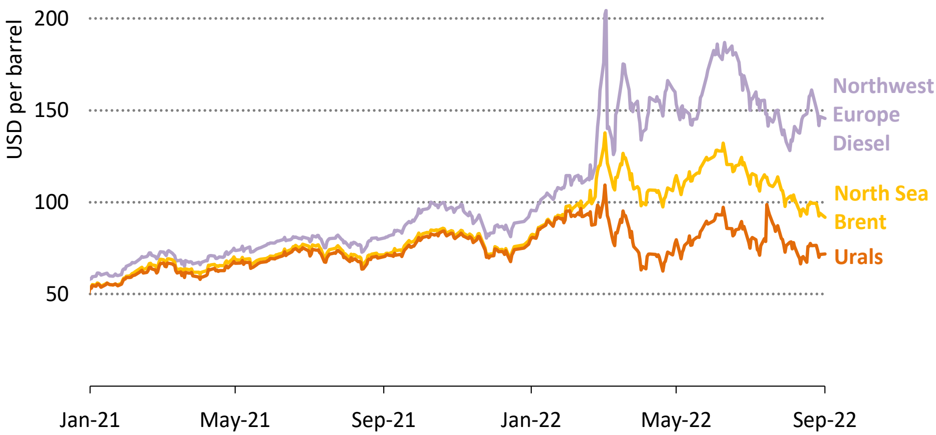
The government has put together an ambitious recovery and reconstruction plan with a strong focus on energy security and greater self-sufficiency. Ukraine's European Union candidate status also underpins its ambition to build a "future-proof" energy system. The plan aims to increase the share of renewables, bring about the building of more nuclear reactors, increase investment in biogas and renewable hydrogen, and reconstruct cities with energy efficient buildings and transport systems. Balancing these long-term goals with urgent short-term repairs – for example, to combined heat and power plants severely damaged by Russian bombing – will be very challenging.

Rebuilding Ukraine's energy sector will be expensive: preliminary government estimates put the total cost of reconstructing Ukraine's energy sector through to 2032 at USD 128 billion. This figure is obviously provisional, given continuing hostilities, but the work of rebuilding will provide an opportunity to create a different, cleaner future for Ukraine's energy sector.

The invasion triggered moves by many of Russia's international partners to limit or cut ties. European Union leaders, meeting in Versailles on 10-11 March, agreed to "phase out our dependency on Russian gas, oil and coal imports as soon as possible". In addition, many international companies – especially those domiciled in Europe or North America – have left Russia or are winding down their business operations there. Some of these intentions have been reinforced by firm commitments, including sanctions. Over time, this will fundamentally reshape Russia's position in international energy.

For the moment, Russian oil production and exports remain close to pre-invasion levels, but there have been some sizeable shifts in trade flows, with exports to Europe and North America falling, but buyers in India, China and Türkiye attracted by the discounted prices on offer. Russian Urals crude has been trading at a discount to Brent crude oil on average of around USD 30/barrel since March (Figure 2.2). An important test for global product and crude markets will come when the European Union ban on seaborne imports of Russian oil enters into force (December 2022 for crude oil and February 2023 for oil products). Not all of the Russian exports displaced from the European Union are likely to find a new home in other markets.

Figure 2.2 ▷ Prices for Brent and Urals crude oil, and diesel in Northwest Europe since January 2021



IEA. CC BY 4.0.

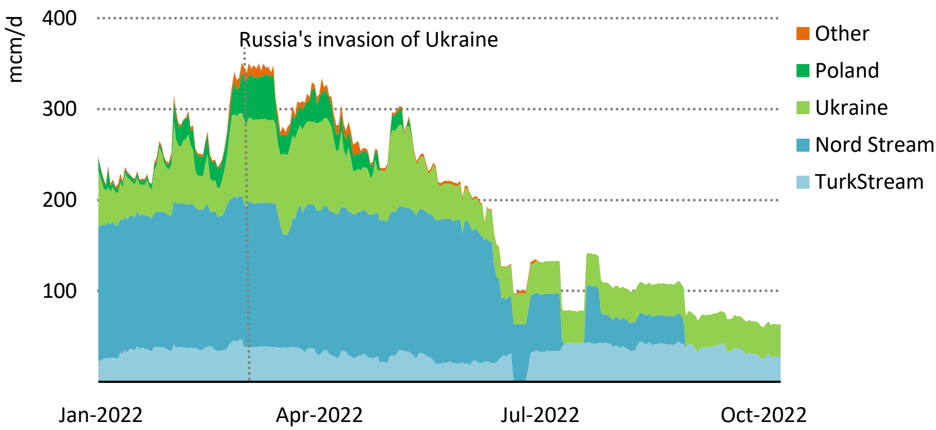
The invasion has produced deep discounts for Russian crudes and a major rise in refining margins as product markets run up against a shortage of global refining capacity

Source: IEA analysis based on Argus Media (2022).

The breakdown of Russia's natural gas relationship with Europe is still more complicated. It is not possible in the near term for Russia to switch its European pipeline exports to other markets, for example to Asia. However, Europe's ability to find alternative supplies in the near term is also constrained. LNG is the clearest candidate. Europe increased its LNG imports by around 45 bcm in the first 8 months of 2022, compared with the same period in 2021. Its ability to do so was helped by relatively muted demand in China (which reduced its spot purchases of LNG significantly over this period) and by new projects in the United States coming on stream. But increased LNG deliveries from a tight international market cover only a small part of the reductions in Russian deliveries over the course of 2022, putting the spotlight and the burden of adjustment firmly on European natural gas demand (Figure 2.3).

The northern hemisphere winter of 2022-23 will be a perilous moment for Europe, international natural gas balances and global energy security. Europe has made progress in refilling its gas storage sites, which were more than 90% full by early October despite regular curtailments of Russian supply that appeared to be aimed at slowing the process. During the winter heating season, withdrawals from storage – alongside continued imports – are vital to meet the seasonal upswing in demand, and the market may be very tight indeed if flows from Russia remain low or cease entirely. Early, co-ordinated action to limit gas use and peak electricity demand (which is typically met by gas-fired power plants) will be essential if Europe is to ward off rising energy security threats.

Figure 2.3 ▷ Natural gas pipeline flows from Russia to the European Union and Türkiye since January 2022



Between May and October 2022, daily pipeline flows from Russia to the European Union dropped by around 80%

Note: mcm/d = million cubic metres per day.

Source: IEA analysis based on ENTSOG Transparency Platform (2022).

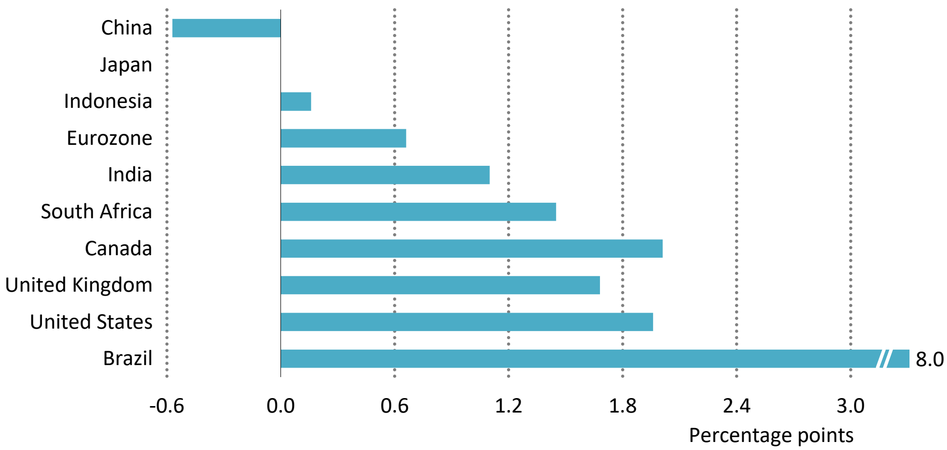
Russia's influence on the energy sector extends beyond oil and gas to encompass coal, uranium, fertiliser and many of the minerals and metals that are vital for clean energy transitions. Russia has been Europe's largest source of imported coal, and a reordering of trade flows is underway as a result of a European Union ban on imports of Russian coal that entered into force in August 2022. Russia also produces around 20% of the world's Class 1 nickel (which is the grade needed for batteries) and accounts for over 40% of global uranium enrichment capacity. In addition, it is the world's second-largest global producer of cobalt and aluminium, and the fourth-largest producer of graphite.

2.2.3 Economic consequences

The macroeconomic reverberations from the global energy crisis, coming on the heels of the pandemic, are having far-reaching economic consequences. In emerging market and developing economies, where the share of energy and food in household budgets is relatively large, energy prices have had a significant impact on inflation, setting back progress towards achieving affordable access to energy and contributing to a sharp increase in extreme poverty in the most vulnerable countries and communities. In South Asia, the crisis is already having destabilising effects, with Pakistan and Sri Lanka in particular suffering widespread energy shortages. In Africa, the number of people living without electricity increased by more than 15 million (or 3%) between 2019 and 2021, reversing almost all the gains made over the previous five years, and this dire trend is set to be reinforced in 2022.

Most projections of economic activity have been scaled back significantly since the start of the year, with the International Monetary Fund (IMF) cutting its expectations of global growth for 2022 from 4.9% in October 2021 to 3.2% in its October 2022 update (IMF, 2022). In energy importing economies, higher prices for fuels and electricity reduce economic output by lowering the real incomes of households and raising the production costs of businesses. Some energy exporting economies stand to benefit from higher energy prices, with better terms of trade boosting national income, expanding production and making investment opportunities more attractive. However, this provides only a partial offset to the drag on global growth, since energy exporting economies tend to save more and spend less of their income than importing economies (World Bank, 2022). The extent to which higher energy prices ultimately impact individual countries depends on a range of factors, including the share of energy in their exports and imports, the energy intensity of their industrial production, their reliance on the energy sector for taxation revenue and the effect of higher energy prices on investor and consumer confidence.

Figure 2.4 ▷ Change in base interest rates in selected economies, year-to-August 2022 relative to 2021



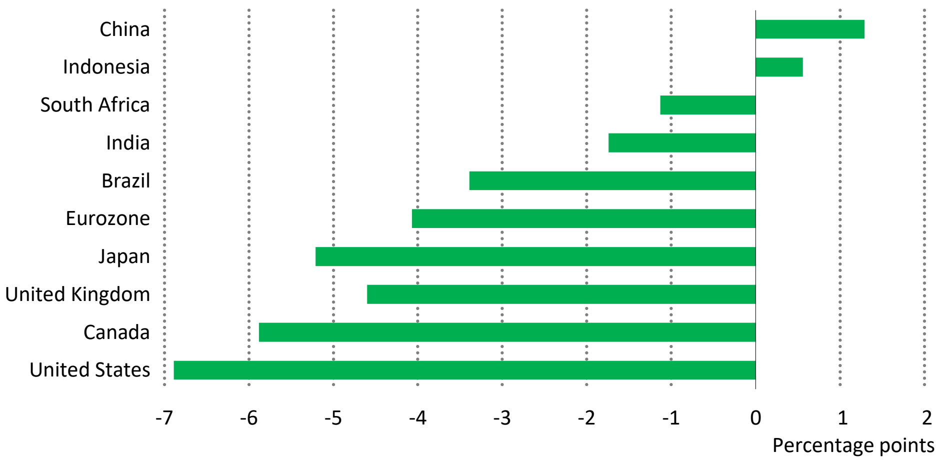
Inflationary pressures, linked in part to higher energy prices, are prompting a shift in monetary policies; further interest rate hikes are likely

Note: Eurozone in this figure includes 19 countries that use the Euro: Belgium, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Austria, Portugal, Finland, Greece, Slovenia, Cyprus, Malta, Slovakia, Estonia, Latvia and Lithuania.

Source: Oxford Economics (2022).

With inflation in many countries well above target level, the ability of authorities to cushion the impact of higher energy prices on activity with accommodative macroeconomic policy may be more limited than it was when the Covid shock hit in early 2020. In advanced economies, higher prices and rising inflation have already brought forward the normalisation of monetary policy. The base rate of central banks in Canada, United Kingdom and United States has risen by close to 200 basis points since 2021 (Figure 2.4). The European Central Bank started to tighten later, raising its base rate for the first time in over a decade by 50 basis points in July 2022, and by a further 75 basis points in September. Japan has thus far been an exception to this tightening trend. Monetary policy varies more among emerging market and developing economies, reflecting their differing cyclical positions. The tightening of monetary policy in many countries comes at a time when public and private debt are at a high level, particularly for this point of the cycle, meaning that any change in interest rates has a larger contractionary and potentially destabilising effect than just a few years ago.

Figure 2.5 ▷ Change in household savings rate in selected economies, year-to-August 2022 relative to 2021



Drawing down savings accumulated during the pandemic provides a safety net for some households, but the broader economic risks are clearly skewed to the downside

Note: Eurozone in this figure includes 19 countries that use the Euro: Belgium, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Austria, Portugal, Finland, Greece, Slovenia, Cyprus, Malta, Slovakia, Estonia, Latvia and Lithuania.

Source: Oxford Economics (2022).

Some partial buffers for the economic outlook – especially in advanced economies – have come from household balance sheets that were buoyed by savings during the pandemic, strong labour market conditions and fiscal support measures (Figure 2.5). This has provided some support to economic activity in the face of headwinds from the energy crisis, and as central banks tighten monetary policy. However, the risks are clearly skewed to the downside. The war in Ukraine shows few signs of ending, curtailment of Russian gas flows and high prices are forcing painful curtailments of industrial output in parts of Europe, geopolitical strains continue to divide and fragment trade and investment flows, and possible new Covid variants cannot be excluded. In this febrile and largely uncharted environment, additional shocks have the potential to cause significant economic harm. Price pressures could also mount, making stagflation a genuine threat.

Overall, the ability of different economies to withstand the crisis varies widely. European countries are directly exposed to shortfalls in energy supply but also have greater possibilities to adjust. Higher borrowing costs, alongside a strong dollar, are hurting many emerging and developing economies – especially those with pre-existing economic weaknesses. Ultimately, the combination of falling real incomes and rising prices is being widely felt, inviting comparisons with the most serious energy shocks of the past (Box 2.2).

2

Box 2.2 ▻ How does this energy crisis differ from previous price shocks?

Today's energy crisis has some features in common with the oil price shocks of the 1970s, notably the combination of slowing growth and rising inflation linked to high commodity prices and tight labour markets. But there are also important differences.

One is that recent oil price movements have been relatively modest by comparison with the 1970s, when prices rose swiftly from less than USD 10/barrel (expressed in current US dollars) before the embargo in 1973 to more than USD 40/barrel at the start of 1974. Higher prices persisted after the embargo was lifted and then rose again to the equivalent of USD 80-90/barrel as oil production in Iran fell after the Iranian revolution.

Another is that the global economy is much less dependent on oil than it was in the 1970s (Figure 2.6). In 1973, USD 10 000 of value added to the global economy required 5.6 barrels of oil; the figure today is closer to 2.4 barrels. In 1973, oil was widely used not just for transportation, but also for more than a quarter of the world's electricity generation – a higher share than renewables. Today, oil generates less than 3% of the world's power (and renewables close to one-third).

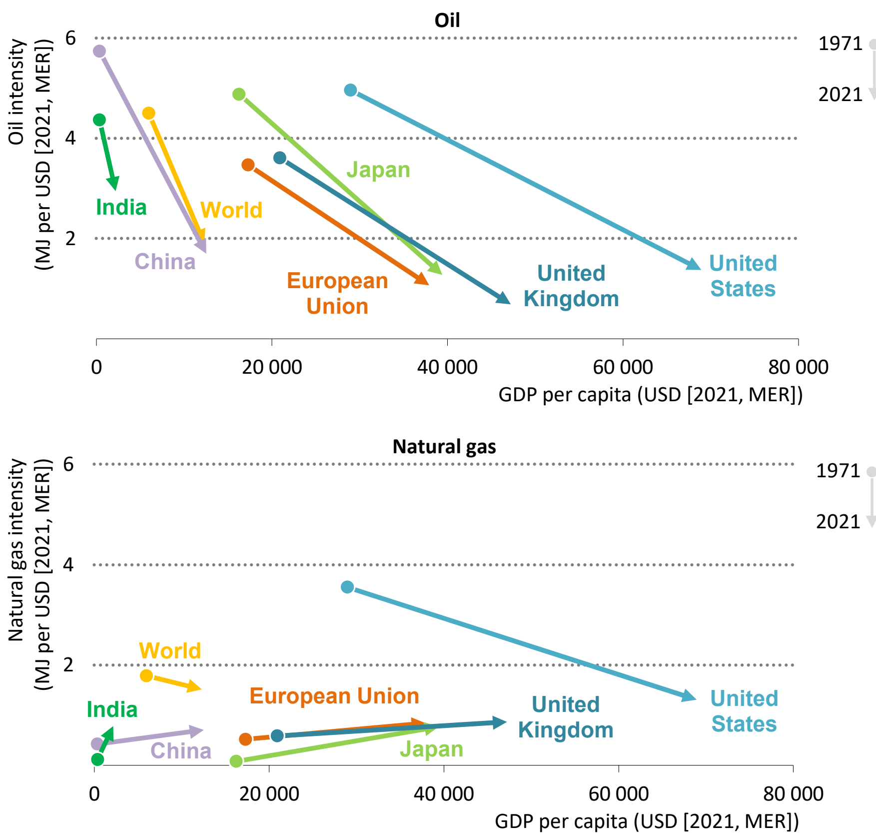
However, to focus on oil in the current energy crisis misses the larger context. The world is experiencing a global energy crisis, with large price increases for all fossil fuels and, in turn, substantial upward pressure on electricity prices as well. Coal and natural gas prices have reached record levels in many markets. The effects of today's crisis are felt very widely across a range of economic activities and countries.

At the same time, the current crisis leaves Europe uniquely exposed. Europe is unusual in being a major gas-consuming region that is heavily dependent on imports – virtually all other countries or regions with comparable levels of dependence on gas are major producers. Although it is wealthy enough to outbid some other parts of the world for available LNG cargoes, this is far from enough to cushion the continent from the effects of reduced Russian supplies.

Searching for silver linings in the current crisis is not easy, but there are two reasons for guarded optimism. First, macroeconomic policy makers and institutions have learned important lessons on how to respond to commodity price shocks. Monetary policy has largely focused on calming demand-side price pressures while letting supply-side shocks flow through, and policy frameworks in many countries are firmly based on the objective of price stability. Labour bargaining arrangements generally also take more account than in the past of the risk of cost-push inflation, with fewer automatic wage indexation provisions than used to be the case.

Second, the 1970s are now remembered not only for the social and economic pain caused by high energy prices but also for rapid energy innovation and diversification. Low-emissions options got a major boost, notably in the form of investment in nuclear power. Energy efficiency took centre stage: the fuel economy of an average new car sold in the United States went from 18 litres/100 km at the start of the 1970s to 15 litres/100 km by the end of the decade.

Figure 2.6 ▷ Oil and gas use relative to GDP per capita in selected countries/regions since 1971



Starting at a much lower level for natural gas, trends in oil and gas intensity for most countries have moved in opposite directions since the early 1970s

Note: MJ = megajoule; MER = market exchange rate.

There is much more scope today to deploy new technologies and diversify than there was in the 1970s. Back then, wind and solar photovoltaics (PV) were just entering the market, whereas now they are mature technologies whose economic advantages are only being reinforced by sky-high prices for fossil fuels. There has also been rapid progress in recent years in the development of technologies that support and enable demand-side management as well as those that support the use and storage of clean electricity from variable sources. As a result, there are opportunities in many countries to pursue a dramatic and immediate scale up of clean energy investment and deployment in ways that were not possible in the 1970s.

2.3 Where do we go from here?

2.3.1 Investment and trade responses

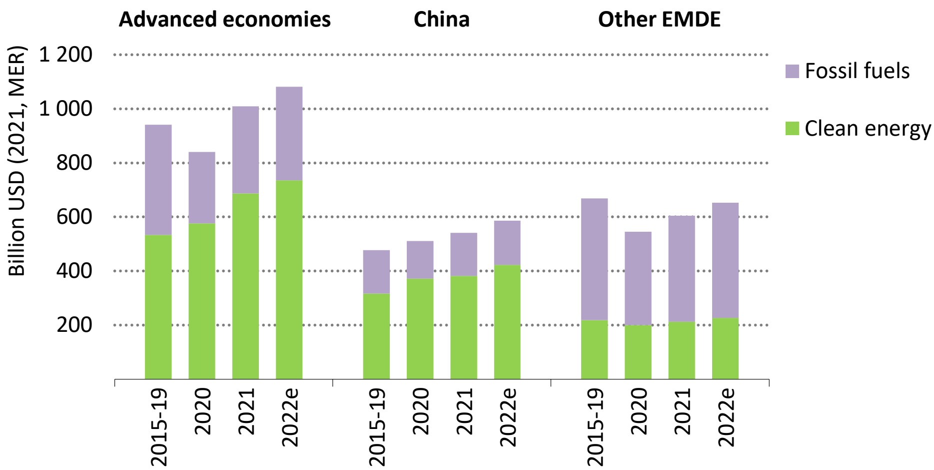
Energy investment and trade flows are being reshaped by the current crisis in ways that will have a significant bearing on the future of energy. Periods of high fossil fuel prices offer strong incentives to move away from reliance on these fuels or to use them more efficiently, reinforcing the momentum behind energy transitions. However, today's crisis could also spur renewed investments in fossil fuel supply in the name of energy security. The relative weight of these responses will be determined by policy priorities, including long-term climate commitments as well as energy security imperatives, and different priorities may not be well aligned. Governments, companies, investors and financial institutions all face a complex and fast-evolving situation as they decide which energy projects to back.

Our latest estimates suggest that the bulk of additional investment in 2022 is being drawn towards clean energy (Figure 2.7). Overall global energy investment is anticipated to rise by 8% in 2022 to reach USD 2.4 trillion, with almost three-quarters of the increase for clean energy, including not just renewable power, but also other low-emissions fuels and technologies as well as grids, storage and energy efficiency. However, this shift towards clean energy investment comes with some important caveats.

First, the total is still well short of the amount that is required to meet rising demand for energy services in a climate sustainable way. Total investment in clean energy, estimated at USD 1.4 trillion in 2022, would need to double by 2030 to be consistent with national climate pledges as reflected in the APS, and to triple over the same period to be aligned with the NZE Scenario.

Second, the impact on the energy system from higher spending is partly absorbed by higher costs and inflationary pressures. Investors fret about inflation because it can reduce their return on investment in ways that are beyond their control. If rising inflation is not contained, there is a risk it will put a brake on the willingness of companies to increase capital spending, despite strong price and policy signals. Equally, tighter monetary conditions increase the cost of borrowing and thus put at risk capital-intensive projects, including many clean energy projects.

Figure 2.7 ▷ **Global energy investment by region**



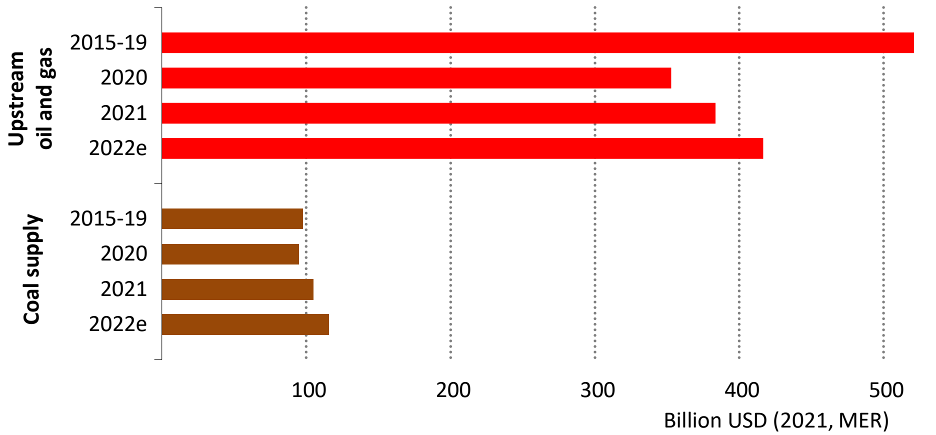
Emerging market and developing economies, other than China, account for two-thirds of the global population, but their share of clean energy investment is both low and declining

Note: EMDE = emerging market and developing economies; MER = market exchange rate; 2015-19 indicates average annual figure; 2022e = estimated values for 2022.

As well, there is the concentration of clean energy investment in advanced economies and China. Virtually all of the global increase in spending on renewables, grids and storage since 2020 has taken place in these economies, and more than 80% of electric vehicle sales are concentrated in China and Europe. Despite some success stories, such as solar investments in India, other emerging market and developing economies risk being left behind. This divergence underlines the material risk of new dividing lines in collective efforts to address climate change and to reach other sustainable development goals.

Today's high fossil fuel prices have generated an unprecedented windfall for producers. Net income for the world's oil and gas producers, for example, is set to double in 2022 to an unprecedented USD 4 trillion. For the moment, however, this is only generating a modest pick-up in overall spending on fossil fuels, with almost half of the cash generated by the majors being used to pay down their debt. Investment in upstream oil and gas is now rising, although the level of investment remains 17% below where it was in 2019, and is around half the investment peak recorded in the sector in 2014 (Figure 2.8). Policy uncertainty is high, intermediated financing can be difficult to secure, and companies are generally shying away from large commitments of capital that may take years to pay back. However, investments in coal supply have been picking up, rising by 10% in 2021 with a further 10% rise expected for 2022. The increase is being led by mining companies in China and India, the dominant players in global coal markets.

Figure 2.8 ▷ Global investment in upstream oil, gas and coal supply



Investment in coal supply is rising at around 10% per year, but oil and gas spending remains below pre-Covid levels, despite sky-high prices

Note: 2015-19 indicates average annual figure; 2022e = estimated values for 2022; MER = market exchange rate.

Russia's invasion of Ukraine is closing off one of the main arteries of international energy commerce, both because of European sanctions on coal and oil imports and Gazprom's decisions to cut gas supply. This is set to generate a reduction in Russian output as well as a profound reshuffling of trade flows around the world. The logical expectation is that, over time, more Russian resources will flow eastwards to Asian markets, rather than westwards to Europe.

There are some signs of this already with crude oil, although the reorientation of oil product flows will involve a wider set of actors, given that both China and India are oil product exporters. An eastward focus for Russia's crude exports sets up a battle for market share with Middle East oil exporters, which have invested both politically and financially in their relationships with key Asian oil consumers.

Reconfiguring global gas flows will be a much more challenging and lengthy process. The distances from the Russian gas fields of western Siberia and the Yamal peninsula to alternative non-European markets are huge, and the infrastructure needed for this is not in place. Russian energy strategy has long sought to increase the diversity of gas export flows, but there has been no contingency planning for a complete breakdown of ties with its primary export market.

The European Union remains very vulnerable to near-term shortfalls in Russian supply, especially for natural gas, but the key elements of a medium-term strategy to reduce reliance on Russian imports have taken shape relatively quickly. Most of the work will need to be done on the demand side, as there is little prospect of large volumes of additional non-

Russian supply becoming quickly available. More LNG from the United States will help, but it will take time to find other major new sources of LNG: for example, large new export facilities in Qatar are not expected to start operations until the middle of the decade. In the meantime, tight markets and fierce competition for available LNG cargoes could leave a lasting reluctance among many price-sensitive developing economies to rely on large-scale gas imports. As discussed in Chapter 8, the downside for gas does not automatically translate into an upside for clean energy; coal or oil could also stand to gain.

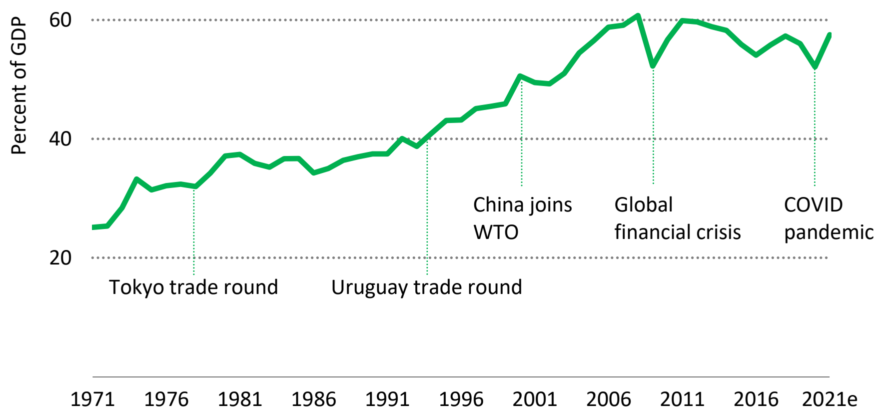
Even before the energy crisis, underlying forces and events were reshaping the broader environment for international trade and foreign investment (Box 2.3). For example, shortages of personal protective equipment and vaccine supplies during the early phase of the Covid pandemic prompted national export restrictions, highlighting the vulnerabilities of just-in-time inventory management. Frustration with the slow pace of change in updating the multilateral trading system is leading to an increasing number of bilateral and plurilateral trade and investment agreements. Geopolitical rivalries and new national security concerns may in the future favour multiple trading blocs centred on trusted partners.

Box 2.3 ▷ Has the world reached peak globalisation?

Trade is both a propagator and an absorber of economic shocks, but in recent years attention has focussed more on the former than the latter. Natural disasters, Covid lockdowns and geopolitical tensions have exposed vulnerabilities in cross-border supply chains, and Russia's use of natural gas in the current conflict to exert pressure on European consumers and decision makers provides a vivid example of the hazards that such supply chains can involve. A reassessment of trade-related economic and security risks in many countries has prompted a host of measures aimed at strengthening supply chain resilience, including support to build domestic production capability in key sectors, the "re-shoring" and diversification of suppliers and calls to update World Trade Organization agreements. This has led some to ask whether we have reached "peak" globalisation.

Globalisation is not a precisely defined concept, but is widely interpreted as the closer integration of economies, especially through international trade and investment. The intensity of trade, measured by the value of imports and exports of goods and services relative to GDP, is a standard indicator used to measure globalisation (Figure 2.9). Following multiple rounds of trade liberalisation, and reductions in shipping and communication costs, global trade intensity rose progressively to reach its highest level in the years before the financial crisis in 2008. Since then, apart from cyclical fluctuations, trade intensity has been broadly steady. It is still too early to judge how recent events will affect this indicator. The plateau in globalisation seems to have begun before the Covid pandemic. At the same time, the plateau does not necessarily presage a fall: in fact, global trade rebounded strongly in 2021 to above pre-pandemic levels as lockdowns eased and travel restrictions were lifted.

Figure 2.9 ▷ Ratio of global trade to GDP



Cyclical fluctuations apart, trade intensity has been steady at a high level for the past 15 years

Notes: Global trade sum of imports and exports to the nominal value of GDP. WTO = World Trade Organization; 2021e = estimated values for 2021.

Sources: World Bank national accounts data; OECD National Accounts data files; IEA calculations.

The capacity of trade to play a role as an absorber of economic shocks is weakened by trade frictions. An illustration of this came at the start of the pandemic when the global surge in demand for personal protective equipment (PPE) could not be met. Many PPE-producing economies put in place export restrictions, which assured national supplies, but did not help to meet the spike in global demand. The restrictions did not last long and were replaced by measures to facilitate trade, notably streamlined certification procedures: these led to a surge in global production that helped to meet worldwide demand and eased local capacity constraints. The restrictions nevertheless served as a reminder of the potential for trade to be curtailed at times of crisis. The possibility of gas shortages in the coming months will provide another important test of the resilience of open markets in Europe and beyond.

Clean energy transitions will affect international trade in significant ways, and by the same token changes in international trade arrangements could profoundly affect the course of those transitions. Trade in fuels will eventually diminish as the share of oil, gas and coal in the energy mix falls. However, this trade may become steadily more concentrated as it diminishes. At the same time, international clean energy supply chains might increase in volume and in strategic importance. Trade enables businesses to buy from the most globally cost-competitive suppliers of clean energy technologies, with solar panels from China being a particularly notable example. This has accelerated the uptake of renewable energy, but the concentration of solar panel production in one country poses potential challenges that governments need to address (IEA, 2022a). Over time, economies with a cost advantage in renewable energy may secure a larger share of international value chains, just as aluminium smelter operators were drawn to countries with low cost hydropower.

The challenge is to harness the positive role that trade has played in reducing the cost and expanding the deployment of renewable energy technologies, such as solar PV and wind, while increasing the resilience and diversity of supply chains – including those for the critical minerals that are vital inputs to many clean technologies. Rather than mounting new obstacles to trade, this requires a determined effort to update the rules of international trade, for example to provide clarity on when and how trade restrictions may legitimately be deployed, to remove remaining tariff barriers on clean energy technologies and the components needed to make them, and to make use of trade facilitation mechanisms, such as mutual recognition, to lower the costs of working with different product standards.

2.3.2 Policy responses

The policy actions taken by governments are a crucial variable in determining where we go from here; they represent the main reasons for the differences in outcomes across the various scenarios in this *Outlook*. In 2021, governments made a number of commitments to sustainability in the run-up to the crucial meeting of COP26 at Glasgow, some of which took the form of new or updated Nationally Determined Contributions (NDCs) under the Paris Agreement – typically for 2030 – or of longer term strategies and targets. By the end of the COP26 meeting, countries representing more than 80% of today's CO_2 emissions had pledged to reach net zero emissions. There were other commitments too, notably the 30% reduction in worldwide methane emissions by 2030 included in the Global Methane Pledge. Less than a year later, however, the global energy crisis and market tumult triggered by Russia's invasion of Ukraine have introduced a host of new pressures.

A key question, explored in the *World Energy Outlook* (*WEO*) scenarios, is whether today's crisis will lead to an acceleration in energy transitions, or whether it is more likely to slow momentum. Governments in Europe and elsewhere are discussing steps to simplify permitting for new clean energy projects and to redouble policy support. However, Europe is also seeing an increase in coal consumption, as well as increased readiness to support new oil and gas projects and infrastructure, and it is not alone in this.

The following major policies and targets are incorporated into the scenarios in this WEO, either in the STEPS or APS, reflecting the degree of concrete policy and legislative developments backing the targets:

- US Inflation Reduction Act, signed into law in August 2022, gives a major boost to a huge array of clean energy technologies from solar, wind and electric vehicles to carbon capture and hydrogen. The new legislation provides for almost USD 370 billion in energy security and climate change resilience investments, which are included in the STEPS.

- The European Commission REPowerEU plan sets out how the European Union can reduce reliance on Russian natural gas through energy savings, diversification of energy supplies and an accelerated roll out of renewable energy. This builds on many of the targets in the Fit for 55 plan, which are largely met – and in some cases exceeded – in the APS, allowing the fulfilment of GHG reductions committed in the EU and its member countries' NDCs while also meeting important energy security goals. The acceleration of key measures, in particular power sector renewables and fuel switching, means that EU imports of Russian natural gas end well before 2030 in the APS, the key objective of the REPowerEU Plan.
- India passed amendments in August 2022 to its Energy Conservation Act that allow for the establishment of a carbon market, make it easier for the government to improve energy-related standards for appliances and for the environmental performance of buildings.
- Japan's 6th Strategic Energy Plan was passed into law, laying out targets to 2030 reflected in the STEPS. Additionally, Japan announced its Green Transformation (GX) plan, which restarts a part of its nuclear power fleet, and also lays out a longer-term vision for efficiency, renewables, storage, and advanced nuclear to reach Japan's carbon neutrality target for 2050.

National recovery plans, designed to help countries bounce back after the pandemic-induced slump, continue to exert a strong near-term influence on energy markets and investment, as do additional measures prompted by the current energy crisis. Since the start of the pandemic, governments have earmarked over USD 1.1 trillion for policies and incentives in support of clean energy, far exceeding the financial commitments made to green recovery measures after the 2008-10 financial crisis.

However, these figures reveal worrying global imbalances. Over 90% of government sustainable recovery spending is in advanced economies. Many emerging market and developing economies are more reliant on public funding for energy investment than advanced economies, but at the same time are increasingly constrained by rising debt levels and limited fiscal leeway.

Countries are also responding to recent developments by giving high priority to energy security, and are having to find ways to balance this with broader energy and emissions reduction policies, including in many cases the achievement of net zero emissions goals. China provides an important example of a near-term rebalancing in energy policy in response to energy security concerns (Box 2.4).

Box 2.4 ▷ Coal and the road to carbon neutrality in China

Few moments have been as important for energy policy in China as the pledge by the president in September 2020 that its emissions would peak before 2030 and that it would achieve carbon neutrality before 2060. The announcement set in motion nationwide efforts to formulate mid- and long-term policy frameworks for decarbonisation, and to identify promising clean energy technologies that would help deliver the goals. These efforts were reflected in China's updated NDC, issued shortly before COP26. China also committed with the United States in the Joint Glasgow Declaration to curb international unabated coal power projects and limit CO_2 emissions in the 2020s.

Since then, there has been a stronger emphasis on the strategic importance of energy security in China, accompanied by higher near-term use of coal to ensure reliable electricity supply. This shift in emphasis pre-dated Russia's invasion of Ukraine: it was prompted by power outages and a spike in energy prices in many provinces during the second-half of 2021, amid rapid economic recovery and coal supply issues. Restrictions on domestic coal output were eased, and coal-producing provinces were encouraged to ramp up production.

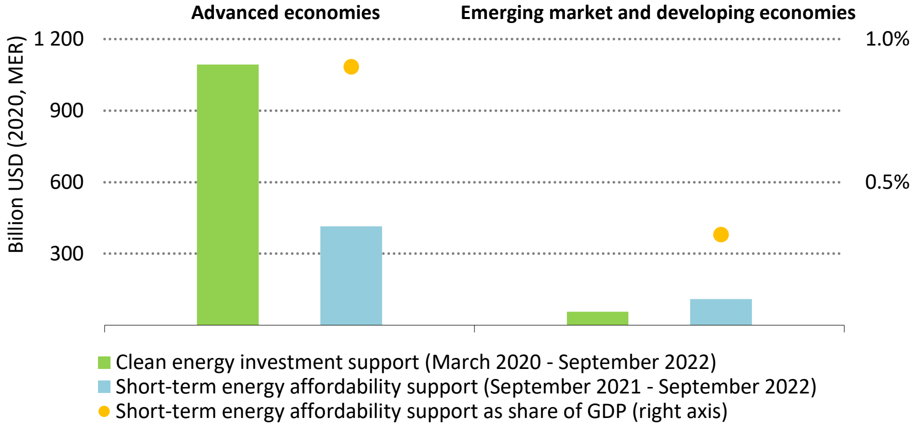
Sourcing energy cheaply and reliably has been a constant priority for China's energy policy. By some distance, China is now the leading global investor in solar, onshore and offshore wind, hydropower and nuclear generation technologies. China's support for clean energy technologies reflects not only environmental and industrial strategy considerations, but also a desire to reduce its increasing reliance on imported fuels. Nonetheless, China's energy sector remains reliant on fossil fuels for 85% of its primary energy, with coal the largest single contributor: China accounts for more than half of both the world's production and consumption of coal. Countering risks from volatile international energy markets means redoubling efforts to develop and deploy clean technologies; for the moment, it also means turning more to domestic coal.

This approach is visible in a succession of recent policy statements, starting in December 2021 with the Central Economic Work Conference, which re-emphasised the importance of coal for China's energy system, while also recognising the need to move away, over time, from traditional energy sources in order to achieve carbon neutrality. The 14th Five-Year Plan for a Modern Energy System, released in March 2022, calls for efforts to jointly promote energy supply security and low-carbon transitions, while underlining the central importance of energy security, and framing it as an aspect of national security.

In March, during a major annual macroeconomic meeting, the National Development and Reform Commission released the Plan on National Economic and Social Development, the details of which underscore China's balancing act. On the one hand, it relaxes coal constraints, indicating some flexibility in respect of the energy consumption and intensity targets set out in the macroeconomic Five-Year Plan in 2021, and calls for the exploitation of domestic coal, oil and gas resources. On the other, it continues to emphasise emissions reduction, nuclear power, feed-in tariff pricing mechanisms and improved wind and solar power generation pricing mechanisms to accelerate broader power market reform efforts.

High prices have also brought forward a range of interventions by governments to provide some protection for consumers from their impact. The value of emergency government spending or foregone revenue provided to cushion consumers and businesses from high energy prices is nearing USD 550 billion as of September 2022 (Figure 2.10). This is set to increase further, with packages currently under consideration, notably in the United Kingdom and Germany. In emerging market and developing economies, short-term consumer support now outweighs the support provided for clean energy investments since March 2020.

Figure 2.10 ▷ Total government outlays on sustainable recovery spending and energy affordability support



Emergency government spending to help keep energy affordable is growing and already half the total allocated to support clean energy investment since the pandemic

Notes: Clean energy investment support encompasses sustainable recovery spending (fiscal spending by national governments in favour of clean energy measures, enacted in the framework of their Covid-19 recovery plans) and clean energy spending from energy crisis packages, aimed at boosting energy efficiency and/or low-emissions production capacity. Short-term energy affordability support are measures enacted in response to the energy price crisis from September 2021 to early September 2022, in the form of emergency consumer support (e.g. temporary energy price subsidies or tax alleviation, state-backed loans).

2.3.3 World Energy Outlook-2022 scenarios

This *Outlook* explores three main scenarios for the future, all of which are fully updated to include the latest energy market and cost data. Common to each is rising demand for energy services, driven by powerful underlying economic and demographic forces. How this demand is met, however, varies substantially across the scenarios. These differences depend largely on the policy choices made by governments, which, in turn, shape investment decisions made by public and private actors, and the ways in which individual consumers meet their energy needs. The modelling framework that produces these scenarios is a dynamic one, covering all fuels and technologies, reflecting the real-world interplay between policies, costs and investment choices, and providing insights into how changes in one area may have (often unintended) consequences for others.

The intention of these scenarios is to provide a framework for thinking about the future of energy, rather than a definitive view on how that future will look. Each scenario models a different set of responses to the current global energy crisis. By comparing them, the reader is able to assess what drives the various outcomes, and the opportunities and pitfalls that lie along the way. The IEA does not have a single view on how the energy system might evolve, so none of these scenarios should be considered as a forecast.

The Net Zero Emissions by 2050 Scenario is a normative scenario, in that it works backwards from a defined outcome. The other two, the Stated Policies and Announced Pledges scenarios, are exploratory, in that they do not target a specific outcome but rather establish different sets of starting conditions and consider where they may lead. These scenarios are modelled for 26 countries and regions for demand, power and fuel transformation, and for all the major producers on the supply side. The scenarios assume that there is no quick or stable end to the war in Ukraine, and that international sanctions on Russia remain in place for a prolonged period. However, they assume a gradual normalisation of the international situation of other major resource-holders subject to sanctions, notably Iran and Venezuela.

The scenarios are:

- **Net Zero Emissions by 2050** (NZE) **Scenario**: This normative scenario sets out a pathway to the stabilisation of global average temperatures at 1.5 °C above pre-industrial levels. It has been fully updated for this *Outlook*, so it starts from a higher level of fossil fuel demand and emissions than the version published in the *WEO-2021*. It also has one year less in which to achieve global net zero CO_2 emissions by 2050. As a result, reaching this goal requires more robust efforts than in the 2021 analysis. The NZE Scenario does this without relying on emissions reductions from outside the energy sector. As in the previous analysis, advanced economies reach net zero emissions before developing economies do. The NZE Scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality. The results for the NZE Scenario are presented at the global level, with some separate indicators for advanced and for emerging market and developing economies.
- **Announced Pledges Scenario** (APS): This scenario assumes that governments will meet, in full and on time, all of the climate-related commitments that they have announced, including longer term net zero emissions targets and pledges in NDCs, as well as commitments in related areas such as energy access. It does so irrespective of whether or not those commitments are underpinned by specific policies to secure their implementation. Pledges made in international fora and initiatives on the part of businesses and other non-governmental organisations are also taken into account wherever they add to the ambition of governments.

  The APS, first introduced in the *WEO-2021*, builds on the analysis released during the Glasgow COP26, which demonstrated that the combined implementation of all net zero emissions pledges and the Global Methane Pledge would lead to a temperature rise of around 1.8 °C in 2100 (with a 50% probability). In this *Outlook*, the analysis is extended to consider the implications for countries that have not made ambitious long-term pledges, but nonetheless benefit in this scenario from the accelerated cost reductions for a range of clean energy technologies. These additional abatement efforts mean that the APS is now associated with a temperature rise of 1.7 °C in 2100 (with a 50% probability).

- **Stated Policies Scenario** (STEPS): This scenario looks not at what governments say they will achieve, but at what they are actually doing to reach the targets and objectives that they have set out. As such, it is based on a detailed sector-by-sector review of the policies and measures that are actually in place or under development in a variety of areas. This analysis assesses relevant regulatory, market, infrastructure and financial constraints. The STEPS reflects a pragmatic exploration of the current policy landscape, and gives a view on where the energy system might be heading in the absence of specific new policy initiatives. As with the APS, this scenario is not designed to achieve a particular outcome. Emissions do not reach net zero and the rise in average temperatures associated with the STEPS is around 2.5 °C in 2100 (with a 50% probability).

We refer to the gap in outcomes between the STEPS and APS as the "implementation gap", i.e. the gap that needs to be filled to realise commitments in full. The gap between the APS and the NZE Scenario is called the "ambition gap" because it reflects those pledges made to date collectively are not ambitious enough to match the goal of a 1.5 °C stabilisation in global average temperatures.

This edition of the *World Energy Outlook* does not include the Sustainable Development Scenario, which is another normative scenario used in previous editions to model a "well below 2 °C" pathway (the upper boundary of the temperature outcomes targeted by the Paris Agreement) as well as the achievement of other sustainable development goals. The APS outcomes in this edition are close, in some respects, to those in the Sustainable Development Scenario, in particular in terms of the temperature outcome. But they are the product of a different modelling approach and so the APS falls short of achieving the outcomes targeted in the Sustainable Development Scenario.

2.4 Inputs to the scenarios

2.4.1 Economic and population assumptions

The global economy is assumed to grow on average at close to trend – nearly 3% per year – over the period to the middle of the century (Table 2.1). There are large differences by country and by region, reflecting the exposure and resilience to shocks as well as variations in growth potential of each geographic area.

The assumed rates of economic growth are held constant across the scenarios. This allows for a comparison of the effects of different energy and climate choices against a common macroeconomic backdrop, but it does not capture feedback loops between climate action, climate change and economic growth. That said, we recognise that the pace, nature and choice of mechanisms used to drive change in the energy system will have broader economic repercussions for different countries and regions, both positive and negative.

Over the near term, the growth trajectory remains positive, but much less so than a year ago when global aggregate demand was experiencing near record growth in response to the removal of pandemic lockdowns and restrictions being eased in many countries. As excess capacity unwinds and macroeconomic support is withdrawn, world GDP growth over the period to 2030 is projected to average 3.3%, and the composition of growth is likely to shift back towards services, such as travel and tourism, following the removal of remaining pandemic-related health and mobility restrictions in most countries.

There are, however, significant downside risks for the outlook to 2030. Possible drags on growth include negative effects from higher interest rates, a mood of insecurity holding back investment decisions and spending on household durables, and uncertainty as to whether macroeconomic authorities are able to contain inflation and avoid a price-wage spiral. If a price-wage spiral were to break out, it would be likely to damage growth through the remainder of the decade and risk inflation becoming stuck at an elevated level, otherwise known as stagflation.

Table 2.1 ▷ GDP average growth assumptions by region

	Compound average annual growth rate			
	2010-2021	2021-2030	2030-2050	2021-2050
North America	1.9%	2.0%	2.0%	2.0%
United States	2.0%	2.0%	2.0%	2.0%
Central and South America	0.9%	2.4%	2.4%	2.4%
Brazil	0.7%	1.8%	2.5%	2.3%
Europe	1.6%	2.0%	1.4%	1.6%
European Union	1.2%	1.9%	1.2%	1.4%
Africa	2.7%	4.1%	4.2%	4.1%
South Africa	1.1%	1.6%	2.8%	2.4%
Middle East	2.0%	3.2%	3.2%	3.2%
Eurasia	2.1%	0.1%	1.4%	1.0%
Russia	1.7%	-1.1%	0.7%	0.1%
Asia Pacific	4.9%	4.7%	3.1%	3.6%
China	6.8%	4.7%	2.8%	3.4%
India	5.5%	7.2%	4.4%	5.2%
Japan	0.5%	0.9%	0.6%	0.7%
Southeast Asia	4.1%	5.0%	3.3%	3.8%
World	**2.9%**	**3.3%**	**2.6%**	**2.8%**

Note: Calculated based on GDP expressed in year-2021 US dollars in purchasing power parity terms.

Sources: IEA analysis based on Oxford Economics (2022) and IMF (2022).

Over the longer term, GDP per capita in emerging market and developing economies continues gradually to move towards the levels in advanced economies, with emerging market and developing economies accounting for a larger share of global GDP in 2050 (66%) than they do today (53%). Russia may be a notable exception, with GDP dropping as many countries seek to end their dependence on Russian exports of energy and resources; Russian GDP is projected to only recover its 2021 level by 2040.

The main energy-related uncertainties for the economic outlook relate to the impact of higher energy prices and input costs on energy investment (especially the mix between investment in clean energy and in traditional fuels), the degree to which higher prices set back progress towards achieving affordable access to energy, and the extent of productivity gains associated with the deployment of new energy technologies. There is an important question in this context about the deployment of how the windfall gains currently accruing to major oil and gas companies in the private sector and large government-owned entities. They could encourage the stepping up of fossil fuel investment, or they could be used to diversify the economic base of hydrocarbon-rich economies. Whichever path is followed will have a large and continuing impact on the composition of fuel supply and on the pace of progress towards achieving climate commitments.

The global population is assumed to rise from 7.8 billion people in 2021 to 8.5 billion in 2030 and 9.7 billion in 2050, an increase of almost one-quarter in 29 years.[1] This brings about a sizeable increase in the number of those requiring energy services, but it also represents a slowing of annual population growth, which halves from close to 1% in 2020 to 0.5% in 2050.

While the pace of population growth slows in all regions, it starts from a high base in sub-Saharan Africa, where high fertility rates and lengthening life expectancy drive almost a doubling of the population by 2050. In some countries, notably Italy, Germany, Japan and China, fertility rates below replacement level translate into falling and ageing populations over the period to 2050.

The Covid-19 pandemic is likely to have had only a small impact on these demographic projections. The number of lives lost directly attributed to the illness is nearly 6.5 million (WHO, 2022), however the number of excess deaths could be much higher, especially in countries where reporting is limited. Strict public health rules, and prompt development and deployment of vaccines in many countries no doubt helped to avoid a situation that could have been a lot worse.

There are two other factors related to demography that have important implications for patterns of energy use. The first is the way in which improvements in health, diet and living conditions have gradually lifted life expectancy of the global population by a decade over the past 40 years. Coupled with declining fertility rates, this translates into a rising share of older

[1] The 2022 Revision of UN DESA's World Population Prospects could not be incorporated in this modelling cycle as the modelling was already advanced by its publication time.

people in the global population, a group that uses more energy than the average at home, but less for transport.

The second is urban development, where the share of the global population living in towns and cities is expected to rise to almost 70% by 2050. In the past, urbanisation has been associated with a rising overall population and economic development. In China, however, the projections anticipate that an additional 215 million people will be living in towns and cities by 2050, a positive driver for energy demand, while over the same period the total population is projected to decline by around 40 million, a negative driver for energy demand.

2.4.2 Energy, mineral and carbon prices

Our scenarios model an energy system in equilibrium, in which energy prices follow a relatively smooth trajectory to balance supply and demand, and where energy markets, investment, technologies and policies all evolve in a mutually consistent direction (Table 2.2). The price trajectories do not attempt to track the fluctuations and price cycles that characterise commodity markets in practice. The potential for volatility is ever present, especially in systems that are undergoing a necessary and profound transformation (see Chapter 4).

Table 2.2 ▷ Fossil fuel prices by scenario

			Net Zero Emissions by 2050		Announced Pledges		Stated Policies	
Real terms (USD 2021)	**2010**	**2021**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
IEA crude oil (USD/barrel)	96	69	35	24	64	60	82	95
Natural gas (USD/MBtu)								
United States	5.3	3.9	1.9	1.8	3.7	2.6	4.0	4.7
European Union	9.0	9.5	4.6	3.8	7.9	6.3	8.5	9.2
China	8.0	10.1	6.1	5.1	8.8	7.4	9.8	10.2
Japan	13.3	10.2	6.0	5.1	9.1	7.4	10.9	10.6
Steam coal (USD/tonne)								
United States	63	44	22	17	42	24	46	44
European Union	113	120	52	42	62	53	60	64
Japan	132	153	59	46	74	59	91	72
Coastal China	142	164	58	48	73	62	89	74

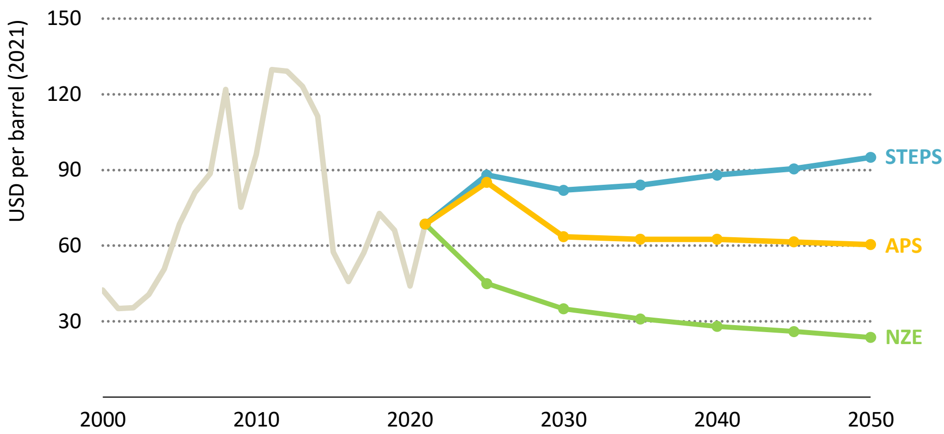
Notes: MBtu = million British thermal units. The IEA crude oil price is a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. The European Union and China natural gas prices reflect a balance of pipeline and LNG imports, while the Japan gas price solely reflects LNG imports. The LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. The US steam coal price reflects mine mouth prices plus transport and handling costs. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports.

Oil

Today's market tightness is assumed to ease in the coming years, although prices could remain high and volatile for a period as the market absorbs a reduction in Russian production, once European Union import restrictions enter into force. The oil market returns to a more stable balance between supply and demand by the late 2020s, although the levels vary widely between scenarios (Figure 2.11).

In the STEPS, long-term demand is broadly similar to last year's *WEO*, and this continues to put a relatively high floor under price levels, with the post-2030 price on a rising trend above USD 80/barrel. Near-term higher prices bring forward additional supply, including tight oil; these developments continue for a number of years, and this exerts some downward price pressure. However, long-term prices are higher than in the *WEO-2021* as a result of uncertain prospects for investment (notably, but not only, in Russia), combined with a strategic shift among some large oil and gas companies away from hydrocarbons.

Figure 2.11 ▷ Average IEA crude import price by scenario



Equilibrium oil prices vary substantially by scenario, reflecting the way that policies, costs and resources affect the supply-demand balance

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

In the APS, a much stronger policy focus on curbing oil demand brings down the price at which the market finds equilibrium, with the international oil price stabilising at around USD 60/barrel. Maintaining prices around this level will depend to a large degree on the stance taken by members of the Organisation of Petroleum Exporting Countries (OPEC), and whether they are ready to moderate long-term production in the name of price stability, even in a market that is shrinking in size. As we have set out elsewhere (IEA, 2020), if major resource-holders were to opt instead to maximise their own market share, then this would result in much lower prices and thus reduce in overall terms the revenues upon which many of these economies are highly reliant.

In the NZE Scenario, any immediate market tightness is quickly relieved by strong efforts to reduce demand, although some continued investment is also required to replace Russian supplies. Over time, prices are increasingly set by the operating costs of the marginal project required to meet falling demand. Costs here include the usual costs of extraction, the remedial work necessary to reduce the emissions intensity of existing fields, and the CO_2 price applied to any residual emissions. It is assumed that some countries at the margin reduce taxes on oil and gas extraction to allow domestic production to continue. Additional near-term oil use – and emissions – compared with last year's NZE Scenario need to be compensated for by an even faster reduction in demand in the 2030s and beyond in order to keep within a very limited emissions budget.

Natural gas

Unlike oil, there is no single global price for natural gas, but instead a set of regional prices that are increasingly interlinked by the ability of LNG tankers to seek out the most advantageous commercial destination. During the current crisis, high gas prices in Europe mean that it has attracted most of the available LNG cargoes to compensate for cuts in Russian supply.

In the STEPS, EU gas prices are much higher through the mid-2020s than anticipated in the *WEO-2021*. Russian exports to the European Union are assumed to fall further in line with the expiry of those contracts that have yet to be cut unilaterally, while additions to global liquefaction capacity are relatively modest over the coming years (with only around 60 bcm in export capacity coming online between 2022-24, compared with 105 bcm between 2019-21). Near-term prices in Europe are higher than in Japan or other Asian markets during this time, a reversal of the usual state of affairs in natural gas markets. By the middle of the decade, however, the EU gas price returns to around USD 8.50/MBtu as new supply comes online and market conditions ease. The Henry Hub price, the marker for natural gas in the United States, is slightly higher than in the *WEO*-2021, a function of higher demand for US LNG exports.

The APS has slightly lower equilibrium gas prices in Europe and Asia than in the STEPS by 2030. This is because there is a more rapid decrease in gas demand in the APS than in the STEPS, due to increased efficiency, electrification and accelerated deployment of renewables. But the European Union still needs to attract additional non-Russian gas in this scenario, keeping near-term gas prices elevated.[2] This has knock-on effects on prices in other

[2] The STEPS and APS price trajectories both assume readiness by Russia to continue some level of natural gas deliveries to the European Union, but the APS incorporates a stronger drive within Europe to reduce these imports, in line with the overall aim of this scenario to reflect announced policy objectives even where they are not backed by specific measures to achieve them. However, there is also the distinct possibility that Russian supply curtailments will bring about a much faster decline in European use of Russian gas than European efforts to diversify or to reduce demand. Russia may even simply stop supplying any gas to Europe.

importing regions, although the effects in Asia are muted by the link to oil prices in many long-term contracts. The additional costs of diversification efforts incurred up to 2030 would be offset thereafter by lower prices and lower overall gas demand, both in the European Union and Japan.

In the NZE Scenario, the decline in natural gas consumption is even more precipitous, although, as with oil, some additional investment is needed to compensate for Russian supplies that have no obvious route to market after the breakdown of the energy relationship with Europe. By the end of this decade, natural gas prices in producing regions fall to the short-run marginal cost of existing projects.

Coal

International coal prices reached record levels in the first-half of 2022. Coal production failed to keep pace with rebounding coal demand in 2021, especially during the first-half of the year, and this cut into stock levels and pushed up prices. Major coal producers, led by China and India, introduced policies to ramp up production and reduce domestic coal shortages, facilitated by the large presence of state-owned companies in production. However, the main coal exporting countries were supply constrained, partly as a result of various weather-related outages, such as flooding in Indonesian mines and infrastructure issues.

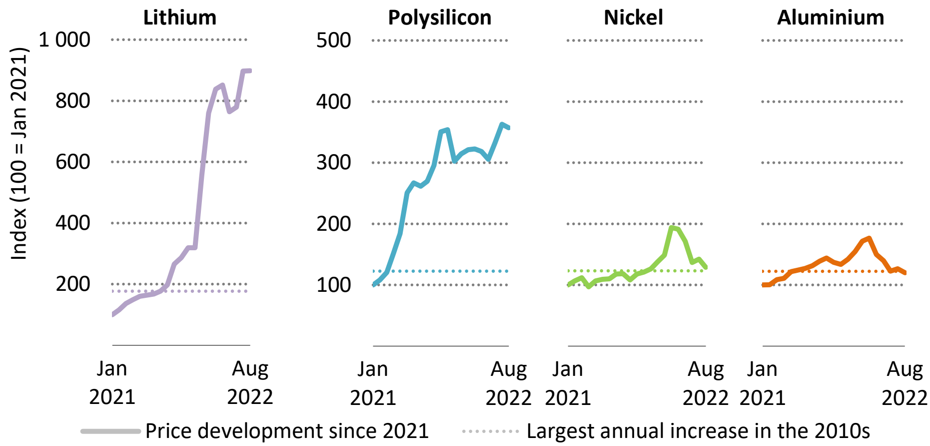
In our scenarios, the coal markets balance at lower prices, but these prices vary considerably depending on overall levels of demand. Relatively robust coal consumption trends in the STEPS offer some support to price levels, particularly given constrained access to finance for new coal supply projects and infrastructure outside China and India. However, prices decline towards the operating costs of existing mines in the APS, and they do the same in the NZE Scenario, but faster.

Critical minerals

In 2021, many important minerals and metals that are essential for clean energy technologies registered broad-based price increases due to a combination of rising demand, disrupted supply chains and concerns around tightening supply (Figure 2.12). Prices for lithium and polysilicon more than tripled in 2021, and those for copper, nickel and aluminium all rose by around 25-40%. These elevated prices continued into the first few months of 2022. The increase in the cost of lithium has been astonishing, with prices going up another two-and-a-half-times between January and April. Prices for nickel and aluminium also soared, driven in part by Russia's invasion of Ukraine and a short squeeze on nickel.

Prices for many materials have started to moderate since April as additional supplies have become available and as weakening economic growth has begun to affect demand. This has not been a smooth process: for example, in August 2022 there were supply disruptions in China, which accounts for around 60% of global lithium chemical supply, when extreme heat and the record low water level on the Yangtze River triggered power shortages in Sichuan and reduced production capacity. Even after taking account of the way prices have come down in recent months, price increases since the start of 2021 have outpaced or been comparable to the largest annual increases seen in the 2010s.

Figure 2.12 ▷ **Price developments for selected critical minerals and metals**



IEA. CC BY 4.0.

Prices for important energy transition minerals and metals have been on a rapid upward march since the start of 2021, although price rises moderated in second-half 2022

Note: Assessment based on Lithium Carbonate Global Average, London Metal Exchange (LME) Cobalt Cash, LME Nickel Cash and LME Aluminium 99.7% Cash prices.

Sources: S&P Global (2022); BNEF (2022) for polysilicon prices.

Several major projects are expected to start bringing new supplies into the market in the latter part of 2022 and in 2023, and this may help to moderate prices, especially if macroeconomic headwinds intensify. Investment levels are rising: thanks to the recent rise in prices, the profits and cash flows of mining companies have increased significantly and capital spending on non-ferrous metal production rose by 20% in 2021. However, current investment trends still fall short of meeting the projected increases in demand in the IEA climate-driven scenarios, including the APS and the NZE Scenario. We do not yet model the supply-demand balances or price trajectories for critical minerals in the same way as for fuels, and take the 2021 average prices as a baseline assumption for the calculation of future revenues. Without a further scaling up of investment in new supplies, together with efforts to improve material efficiency and find substitutes for existing metals and minerals, there is a risk in the future of higher prices and high price volatility, and this could hamper clean energy transitions.

Carbon prices

The adoption of carbon pricing instruments continues worldwide, with about 23% of global emissions now covered by a carbon price of some description.

The main development since the *WEO-2021* has been the increase in price levels in multiple market-based carbon pricing systems. Over the course of 2021, the price of carbon tripled in the European Union Emissions Trading System (ETS) and doubled in Korea, New Zealand and state-level schemes in the United States. Following Russia's invasion of Ukraine, prices in some jurisdictions have fallen below their all-time highs, but they are still at historically high levels. Higher carbon prices led to a sharp increase in global carbon pricing revenue to USD 84 billion in 2021, which is nearly 60% higher than in 2020.

Other developments include the increasing use of carbon pricing, with the launch of schemes in Austria, Canada and Uruguay and at the state level in the United States. Indonesia's carbon pricing scheme is scheduled to start this year. India has announced plans for the phased launch of a carbon market. South Africa has announced plans for steady increases in its carbon tax to 2030 and beyond.

At the international level, governments reached an agreement at COP26 on the rules governing international carbon markets (Article 6 of the Paris Agreement). Around 85% of new or updated NDCs indicate that the countries submitting them will or may use these markets to help deliver their commitments. Voluntary carbon markets, mostly used by companies as a means to fulfil their voluntary commitments, have also been growing fast in the last two years. Global issuance of carbon credits in 2021 was around 480 million tonnes of carbon-dioxide equivalent (Mt CO_2-eq), with a market valuation exceeding USD 1 billion for the first time.

In our scenarios, the STEPS incorporates existing and announced carbon pricing initiatives, whereas the APS and the NZE Scenario include additional measures of varying stringency and scope. In the NZE Scenario, for example, carbon prices are quickly established in all regions, rising by 2050 to an average of USD 250/tonne CO_2 in advanced economies, to USD 200/tonne CO_2 in other major economies (e.g. China, Brazil, Russia and South Africa), and to lower levels elsewhere. As with other policy measures, CO_2 prices need to be introduced carefully, with a view to the likely consequences and distributional impacts. The level of CO_2 prices included in the scenarios should be interpreted with caution. The scenarios include a number of other energy policies and accompanying measures designed to reduce emissions, and this means that the CO_2 prices shown are not the marginal costs of abatement (as is often the case in other modelling approaches).

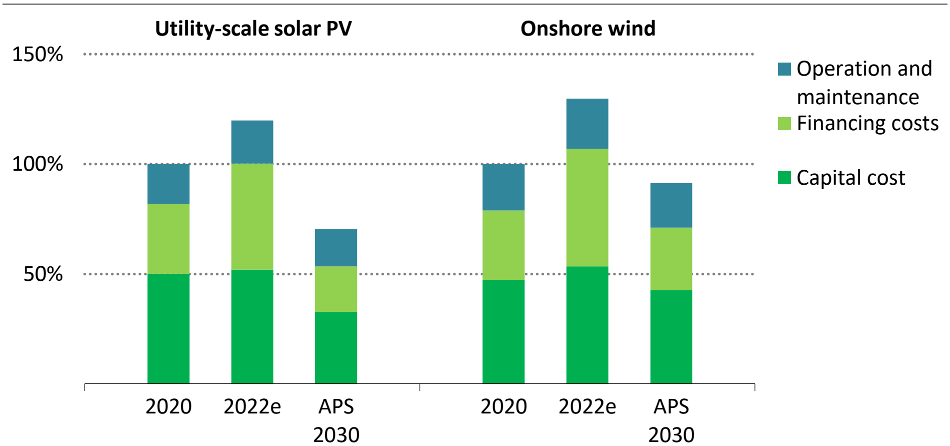
2.4.3 Technology costs

Technology costs are crucial in determining how demand for energy services is met in a given sector or country. The Global Energy and Climate Model (GEC-M) that is now used for our projections contains a very rich representation of energy technologies, including not only those that are widely available, but also those that are judged to be approaching commercialisation. We do not assume any major new technology breakthroughs in the *WEO* scenarios (on the grounds that these are inherently difficult to anticipate), but a continuous process of technology improvement and learning is built into the modelling. This applies to appliances and vehicles purchased by end-users; infrastructure for transporting energy products, including smart grids; and storage and other technologies for energy extraction, generation and transformation.

The starting point is a rising trend in costs for most fuels and technologies. Cost pressures are being felt across much of the energy sector, due to persistent supply chain pressures, tight markets for specialised labour and services, bottlenecks in critical mineral supply, and higher prices for essential construction materials like steel and cement. Ebbs and flows in underlying costs for fossil fuel production are not unusual and have been observed many times. Recent rises in costs for clean energy technologies, however, mark a distinctive break with the steady, and sometimes dramatic, reductions seen in recent years.

Oil and gas resources generally become more expensive to extract over time in our scenarios, as continued upstream innovation and technology improvements are more than offset by the effects of depletion, meaning that resources become more difficult and geologically challenging to develop. As a result, these fuels face increasingly stiff competition in a growing number of areas from clean energy technologies.

Figure 2.13 ▷ Changes in levelised costs for a benchmark project in Europe and North America, 2020, 2022 and 2030



Tight supply chains and higher financing costs are putting upward pressure on renewables costs, but they remain the least-cost option for new generation in most countries

Notes: 2022e = estimated values for 2022. Assumptions based on the APS and the IEA World Energy Investment 2022 report (IEA, 2022b).

With regard to cost trends for these clean technologies, the key question is whether today's elevated costs are simply a bump in a downhill journey or whether they represent a more profound change in the direction of travel. For many technologies, this puts the spotlight firmly on raw material inputs, which now account for a larger proportion of overall costs than they did before. Increases in the prices of polysilicon (tripled in 2021), steel (up by 70% over the same period) and aluminium (up 40%) now feed much more directly into the costs of solar panels and wind turbines, which are up by between 10% and 20% since 2020. Financing costs also play a major role in levelised costs, and are likely to rise as monetary policy tightens in many countries (Figure 2.13). Nonetheless, clean technologies in the power sector remain the most cost-efficient option for new power generation in many countries, even before taking account of the exceptionally high prices seen in 2022 for coal and gas.

We do not assume that current pressures will result in a lasting uptick to the cost of clean energy technologies. Pressures from higher commodity prices are real, but they do not rule out further cost reductions for clean energy technologies. There is scope to reduce other cost elements via technology innovation, efficiency improvements and economies of scale. Material costs could also be reduced as technologies adapt to reduce reliance on critical materials. As a result, clean technology costs continue to come down in our scenarios, albeit with variations across the different scenarios, depending on the level of policy support and the extent of deployment.

However, the current pressures on costs provide a reminder that cost trajectories may not be smooth and linear, and that governments need to pay close attention to potential vulnerabilities and imbalances in clean energy supply chains (see Chapter 4). For example, the scale of China's investment in solar PV manufacturing has been instrumental in bringing down costs worldwide, with multiple benefits for energy transitions. At the same time, IEA analysis has highlighted that China's share in all the key manufacturing stages of solar panels already exceeds 80% today and that, for key elements including polysilicon and wafers, this is set to rise to more than 95% in the coming years, based on manufacturing capacity under construction (IEA, 2022c). There is a clear need for countries and regions to help diversify clean energy supply chains and make them more resilient.

PART B

ROADMAP TO NET ZERO EMISSIONS

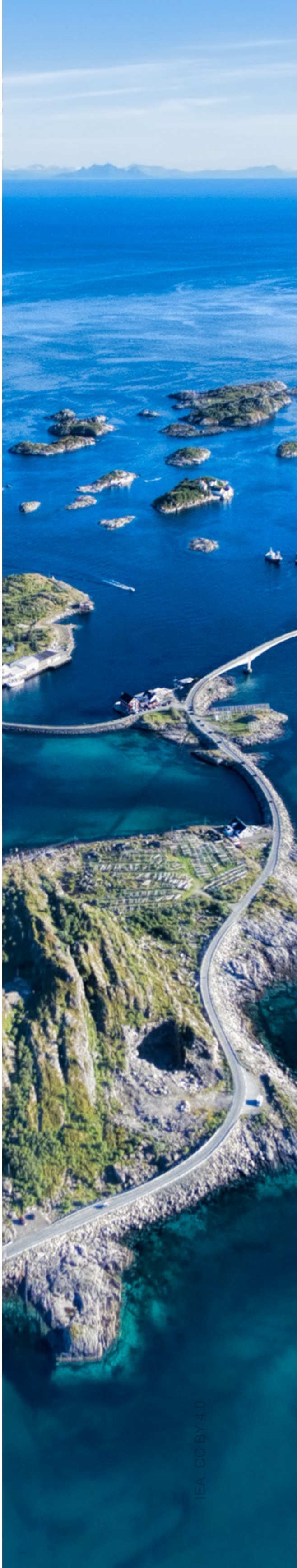
Part B of this *WEO* focusses on the pathway for the global energy sector to reach net zero emissions by 2050, while addressing energy security and affordability concerns.

In 2021, the IEA published *Net Zero by 2050: A Roadmap for the Global Energy Sector*. In the short time since then, much has changed. To take into account the new landscape, Chapter 3 presents an updated Net Zero Emissions by 2050 (NZE) Scenario.

It emphasises the key results of the NZE Scenario for energy supply, demand and emissions, and focusses on the actions needed by sector to achieve deep reductions in energy-related emissions. It examines the measures needed to curb growth in demand including energy and materials efficiency, electrification and behavioural change.

The challenges of scaling up clean technology supply chains to meet the surge in deployment projected in the NZE Scenario are assessed. This includes a review of the announced and under development manufacturing capacity for solar PV, electrolysers for hydrogen production, batteries, as well as for carbon, capture, utilisation and storage, and direct air capture and storage projects.

Chapter 3 includes a special focus on the NZE Scenario relative to the scenarios assessed by the Intergovernmental Panel on Climate Change. Plus, it looks at the future of flying in the context of the NZE Scenario.



An updated roadmap to Net Zero Emissions by 2050

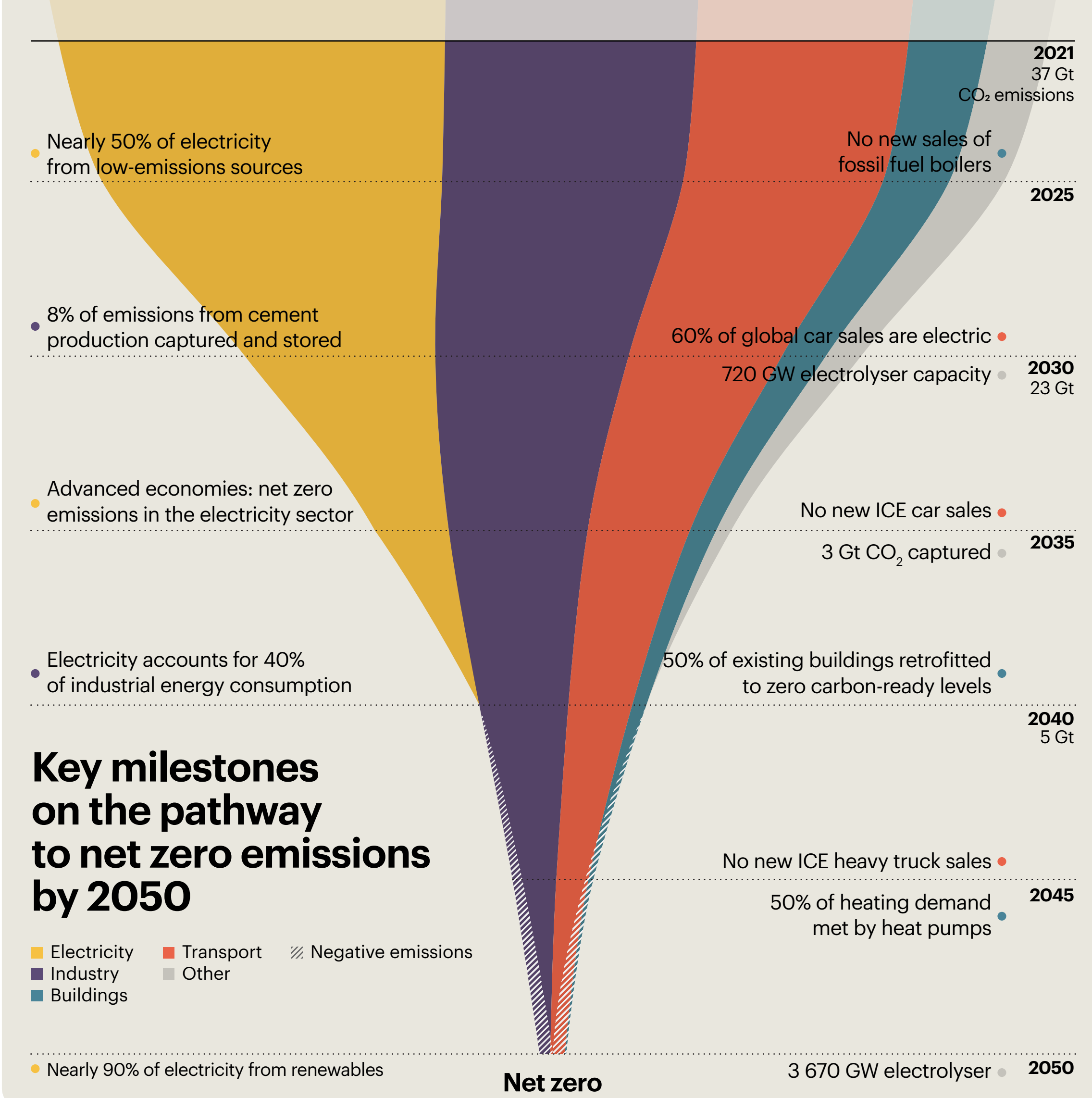
Energy transition for 1.5 °C

SUMMARY

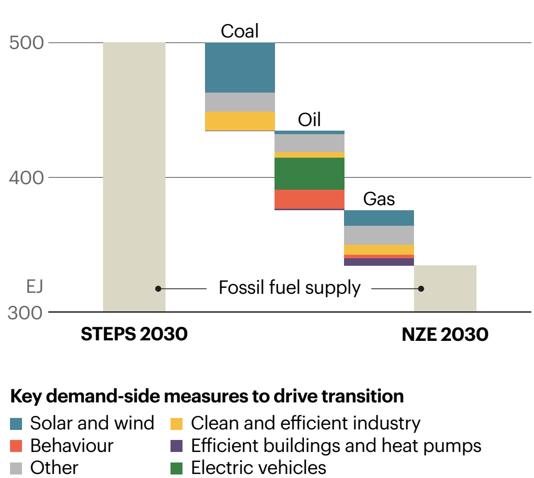
- In 2021, the IEA published its report Net Zero by 2050: A Roadmap for the Global Energy Sector. However, in the short time since then much has changed. The global economy has rebounded from the Covid-19 pandemic, and the first global energy crisis has seen world energy prices touching record levels in many markets, bringing energy security concerns to the fore.
- In 2021, emissions rose by a record 1.9 Gt to reach 36.6 Gt, driven by extraordinarily rapid post-pandemic economic growth, slow progress in improving energy intensity, and a surge in coal demand even as renewables capacity additions scaled record heights. Recent investment in fossil fuel infrastructure not included in our 2021 NZE Scenario would result in 25 Gt of emissions if run to the end of its lifetime (around 5% of the remaining carbon budget for 1.5 °C).
- Despite these mostly discouraging developments, the pathway detailed in the Net Zero Emissions by 2050 (NZE) Scenario remains narrow but still achievable. This update to the NZE Scenario offers a comprehensive account of how policymakers and others could respond coherently to the challenges of climate change, energy affordability and energy security.
- Between 2021 and 2030, low emissions sources of supply grow by around 125 EJ in the NZE Scenario. This is equivalent to the growth of world energy supply from all sources over the last fifteen years. Among low emissions sources, modern bioenergy and solar increase the most, rising by around 35 EJ and 28 EJ respectively to 2030. Over the period to 2050, however, the largest growth in low-emissions energy supply comes from solar and wind. By 2050, unabated fossil fuels for energy uses account for just 5% of total energy supply: adding fossil fuels used with CCUS and for non-energy uses raises this to slightly less than 20%.
- In the NZE Scenario, electricity becomes the new linchpin of the global energy system, providing more than half of total final consumption and two-thirds of useful energy by 2050. Total electricity generation grows by 3.3% per year to 2050, which is faster than the global rate of economic growth across the period. Annual capacity additions of all renewables quadruple from 290 GW in 2021 to around 1 200 GW in 2030. With renewables reaching over 60% of total generation in 2030, no new unabated coal-fired plants are needed. Annual nuclear capacity additions to 2050 are nearly four-times their recent historical average.
- Increased supplies of clean energy are complemented in the NZE Scenario by measures to save energy, bringing benefits in terms of emissions reductions, affordability and energy security. In the NZE Scenario, energy intensity improvements

to 2030 are nearly three times faster than over the past decade. In 2030, energy savings from energy efficiency, material efficiency, and behavioural change amount to around 110 EJ, equivalent to the total final consumption of China today.

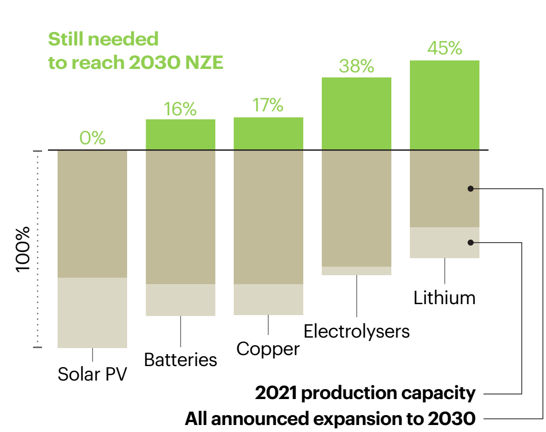
- End-use sectors all achieve emissions reductions of over 90% by 2050. Hydrogen and hydrogen-based fuels are deployed in heavy industry and long-distance transport, and their share in total final consumption reaches around 10% in 2050. Bioenergy use is kept to around 100 EJ in the interests of sustainability and reaches around 15% of total final consumption in 2050. CO_2 capture totals 1.2 Gt in 2030, rising to 6.2 Gt in 2050, and more than 60% of this occurs in industry and other fuel transformation sectors.
- The NZE Scenario requires a large increase in investment in clean energy. Energy investment accounted for just over 2% of global GDP annually between 2017 and 2021, and this rises to nearly 4% by 2030 in the NZE Scenario. Electricity generation from renewables sees one of the largest increases, rising from USD 390 billion in recent years to USD 1 300 billion by 2030. This level of spending in 2030 is equal to the highest level ever spent on fossil fuel supply (USD 1.3 trillion spent on fossil fuels in 2014).
- There are some positive indications that clean energy technology is now rapidly scaling up. Announced EV battery production capacity for 2030 is only 15% lower than the level of battery demand underpinning the NZE Scenario in the same year, while announced expansions of solar PV production capacity would be essentially sufficient to achieve the level of deployment envisaged in the NZE Scenario, if they are successfully delivered on time. Assuming full implementation of all announced manufacturing capacity expansions including speculative projects, the cumulative output of electrolyser manufacturing capacity could reach 380 GW by 2030, which is still little more than half of 2030 needs in the NZE Scenario.
- There are however many areas where progress is well short of what is envisaged in the NZE Scenario. The path to success requires policy makers to do much more to provide signals on the demand side, to develop the clean technology supply chain as a whole, to ensure that supply chains are diverse and resilient, and to promote the coordinated growth of different parts of particular supply chains.
- Total energy sector employment increases from just over 65 million today to 90 million in 2030 in the NZE Scenario. New jobs in clean energy industries reach 40 million by 2030, outweighing job losses in the fossil fuel-related industries. Fossil fuel supply jobs decrease by 7 million by 2030 in the NZE Scenario, with coal supply seeing the sharpest decline as mechanisation and decarbonisation efforts lead to further downsizing of the industry. Shortages of skilled labour in clean energy construction projects are already starting to be seen, underlining the importance of strategic and proactive labour policies to build up the workforce needed for the rapid expansion of clean energy technologies.



A demand-led transition



Scaling up production capacity



Introduction

In 2021, the IEA published its *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA, 2021), which sets out a narrow but achievable pathway for the global energy sector to reach net zero emissions by 2050. However, much has changed in the short time since that report was published.

The global economy rebounded at record speed in 2021 from the COVID-19 pandemic, with GDP growth reaching 5.9%. As energy intensity improvements stalled, global energy demand increased by 5.4%. Surging energy demand was in part met by increased use of coal, resulting in a 1.9 gigatonnes (Gt) jump in emissions in 2021, the largest annual increase in global CO_2 emissions from the energy sector ever recorded. This brought total CO_2 emissions from the energy sector to 36.6 Gt in 2021. Recent investment in fossil fuel infrastructure not included in the 2021 Net Zero Emissions by 2050 Scenario would result in 25 Gt of emissions if run to the end of its lifetime (around 5% of the remaining carbon budget for 1.5 °C). At the same time, 2021 also saw renewables-based electricity generation reach an all-time high, a record more than 500 terawatt-hours (TWh) above the level in 2020.

As a consequence of the surge in demand, bottlenecks in supply, and above all Russia's invasion of Ukraine, the world is currently experiencing the worst energy shock since the 1970s, with prices of fuels and commodities hitting record levels in many markets. In the face of this shock, some governments are announcing new targets for the deployment of clean energy technologies, or temporarily increasing the use of coal, and in some cases doing both at the same time. How energy security and climate objectives can be aligned is therefore a critical question for policy makers (see Chapter 4).

The Intergovernmental Panel on Climate Change (IPCC) published the first volume of its Sixth Assessment report in August 2021, after the IEA published its *Net Zero by 2050* report. The IPCC report confirms that rapid and deep reductions in CO_2 emissions are necessary to limit warming to 1.5 °C (IPCC, 2021). In scenarios that achieve this objective with no or limited temperature overshoot, net emissions of greenhouse gases (GHGs) need to be reduced by 43% by 2030 compared with 2019 levels, and CO_2 emissions need to reach net zero by around 2050 (IPCC, 2022a). The Glasgow Climate Pact which was adopted at COP26 reinforced the Paris Agreement objective of limiting warming to 1.5 °C by achieving net zero CO_2 emissions by around mid-century as well as deep reductions in other GHGs.

In this context, this chapter presents a 2022 update to the IEA Net Zero Emissions by 2050 (NZE) Scenario. Its central purpose is still to reach net zero emissions from the energy sector by 2050, but this updated version takes into account the latest information about energy markets and technologies, and reflects concerns about energy security. The NZE Scenario is supported by new modelling using the climate model MAGICC which is widely used in the IPCC analyses and makes possible a richer assessment of the implications of the NZE Scenario for the global temperature.

The design approach for the updated NZE Scenario sticks closely to the approach followed in the IEA 2021 report:

- The NZE Scenario is based on the deployment of a wide portfolio of clean energy technologies, with decisions about deployment driven by costs, technology maturity, market conditions and policy preferences. The pathway reflects the particular circumstances of various countries in terms of resource and infrastructure endowments, development pathways and policy preferences.
- The NZE Scenario sees all countries contribute to the pathway to net zero emissions by 2050, with advanced economies taking the lead and reaching net zero emissions well before emerging market and developing economies. Rapid transition is supported by global collaboration to facilitate ambitious policies, drive down the costs of clean energy technologies, create bigger and more international markets for those technologies, and support emerging market and developing economies to achieve emissions reductions and the energy-related United Nations Sustainable Development Goals (SDGs).
- The NZE Scenario aims to safeguardenergy security through rapid deployment of clean energy technologies, energy efficiency and demand reduction while minimising energy market volatility and stranded assets to the extent possible. It targets a smooth transition through strong and co-ordinated policies and incentives that enable all actors – governments, investors, companies and workers – to anticipate the rapid change required.

The NZE Scenario is *a* pathway to reach net zero emissions by 2050, not *the* pathway. It sets out a comprehensive and detailed view of how the energy sector could respond coherently to the challenges of climate change while taking account of concerns about energy security and affordability.

Net Zero Emissions Scenario

3.1 Emissions and temperature trends

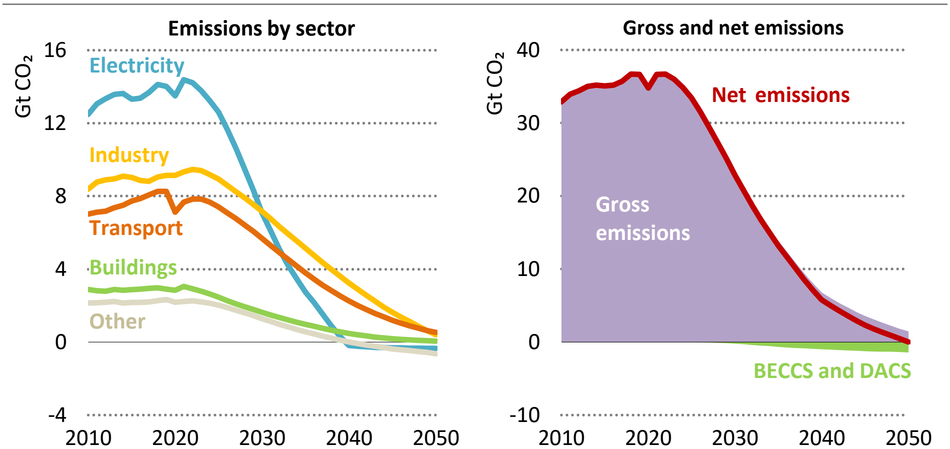
Between 2021 and 2030, CO_2 emissions from the energy sector decrease by more than one-third in the NZE Scenario, falling from 36.6 Gt today to less than 23 Gt in 2030.[1] The electricity sector leads the way: emissions from electricity generation halve between 2021 and 2030, accounting for more than half of the overall emissions reductions from the energy sector. Growing electrification and the widespread deployment of efficiency and energy savings measures enable the buildings sector to almost halve its emissions by 2030. Rapid reductions are also seen in the transport sector, with emissions falling by one-quarter by 2030, thanks to electrification, efficiency improvements and behavioural change. The industry sector also sees a reduction of nearly a quarter by 2030 from 2021 levels, driven in particular by effective policies on materials efficiency, energy efficiency and fuel switching.

[1] Here and henceforth unless otherwise specified, CO_2 emissions from the energy sector include industrial processes.

Between 2031 and 2040, the speed of emissions reductions in the industry and transport sectors accelerates to almost 10% per year, as electrification, low-emissions fuels, and carbon capture, utilisation and storage (CCUS) technologies start to make bigger inroads into the existing stock of assets. The electricity sector reaches zero net emissions in advanced economies by 2035, and in emerging market and developing economies by 2040. The rapid drop in emissions in electricity helps to bring about continued reductions in emissions in the transport and buildings sectors as they electrify. By 2040, most of the remaining 5.8 Gt of energy sector emissions are from the transport sector (40% of the total, mainly from ships, planes and heavy trucks), and the industry sector (55%).

By 2050, all end-use sectors achieve emissions reductions of more than 90% compared to current levels, although residual CO_2 emissions are about 0.5 Gt in transport and 0.4 Gt in industry. These, and net residual emissions from other sectors, are counterbalanced by carbon dioxide removal (CDR) from the atmosphere through bioenergy with carbon capture and storage (BECCS) in electricity generation and biofuels production, and through direct air capture and storage (DACS). By 2050, CDR reaches 1.5 Gt per year (Figure 3.1).

Figure 3.1 ▷ Energy-related CO_2 emissions by sector and gross and net emissions in the NZE Scenario, 2010-2050



IEA. CC BY 4.0.

The power sector leads emissions reductions to 2030, but all sectors contribute to the net zero emissions goal, with residual emissions in 2050 balanced by atmospheric removals

Notes: BECCS = bioenergy equipped with CCUS; DACS = direct air capture and storage. Other includes agriculture and other energy transformation sectors.

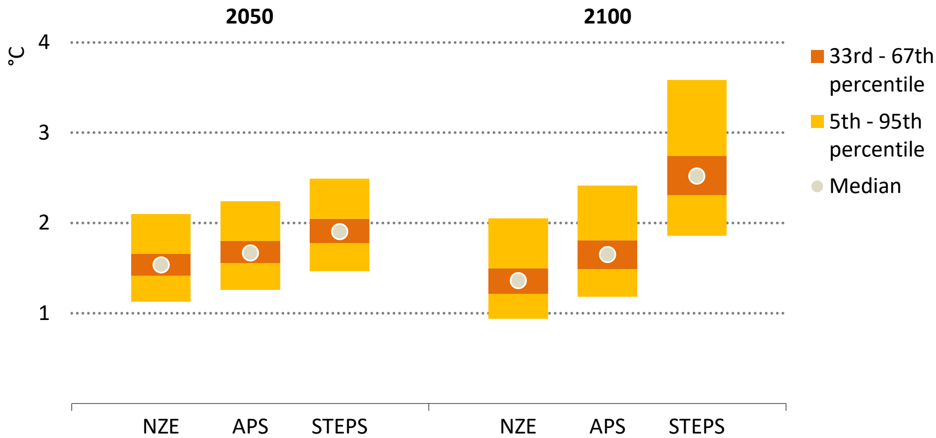
In addition to rapid cuts in CO_2, the NZE Scenario entails a steep fall in other energy-related GHGs. For example, energy-related methane emissions drop by 75% from 120 million tonnes (Mt) in 2021 to 30 Mt in 2030, on track for less than 10 Mt in 2050. There are also reductions in energy-related nitrogen dioxide emissions.

Our modelling of land-use change and bioenergy production indicates that, taking account of the level of bioenergy production in the NZE Scenario and assuming parallel action to halt and reverse deforestation, CO_2 emissions from agriculture, forestry and other land use (AFOLU) would drop to become a net CO_2 sink before 2030. (See Chapter 9)

The steep reductions in GHG in the NZE Scenario would achieve the goal of the Paris Agreement to limit the long-term global temperature rise to "...well below 2 °C above pre-industrial levels ... pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". The global temperature rise in the NZE Scenario peaks under 1.6 °C around 2040 before dropping to around 1.4 °C in 2100 (Figure 3.2).[2] In the Stated Policies Scenario (STEPS), by contrast, temperatures reach 2 °C around 2060, and continue to rise thereafter.

Due to uncertainties about the physical response of the climate to GHG emissions, it should be noted that such projections of future levels of warming are probabilistic in nature: for example, in the STEPS there is an 10% chance of a temperature rise above 3.2 °C in 2100. Such an increase would pose a severe threat to the wellbeing of humans and global ecosystems, with some of the starkest consequences manifesting themselves in the least wealthy parts of the world (IPCC, 2022b and IEA, 2022a).

Figure 3.2 ▷ Temperature rise in 2050 and 2100 in the *WEO-2022* scenarios



Temperature rise peaks at less than 1.6 °C in 2050 in the NZE Scenario and falls to around 1.4 °C by 2100. In the STEPS, it exceeds 2 °C around 2060 and continues rising

Notes: NZE = Net Zero Emissions by 2050 Scenario; APS = Announced Pledges Scenario; STEPS = Stated Policies Scenario. Temperature rise estimates in this section are relative to 1850-1900 and match the IPCC Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014 (IPCC, 2021).

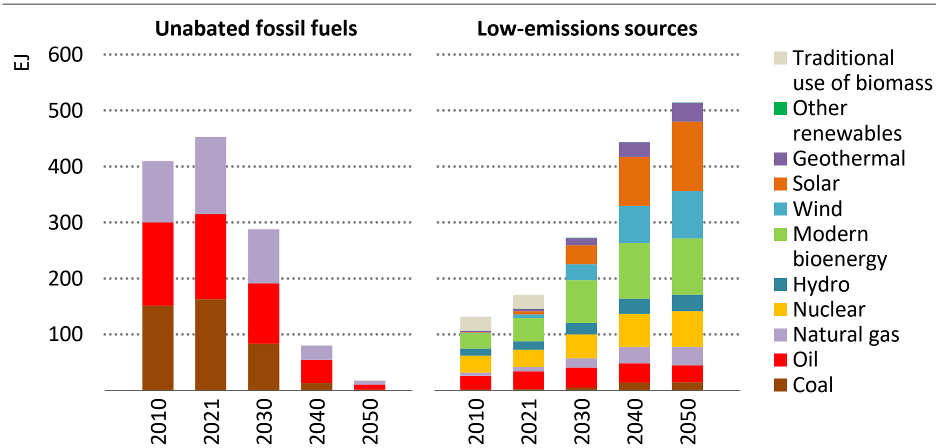
[2] Temperature rise estimates quoted in this section refer to the median temperature rise, meaning there is a 50% probability of remaining below a given temperature rise.

3.2 Energy trends

In the NZE Scenario, the global energy mix undergoes a profound transformation as low-emissions sources ramp up dramatically and displace unabated sources across the whole energy sector. Between 2021 and 2030, low-emissions sources of supply increase by around 125 exajoules (EJ) (Figure 3.3). The traditional use of biomass is phased out as energy access goals are achieved. Among low-emissions sources, modern bioenergy and solar increase the most to 2030 by around 35 EJ and 28 EJ respectively.

Thanks to electrification, improvements in energy efficiency and behavioural changes total energy supply declines by 10% between 2021 and 2030 even as the global economy grows by nearly a third. The annual rate of energy intensity improvement nearly triples as it rises to more than 4% per year (see section 3.8). Unabated sources of supply decline by nearly a third, with unabated coal falling by nearly one-half and unabated natural gas by more than one-quarter by 2030. This contrasts with the NZE Scenario in the *World Energy Outlook 2021 (WEO-2021)*, in which natural gas held on to a larger share of the global energy mix for a little longer: the change reflects heightened energy security concerns around natural gas precipitated by Russia's invasion of Ukraine (see Chapter 2). Oil also declines by around one-fifth to 2030 as a result of energy efficiency gains, behavioural change and increasing electrification in transport.

Figure 3.3 ▷ Total energy supply of unabated fossil fuels and low-emissions sources in the NZE Scenario, 2010-2050

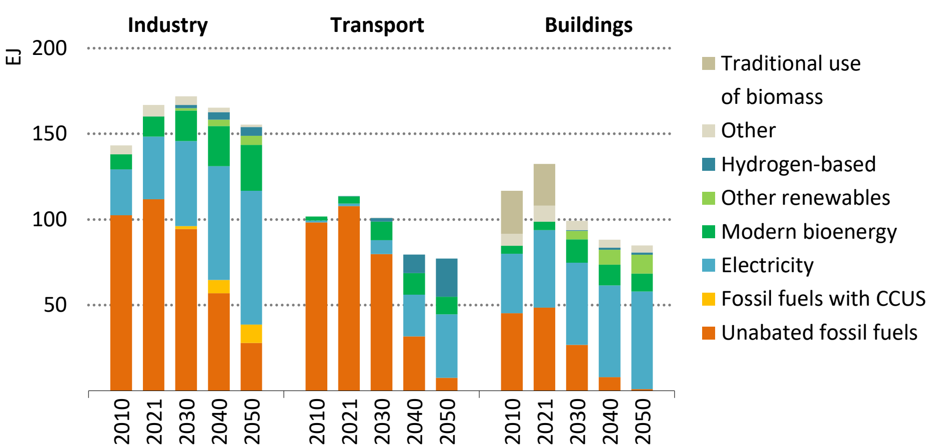


A profound change in global energy supply underpins the NZE Scenario, with low-emissions sources increasing by around 125 EJ by 2030

Notes: Unabated fossil fuels are those used for energy purposes without CCUS. Low-emissions fossil fuel sources are those equipped with CCUS or those for non-energy uses. Hydrogen and hydrogen-based fuels are not shown directly in this figure as these are not primary sources of energy supply.

The transformation of energy supply is matched by a change in energy consumption (Figure 3.4). Total final consumption in 2021 amounted to around 440 EJ, an increase of 5.2% over the 2020 level. By 2030, total final consumption in the NZE Scenario is down by almost 10% on the 2021 level, despite rapid growth of global GDP. Over this period, the total final consumption intensity of GDP improves more than two-and-a-half- times faster than the average over the last decade. Four factors drive this improvement: efficiency benefits of switching from the traditional use of biomass; technical gains in energy consuming equipment and building envelopes; efficiency benefits of electrification; and behavioural change and avoided demand (see section 3.8).

Figure 3.4 ▷ Total final consumption by source in the NZE Scenario, 2010-2050



End-use sectors come to be dominated by electricity, which provides more than half of total final consumption by 2050

Note: Other renewables include solar thermal and geothermal used directly in end-use sectors.

Unabated fossil fuels directly provided nearly 60% of total final consumption in 2021, excluding fossil fuel use for non-energy purposes such as chemical feedstocks. In the NZE Scenario, this falls to around 45% in 2030, and to only 5% by 2050 (Box 3.1). Electricity becomes the "new oil" in terms of its dominance of final consumption; unlike oil, however, it plays a key role in all end-use sectors. The share of electricity in total final consumption rises from 20% today to slightly less than 30% by 2030 and more than 50% by 2050. Hydrogen and hydrogen-based fuels take off after 2030 and account for 10% of total final consumption by 2050.[3] In absolute terms, the consumption of bioenergy in end-use sectors remains broadly stable from today to 2050, rising from 46 EJ to slightly less than 50 EJ. However, this

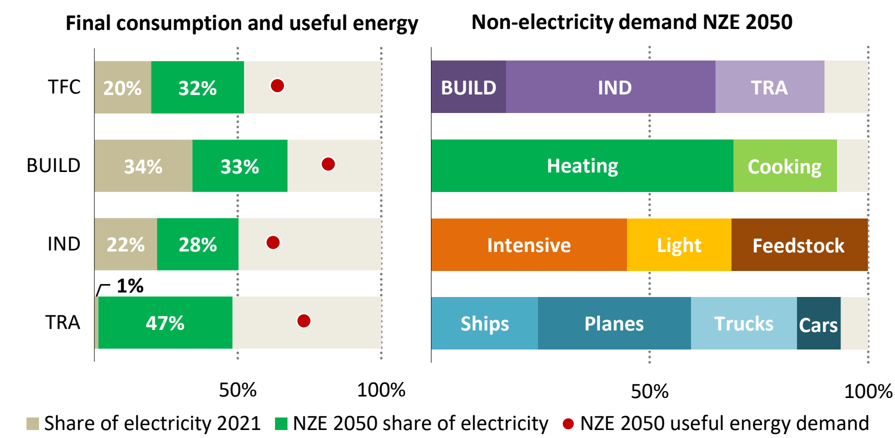
[3] Excluding the onsite production of hydrogen in industry. In IEA energy balances the onsite production of hydrogen in industry appears as electricity consumption, raising the share of electricity in final energy consumption.

masks a shift in composition: the use of modern bioenergy rises sharply while the traditional use of bioenergy declines and then ends as full access to modern forms of energy is achieved in all countries by 2030 (Box 3.3).

Box 3.1 ▷ Why doesn't electricity reach a higher share of TFC?

In the NZE Scenario, electricity accounts for more than 50% of total final consumption by 2050, higher than the highest ever share of oil products in the global final consumption mix (i.e. around 47% in 1973). However, given the efficiency benefits of electricity, why is its share in a low-emissions consumption mix not even higher? The answer to this question has two parts.

Figure 3.5 ▷ Final consumption, useful energy and non-electricity demand by sector and use in the NZE Scenario, 2021 and 2050



Electricity provides more than half of final consumption by 2050, but two-thirds of useful energy

Notes: TFC = total final consumption; BUILD = buildings sector; IND = industry sector; TRA = transportation sector. NZE 2050 = Net Zero Emissions by 2050 Scenario. In industry, intensive and light refer to energy-intensive and light industry sub-sectors. Trucks = medium and heavy freight trucks.

First, the efficiency of electricity means that its share in useful energy supplied to the end-user is higher than its share in final consumption.[4] The efficiency of an EV is three-times higher than that of a gasoline car, for example, while the efficiency of a heat pump can be substantially more than one, so it can deliver more useful energy to the consumer

[4] Useful energy refers to the portion of final energy available to the end-user after the final conversion. For example, an internal combustion engine converts the chemical energy in gasoline (final energy) into kinetic energy, i.e. the motion of the car (useful energy).

than it consumes in final energy (efficiencies of between 2 and 5 are prevalent in available models today). The efficiency of electricity means that its share in useful energy enjoyed by consumers (two-thirds) is much higher than its share in final consumption (more than half) (Figure 3.5).

Second, there are end-uses for which it is not feasible or cost effective to electrify directly with the technologies currently available on the market or likely to be commercialised in coming decades. Around half of energy demand in energy-intensive industries is for high-grade process heat (above 400 °C), which is challenging to electrify with current technologies. Ships, planes and heavy trucks make up around 85% of transport non-electricity demand in 2050; at present it is very difficult to see how most of the energy they use could be electrified, although the NZE Scenario does see an increasing amount of electricity used even in these segments, particularly in the case of heavy trucks (see section 3.6). In the buildings sector, existing district heating networks are strategic assets, and are in part decarbonised with non-electrical energy sources in the NZE Scenario, notably modern solid bioenergy. In addition, industry feedstocks by definition cannot be electrified, and account for nearly one-third of non-electrical demand in industry in 2050 in the NZE Scenario.

SPOTLIGHT

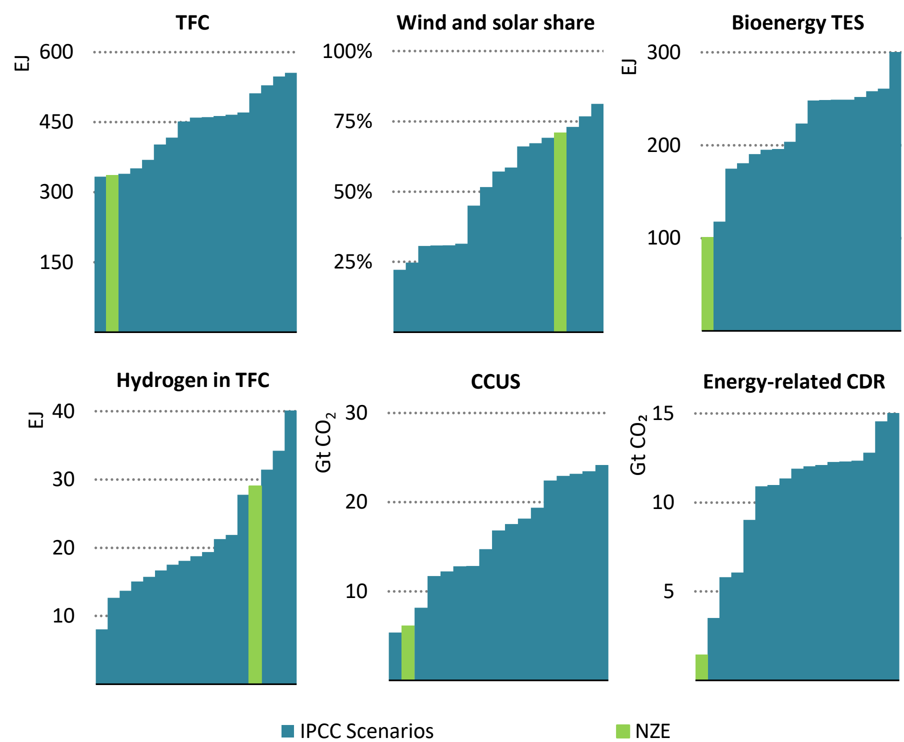
Comparison with the new scenarios assessed by the IPCC

The third volume of the IPCC Sixth Assessment Report deals with climate mitigation (IPCC, 2022a). Published in April 2022, it includes a new scenario database (IIASA, 2022). Among the more than 1 000 scenarios vetted by the IPCC, only 16 achieved net zero emissions from the energy sector in 2050, and therefore are comparable in terms of energy sector ambition with the IEA NZE Scenario. Here we highlight a comparison between those IPCC assessed scenarios and the IEA NZE Scenario (Figure 3.6).

- The IEA NZE Scenario entails very ambitious policies and measures to improve energy efficiency and reduce energy demand, including through behavioural change (see section 3.8). As a consequence of this and the benefits of electrification, total final consumption is around 340 EJ in 2050, compared to around 460 EJ in the median IPCC scenario.
- The NZE Scenario sees the share of wind and solar in electricity generation reach over 70% in 2050, compared to around 55% in the median IPCC scenario.
- The NZE Scenario sees total energy supply from bioenergy of around 100 EJ, reflecting the importance of remaining within identified sustainable limits for global bioenergy supply. The median IPCC scenario reaching net zero emissions by 2050 sees around 235 EJ of bioenergy demand, more than double the level of the NZE Scenario and three-and-a-half-times the current level.

- The NZE Scenario sees about 30 EJ of hydrogen and hydrogen-based fuels used to decarbonise end-use sectors that are difficult to electrify. The median IPCC scenario uses about 18 EJ of hydrogen and hydrogen-based fuels.
- The NZE Scenario uses 6.2 Gt of CCUS in 2050 while the median of the IPCC scenarios see about 17 Gt.
- The NZE Scenario relies on around 1.5 Gt of energy sector CDR from both BECCS and DACS, while the median IPCC scenario sees 12 Gt of energy sector CDR in 2050, largely from BECCS and mostly to offset continued use of oil in the transport sector.

Figure 3.6 ▷ Comparison of key indicators for the selected IPCC scenarios and the IEA NZE Scenario in 2050



IEA NZE Scenario requires less CCUS and CDR than comparable IPCC scenarios, and it relies more on energy efficiency, renewables and hydrogen

Notes: TFC = total final consumption; TES = total energy supply; CCUS = carbon capture, storage and utilisation; CDR = carbon dioxide removal. IPCC Scenarios refers to the 16 vetted C1 IPCC scenarios that reach net zero energy sector emissions by 2050 (IIASA, 2022).

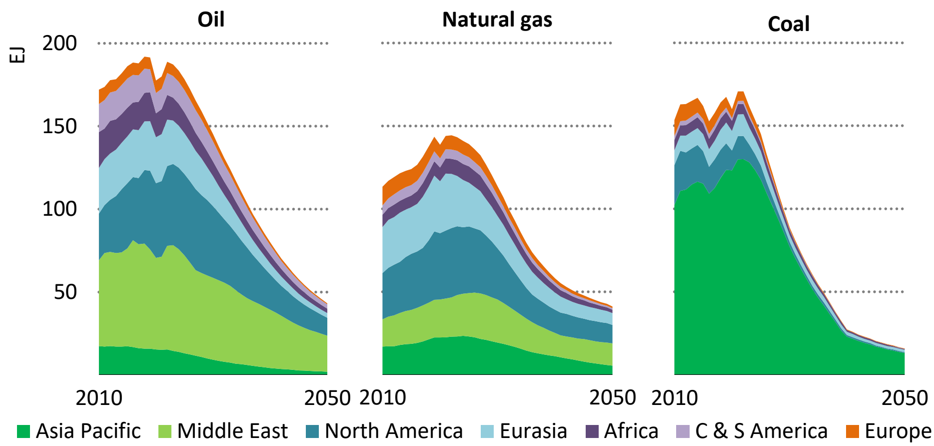
3.3 Fuel supply

Fossil fuel supply

Oil, natural gas and coal accounted for around four-fifths of total energy supply worldwide in 2021. In the NZE Scenario, this share falls to around two-thirds in 2030 and less than one-fifth in 2050, a proportion of which is used with CCUS and for non-energy uses. Between 2021 and 2050, coal demand declines by 90%, oil declines by around 80%, and natural gas declines by more than 70%.

Just under 100 EJ of fossil fuels are consumed in 2050 in the NZE Scenario. Just over 40% of this, including 65% of natural gas and 90% of coal, is consumed in facilities equipped with CCUS. A further 40% – including more than 70% of the oil still being used – is consumed in applications where the carbon is embodied in the product and there are no direct CO_2 emissions (examples include chemical feedstocks, lubricants, paraffin waxes and asphalt). The remaining 20% is used in sectors where clean energy technologies are least feasible and cost effective: for example, oil still accounts for around 20% of fuel use in aviation in 2050 in the NZE Scenario. The unabated combustion of fossil fuels results in 1.2 Gt CO_2 emissions in 2050, and these are fully offset by BECCS and DACS.

Figure 3.7 ▷ Oil, natural gas and coal supply by region in the NZE Scenario



Declines in demand can be met without approving new long lead time upstream conventional oil and gas projects, new coal mines or mine lifetime extensions

Note: C & S America = Central and South America.

Coal use declines from 5 600 million tonnes of coal equivalent (Mtce) in 2021 to 3 000 Mtce in 2030 and to less than 600 Mtce in 2050 (Figure 3.7). Supply declines on average by more than 10% every year during the 2030s. Natural gas demand drops from around 4 200 bcm in 2021 to 3 300 bcm in 2030, and 1 200 bcm in 2050. Rates of decline are fastest in the 2030s, when natural gas use falls by 7% per year on average. Natural gas use continues to fall in the 2040s, but at a slower rate (around 3% per year) as reductions in gas use in power generation, industry and buildings are partly offset by increases in the volumes of gas being converted to low-emissions hydrogen. Oil demand declines from 95 million barrels per day (mb/d) in 2021 to 75 mb/d in 2030, and to less than 25 mb/d in 2050, with an annual decline rate of 6% on average from 2030 onwards.

The declines in fossil fuel demand in the NZE Scenario stem primarily from a major surge in clean energy investment (from around USD 1.2 trillion in recent years to USD 4.2 trillion in 2030). Some investment in existing supply projects continues in the NZE Scenario to ensure supply does not fall faster than the decline in demand. Other investment is undertaken to reduce the emissions intensity of remaining fossil fuel operations. In the NZE Scenario, this leads to a 50% reduction in the global average emissions intensity of oil and gas production between 2021 and 2030. If demand were to fall at the rates projected in the NZE Scenario, it could be met without approving the development of any new long lead-time upstream conventional oil and gas projects and without any new coal mines or coal mine lifetime extensions worldwide.

Reducing fossil fuel investment in advance of, or instead of, policy action and clean energy investment to reduce energy demand would not lead to the same outcomes as in the NZE Scenario. If supply were to transition faster than demand, with a drop in fossil fuel investment preceding a surge in clean energy technologies, this would lead to much higher prices – possibly for a prolonged period – even if the world moves towards net zero emissions. The scope for reductions in fossil fuel expenditure is closely linked to the scale and speed of increases in clean energy expenditure, and to the success of efforts to reduce energy demand: it does not make sense to look at any one of these factors in isolation from the others.

Russia's invasion of Ukraine adds an additional dimension to this analysis because it could lead to a substantial and prolonged reduction in Russian energy supplies. This is reflected in the updated NZE Scenario.

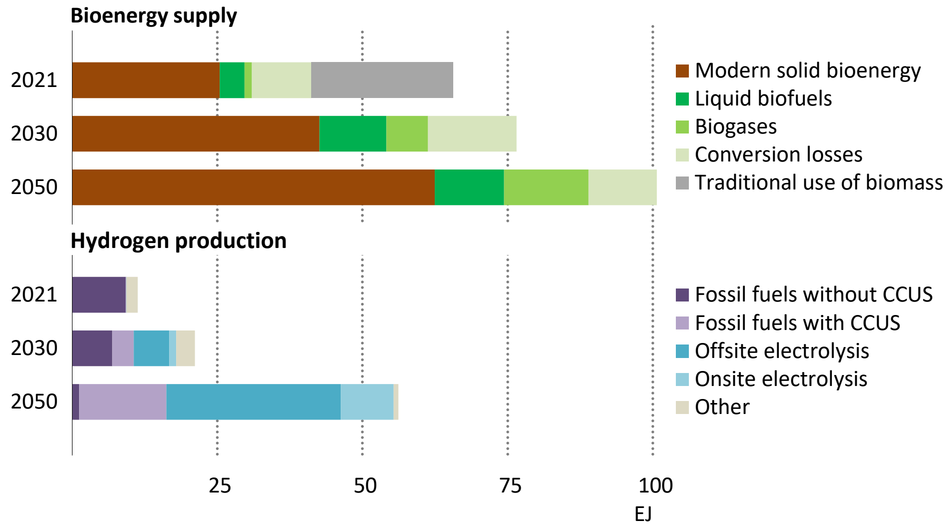
Turning first to oil, Russian production is lower in the 2022 NZE Scenario than it was in last year's NZE Scenario. The failure to ensure a sustainable recovery from the pandemic means that projected oil demand is at the same time higher in the mid-2020s in this NZE Scenario. The more suitable options to fill this combined gap are investments with shorter lead times and quicker payback periods, including extending production from existing fields and tight oil. The updated NZE Scenario also requires higher near-term production from members of OPEC than before to keep markets in balance, and a continuing high level of reliance on this production to meet remaining oil demand through to 2050. The share of oil supply coming from OPEC members rises from 35% in 2021 to 52% in 2050. Even though the oil market is much smaller in 2050 than today, the share of OPEC by then would be higher than at any point in the history of oil markets.

For natural gas, Russian production in the mid-2020s is lower than it was in the 2021 Net Zero Roadmap. However, in contrast to oil, near-term gas consumption has been revised downwards in this year's NZE Scenario as higher prices curb the cost effectiveness of gas helping to displace coal. Some new infrastructure may be needed to facilitate the diversification of supply away from Russia, and, with careful investment planning, there are opportunities for these to facilitate future imports of hydrogen or hydrogen-based fuels. Nonetheless, natural gas demand in the NZE Scenario can be met through continued investment in existing assets and already approved projects but without any new long lead time upstream conventional projects.

Low-emissions fuels

Net zero emissions does not mean the total phase out of fuels. Fossil fuel use declines, but there is rapid growth in low-emissions fuels (including solid, liquid and gaseous modern bioenergy, hydrogen and hydrogen-based fuels) (Figure 3.8). These play a key role in reducing emissions from long-distance transport and high-temperature industrial processes. In the NZE Scenario, low-emissions fuels comprise 20% of all liquid, solid and gaseous fuels used worldwide in 2030 and 65% by 2050.

Figure 3.8 ▷ Bioenergy supply and hydrogen production by source in the NZE Scenario, 2021-2050



Hydrogen production rises nearly fivefold from today to 2050, but modern bioenergy supply, limited by sustainable potentials, increases by two-and-a-half-times

Note: For hydrogen production, other includes refinery by-products.

For **bioenergy**, around 24 EJ of current consumption comes from the traditional use of biomass; this drops to zero as full access to modern cooking solutions is achieved by 2030 in the NZE Scenario. Modern bioenergy use increases from around 41 EJ today to more than 75 EJ in 2030 and to 100 EJ in 2050. In 2050, around one-third of this is used in the power sector, providing an important source of low-emissions dispatchable generation, and more than one-third is used in industry and buildings. Slightly less than 6 million barrels of oil equivalent per day (mboe/d) of liquid biofuels and 400 billion cubic metres equivalent of biogases are consumed in 2050. To avoid conflicts between food production and affordability, there is a general shift in the NZE Scenario away from conventional bioenergy sources towards advanced bioenergy, with around 50% of bioenergy supply coming from organic waste streams and forestry residues that do not require dedicated land use. Most of the remaining supply is provided by dedicated short rotation woody crops grown on cropland, pasture land and marginal lands that are not suited to food crops. There is no net increase in cropland use for bioenergy, and no bioenergy crops are grown on existing forested land in the NZE Scenario (see Chapter 9).

The supply of **low-emissions hydrogen** increases from 0.3 Mt (45 petajoules) today to 90 Mt in 2030 and 450 Mt in 2050.[5] More than 95% of total hydrogen and hydrogen-based fuel use in 2050 is in transport, power and industry. Of the low-emissions hydrogen produced in 2050, a little less than three-quarters is produced via water electrolysis, and a bit more than one-quarter is produced from fossil fuels with CCUS. The installed capacity of electrolysers reaches 720 gigawatts (GW) in 2030 and 3 670 GW in 2050 (existing electrolyser capacity is around 510 MW). In 2050, more than 14 800 TWh of electricity is used to produce low-emissions hydrogen, equivalent to more than half of today's global electricity demand from all sources. Around 25% of total low-emissions hydrogen in 2050 is converted to low-emissions hydrogen-based fuels. Synthetic kerosene produced from hydrogen (and combined with a non-fossil fuel source of CO_2) provides around 25% of energy use in the aviation sector, and ammonia and hydrogen provide more than 40% of energy use in shipping.

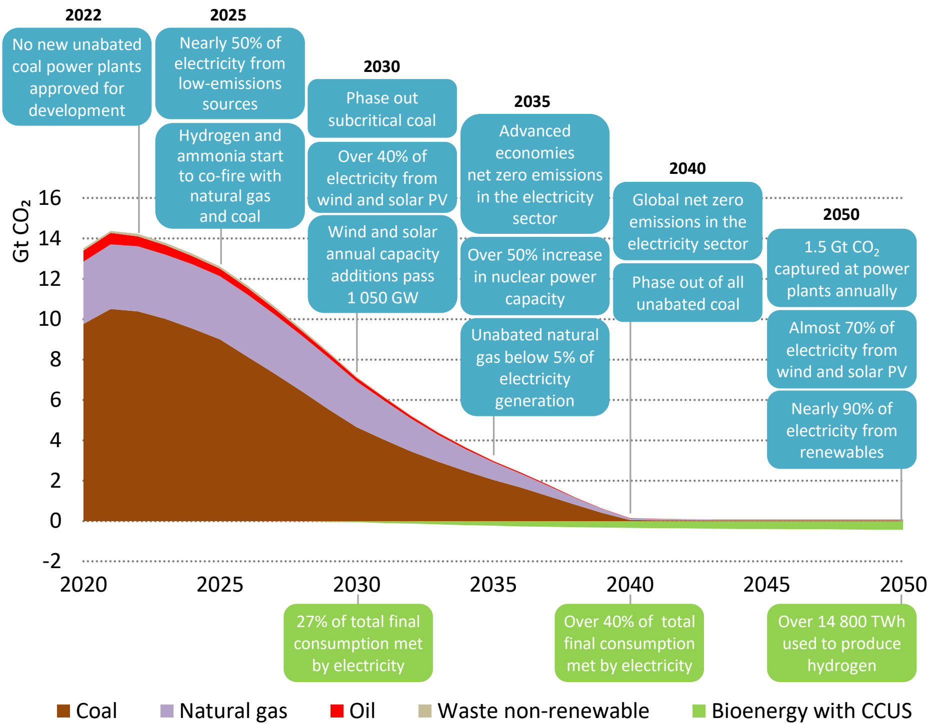
3.4 Electricity generation

Global electricity generation increases over two-and-a-half-times in the NZE Scenario from 2021 to 2050. Total electricity generation increases by 3.2% per year to 2030 and then by 3.4% per year from 2030 to 2050, compared with 2.5% per year from 2010 to 2021. The electrification of end-uses ranging from EVs to space heating to industrial production raises the share electricity in final consumption from 20% in 2021 to almost 30% in 2030, and more than 50% in 2050. The rapid growth of low-emissions hydrogen adds almost 3 000 TWh of demand growth by 2030, and more than 14 800 TWh by 2050.

[5] This includes both low-emissions hydrogen and the hydrogen contained in hydrogen-based fuels. See Chapter 5 and Annex C for definitions.

Low-emissions sources of electricity – renewables, nuclear power, fossil fuel power plants with CCUS, hydrogen and ammonia – expand rapidly in the NZE Scenario, overtaking unabated fossil fuels just after 2025 and reaching three-quarters of total generation by 2030, almost twice the share in 2021. Electricity sectors in advanced economies reach net zero emissions by 2035 in the NZE Scenario, and globally by 2040, at which point low-emissions sources provide nearly all electricity generation (Figure 3.9). This makes electricity the first energy sector to reach net zero emissions in the NZE Scenario, and that helps bring about emissions reductions in other sectors as they increasingly look to electricity to meet rising demand for energy services.

Figure 3.9 ⊳ CO_2 emissions by source and key milestones in the electricity sector in the NZE Scenario, 2020 to 2050



Electricity is the first sector to reach net zero emissions in 2040, tapping a wide set of low-emissions sources and enabling other sectors to cut emissions through electrification

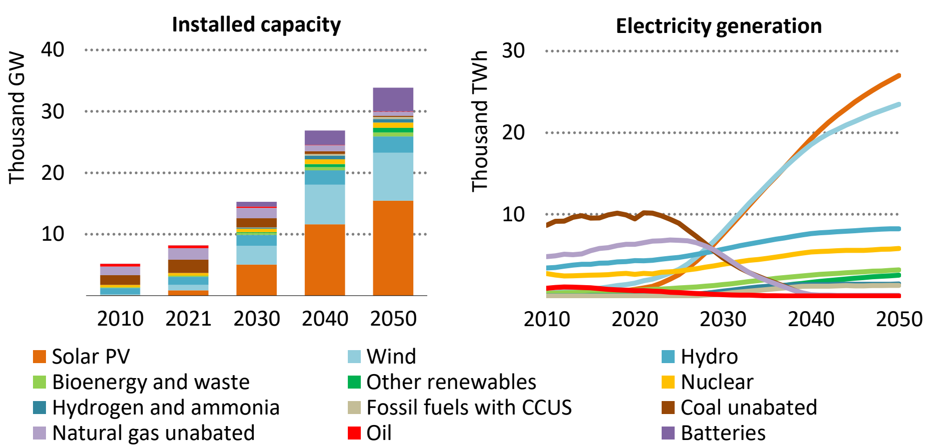
Notes: TWh = terawatt-hour; CCUS = carbon capture, utilisation and storage. Waste non-renewable represents any non-biogenic waste combusted for energy purposes.

Renewables rapidly become the foundation of the global electricity sector in the NZE Scenario. The share of renewables in electricity generation rises from 28% in 2021 to over

60% in 2030, and nearly 90% in 2050. The total installed capacity of renewables triples to 2030 and rises sevenfold to 2050. Annual renewables capacity additions quadruple from 290 GW in 2021 to nearly 1 200 GW in 2030, and average above 1 050 GW from 2031 to 2050.

Solar PV and wind are the leading means of cutting electricity sector emissions: their global share of electricity generation increases from 10% in 2021 to 40% by 2030, and 70% by 2050 (Figure 3.10). Solar PV additions expand more than fourfold to 650 GW by 2030, and wind additions to over 400 GW, with more than 20% of this from the developing offshore wind industry. Capacity additions of hydropower and other dispatchable renewables triple by 2030 to over 125 GW, helping to cut emissions and providing low-emissions means of integrating the growing amounts of solar PV and wind.

Figure 3.10 ▷ Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050



Total electricity generation nearly triples to 2050, with a rapid shift away from unabated coal and natural gas to low-emissions sources, led by solar PV and wind

Nuclear power generation more than doubles in the NZE Scenario by 2050, although its share falls from 10% in 2021 to 8% in 2050, as total generation expands rapidly. More than 30 countries, where nuclear power is accepted, increase their use of nuclear power. Widespread lifetime extensions in advanced economies provide a foundation. An annual average of 30 GW of new nuclear capacity comes online in the 2030s, marking a major comeback for the nuclear industry, and innovative technologies including small modular reactors become available on the market.

The use of low-emissions hydrogen and ammonia in natural gas- and coal-fired power plants and the addition of carbon capture technologies both provide important means of cutting emissions from existing power plants while supporting electricity security. The use of hydrogen and ammonia blended with natural gas and coal scales up in the late 2020s, and a total of 410 GW of natural gas-fired power plants and 160 GW of coal-fired plants are retrofitted by 2050 to co-fire ammonia and hydrogen, providing 2-3% of global electricity generation from 2030 to 2050. A total of over 60 GW of coal- and gas-fired power plants are retrofitted with CCUS by 2030, and this rises to over 330 GW by 2050. Fossil fuels with CCUS provide 1-2% of global electricity generation from 2030 to 2050

Phasing out unabated use of coal to generate electricity is a central pillar of the NZE Scenario as coal is an emissions-intensive fossil fuel still in widespread use. Emissions from unabated coal were 9.7 Gt CO_2 in 2021, accounting for 74% of the electricity sector total and 26% of total energy sector emissions. Despite a temporary boost from the current energy crisis as consumers switch from natural gas because of concerns about high prices and security of supply, the share of unabated coal in global electricity generation falls rapidly from 36% in 2021 to 12% in 2030, and to zero percent by 2040 and beyond. Low-emissions sources of generation grow so rapidly that no new unabated coal plants beyond those already under construction are built in the NZE Scenario.

Phasing out unabated coal emissions from power generation by 2040 worldwide depends on current power plants ceasing to provide regular baseload power. If the existing fleet of coal-fired power plants were to operate as they have in recent years, this alone would take up more than half of the remaining carbon budget consistent with limiting the global average temperature rise to 1.5 °C. However, such phasing out is not an easy proposition with an existing fleet of over 8 000 coal plants operating in some 90 countries and providing 2 million jobs. Against this background, it is important for there to be a range of options from which policy-makers can choose, which should include repurposing plants to focus on flexibility, retrofitting with carbon capture technologies, retrofitting to co-fire ammonia or biomass, and retiring them early.

Natural gas in the NZE Scenario faces a reduced role in this update compared with the 2021 version. This reflects current market conditions and changing perceptions of the affordability and security of natural gas. In this updated NZE Scenario, natural gas-fired generation peaks by 2025 before starting a long-term decline. By the time the global electricity sector reaches net zero emissions in 2040, the unabated use of natural gas is 97% lower than it was in 2021. Even as output falls, however, natural gas-fired capacity remains a critical source of power system flexibility in many markets, particularly to address seasonal flexibility needs.

Battery storage takes off in the NZE Scenario, expanding 30-fold from 2021 to 2030. This growth reflects its increasingly important role in helping to integrate rising shares of solar PV and wind by regularly charging at times of plentiful renewables supply and discharging when most needed in the system. Battery storage is also able to bolster the stability and reliability of electricity networks, for example by providing fast frequency response. By 2030, global battery capacity reaches 780 GW in the NZE Scenario and accounts for about 15% of all dispatchable power capacity. By 2035, battery capacity surpasses natural gas-fired capacity as the principal source of flexibility in many markets. Other forms of storage, such as heat or gravity-based systems, are under development and may emerge to complement or compete with battery storage.

Electricity transmission and distribution grids expand to meet the growing demands of electrification, connect thousands of new renewable energy projects, and reinforce systems that need to adapt to changing system dynamics. Global investment in grids to 2030 reaches close to USD 750 billion per year in the NZE Scenario, and it remains at a high level through to 2050. Close to 70% of this investment is for distribution grids with the aim of expanding, strengthening and digitalising networks.

Electricity security is of paramount importance in the NZE Scenario as the global economy becomes more and more dependent on reliable and stable electricity supply. Security depends on grids being modernised and digitalised to facilitate more advanced and smarter operations as the number of users and uses of electricity expands and as the nature of electricity supply evolves. It also depends on system flexibility, which is fast becoming the cornerstone of electricity security. In the NZE Scenario, power system flexibility needs quadruple between today and 2050, driven by the fast-rising share of variable renewables and changes in electricity demand patterns. Unabated coal and natural gas power plants and hydro have traditionally provided the lion's share of flexibility to power systems. This changes dramatically in the NZE Scenario as electricity shifts to low-emissions sources of generation. Batteries and demand-side response meet more than half of the flexibility needs in 2050, with another quarter coming from hydropower and most of the rest from low-emissions thermal power plants, including nuclear, fossil fuels equipped with CCUS and plants that co-fire hydrogen or ammonia. Around 5% is still provided by unabated natural gas.

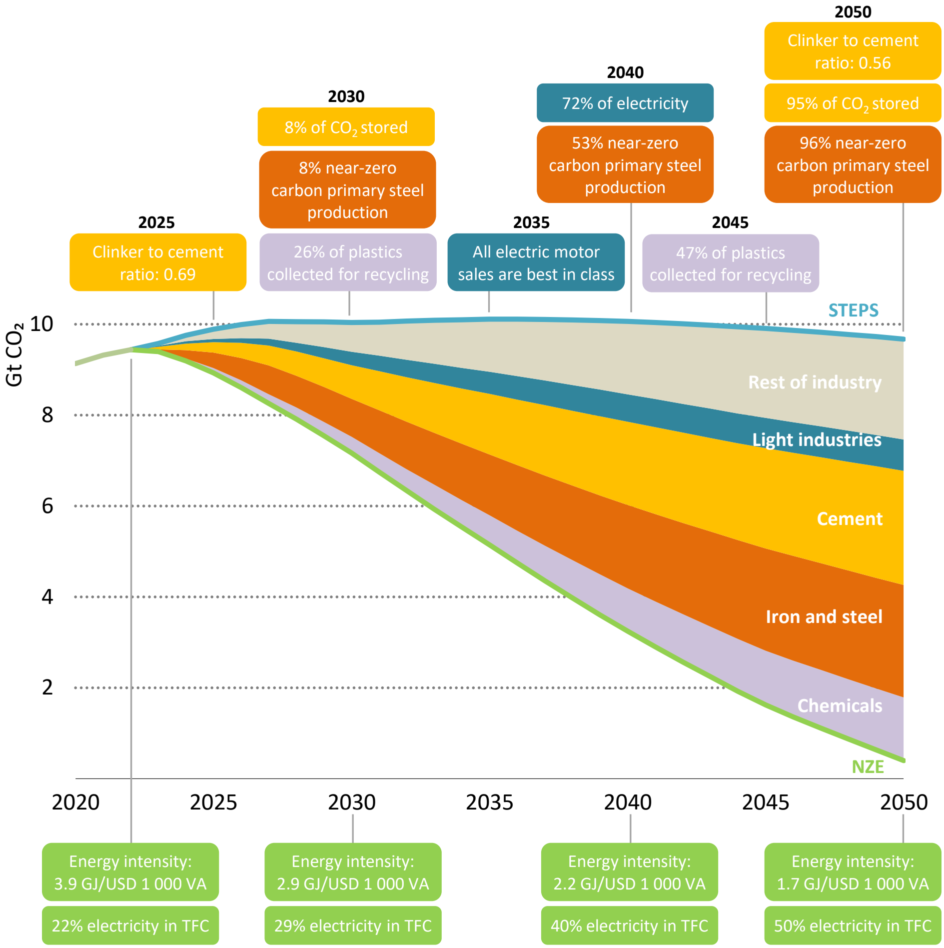
The affordability of electricity is a critical concern for consumers and policy makers in energy transitions, and it will become more critical still as electricity comes to represent an ever larger share of final consumption and total energy bills. In absolute terms, global electricity supply costs – including generation, storage and grids - more than double from today's level to USD 4.7 trillion annually in 2050. However, this increase in supply costs is less than the growth in electricity demand over the same period. In the NZE Scenario, electricity costs come down from their current high levels as cost-effective solar PV and wind are scaled up, and total electricity supply costs per unit of electricity generation are broadly stable to 2030. By 2050, the average cost of electricity is 10% below the level in 2021.

Massive investment in renewables and other low-emissions sources means that electricity supply becomes more capital intensive. Capital recovery rises from about 40% of electricity supply costs today to almost 80% in 2050 in the NZE Scenario, while fuel costs fall from one-third to just 5% in 2050. As a result, electricity system costs become more predictable and energy market volatility declines. Both advanced economies and emerging market and developing economies see lower electricity system costs by 2050. The costs of transitions in emerging market and developing economies are kept down by particularly low solar PV and wind costs, linked to lower technology costs and high quality solar resources in many countries.

3.5 Industry

In 2021, the industry sector worldwide accounted for almost 170 EJ of energy consumption, which is slightly more than the total energy supply of China. Industry represents more than one-third of total final energy consumption, and its 9 Gt CO_2 emissions make up 45% of total direct emissions from end-use sectors. There is no way to reach net zero emissions without strong and co-ordinated action on emissions reduction in the industry sector.

Figure 3.11 ▷ Emissions reductions and key milestones in the industry sector in the NZE Scenario relative to the STEPS, 2020-2050



Industry requires a portfolio of technologies and measures to reach net zero emissions, such as energy and material efficiency, electrification, hydrogen and CCUS

Notes: VA = value added; TFC = total final consumption. Innovative routes for iron and steel include hydrogen-based and CCUS-based routes. Milestones in green relate to the whole of the industry sector.

The world has not yet reached peak materials demand in industry. In the STEPS, world output of crude steel increases by around 10% by 2030, and around 30% by 2050, driven by India, Southeast Asia, and Africa. Global output of cement also increases as Africa and India continue the processes of urbanisation and industrialisation. A much stronger focus on more efficient use of materials tempers this growth in the NZE Scenario, but it is not enough to prevent an overall increase in demand for industrial materials.

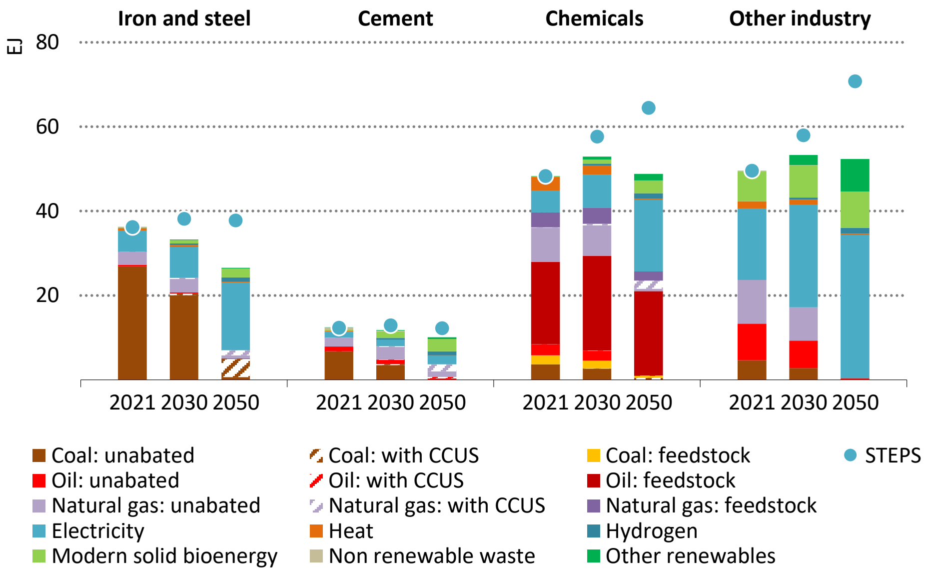
Several other challenges stand in the way of industry sector decarbonisation. First, many technologies required for the transition in the industry sector are still at prototype or demonstration stage and not yet ready for deployment at scale. Second, in a number of cases new production processes with substantially lower emissions intensities will – at least initially – have higher costs. Third, many heavy industry sector products, such as steel, are traded internationally in competitive markets, with margins that are too slim to absorb elevated production costs or to encourage first movers to adopt new technologies. In addition, heavy industrial facilities are long-lived and capital intensive. These challenges call for a multi-pronged approach to decarbonisation in industry in the NZE Scenario.

Central to the pathway for the industry sector are measures to avoid energy demand growth through improved energy and materials efficiency. In the NZE Scenario, total final consumption in the sector is nearly 10% lower than in the STEPS by 2030 (Figure 3.12). Energy efficiency contributes nearly half of the additional energy savings achieved in the NZE Scenario. Policies to speed the deployment of best available technologies in electric motor systems, and thermal and mechanical equipment are central to the achievement of these savings, together with process integration strategies. Materials efficiency reduces demand for materials and accounts for nearly one-fifth of the additional energy savings. Significant measures include to increase light-weighting and life extensions of equipment and infrastructure and to support product reuse and recycling.

These measures are especially important in the near term to help avoid growth in unabated production capacity while low-emissions technologies are reaching market maturity and scaling up. However, changes in the industry sector fuel mix are already clearly visible by 2030 in the NZE Scenario (Figure 3.12).

In **steel,** nearly three-quarters of total final consumption is currently provided by coal, a higher share than in any other sub-sector. Coke, produced from coking coal, provides high-temperature process heat and serves as a reducing agent for the reduction of iron ore in the blast furnace route. In the NZE Scenario, the share of unabated coal in total sector demand falls to slightly more than 60% by 2030, while the share of electricity rises by eight percentage points. By 2050, the share of electricity reaches nearly 60%, driven by increased secondary steel production (only limited by scrap availability) and by increasing demand for onsite electrolytic hydrogen production. This transition is facilitated by higher recycling rates globally, which enable secondary steel production to rise from around 20% today to more than 25% by 2030. Hydrogen-based direct reduced iron (DRI) becomes a key technology for primary steel production in the long term: the electricity required for the onsite production and use of hydrogen accounts for 3% of total steel making final energy consumption in 2030, and this surges to more than 25% in 2050.

Figure 3.12 ▷ Final energy consumption by source in industry sub-sectors in the NZE Scenario, 2021-2050



Electricity makes inroads in all industry sub-sectors; in some it is used to produce hydrogen onsite. In 2050, the share of unabated fossil fuels is less than 5%, from around 50% today.

Notes: EJ = exajoules; CCUS = carbon capture, utilisation and storage; STEPS = Stated Policies Scenario. Onsite electrolytic hydrogen use is reported as electricity demand rather than as hydrogen demand. Other industry includes light industries and non-specified industry.

Electricity is complemented by a range of additional low-emissions fuels. From almost zero today, the use of coal and natural gas with CCUS increases to meet 2% of steel sector demand by 2030 and more than 20% by 2050. CCUS is deployed in particular in regions where there is stock of very young blast furnaces, notably in China, and where there is limited access to high quality renewable resources but easy access to competitive coal and natural gas. The share of modern bioenergy, mainly solid bioenergy, reaches around 10% and merchant hydrogen, i.e. not produced onsite, accounts for around 5%.

These transformations in the iron and steel sector require strong policies, linking demand pull and supply pull measures. Common definitions of near zero emissions material production are an essential foundation for such policies (Box 3.2).

Box 3.2 ▷ Near zero emissions material production: moving towards common definitions

The IEA tracks the deployment of EVs in transport, heat pumps in buildings, and solar and wind generation in electricity. But what is the equivalent for industrial sub-sectors such as steel and cement? Defining what level of emissions intensity "makes the cut" for the transition to net zero emissions is critical, particularly for measures designed to create leading markets for near zero emissions products (demand pull) and to help direct investment for deployment (supply push). For example, with commonly understood definitions in place, private and public sector actors could commit to procure near zero emissions steel and cement at a premium, incentivising industry to scale up production.

The IEA undertook an analysis in the last year, at the request of the German G7 Presidency, to develop definitions for near zero emissions steel and cement production. Incorporating input from a diverse group of stakeholders, the definitions were proposed in *Achieving Net Zero Heavy Industry Sectors in G7 Members* (IEA, 2022a). The objective is to work towards internationally agreed definitions that can help to accelerate progress.

The near zero emissions definitions are designed to be stable, absolute and ambitious, and to be compatible with a global energy system trajectory that achieves net zero emissions by mid-century. The thresholds are:

- **Steel:** The threshold is a function of the proportion of scrap use in total metallic inputs – the more scrap used, the lower the threshold – as the use of scrap in steel making inherently reduces emissions intensity and its use is already well incentivised. For steel with no scrap use, the proposed threshold is 400 kilogrammes CO_2-equivalent per tonne (kg CO_2-eq/t) of crude steel, and for 100% scrap use it is 50 kg CO_2-eq/t.
- **Cement:** Similarly, the threshold for cement is a function of the proportion of clinker use – the more clinker used, the higher the threshold – given that use of supplementary cementitious materials (SCMs) leads to lower emissions intensity and is already well incentivised. For cement with 100% clinker use, the proposed threshold is 125 kg CO_2-eq/t cement, while for full use of SCMs the threshold is 40 kg CO_2-eq/t (noting that for most applications, the minimum practically achievable clinker content of cement is thought to be about 50%).

Interim measures that substantially lower the emissions intensity of materials production, but fall short of the near zero emissions thresholds, should also be recognised. As such, complementary definitions for "low emissions production" of steel and cement have been proposed in order to recognise the important interim steps taken along a clear path towards near zero emissions intensity.

The IEA analysis was recognised by G7 ministers in the 2022 Climate, Energy and Environment meeting communiqué, and is already being put to use. For example, they are used in the Clean Energy Ministerial (CEM) Industrial Deep Decarbonisation

Initiative's Green Public Procurement Pledge announced at the CEM in Pittsburgh, Pennsylvania (United States) in September 2022. Further efforts to expand the use and recognition of agreed thresholds and definitions will be important to enable accelerated clean energy transitions for industry.

Cement production today is fuelled by a broader range of sources than steel, although coal still accounts for around half of total energy consumption in the sub-sector. In the near term, reducing the amount of clinker in cement is a key strategy that prevents more than 250 Mt CO_2 of process and energy-related emissions by 2030 in the NZE Scenario compared with the STEPS. CCUS is the only other measure that simultaneously avoids both energy-related and process emissions from cement production. The integration of CCUS in cement kilns is therefore central to the decarbonisation of the cement sub-sector. In the NZE Scenario, the use of CCUS results in 1.3 Gt CO_2 being captured and stored from cement production by 2050, or almost 95% of the emissions generated in the sub-sector.

There is also some switching to the use of low-emissions fuels in cement kilns. This is dominated by modern solid bioenergy, whose share increases from slightly more than 5% today to nearly 15% by 2030, and almost one-third by 2050. Electricity, currently largely used for mechanical energy in uses such as clinker grinding, increases its share of the cement production market from 12% today to more than 20% by 2050 as electric kilns start to be deployed after 2040. Merchant hydrogen is also deployed in cement production, reaching around 5% of total consumption by 2050.

The **chemicals** sub-sector is less emissions intensive than steel and cement. This is partly because oil and natural gas are the dominant fuels instead of coal, but much more because 90% of oil consumption is for non-energy uses as feedstock. In the NZE Scenario, materials efficiency strategies such as single-use plastics bans, plastic reuse and recycling are pursued through targeted and stringent policies, which by 2050 result in the saving of around 30% of the oil feedstock used in the STEPS.

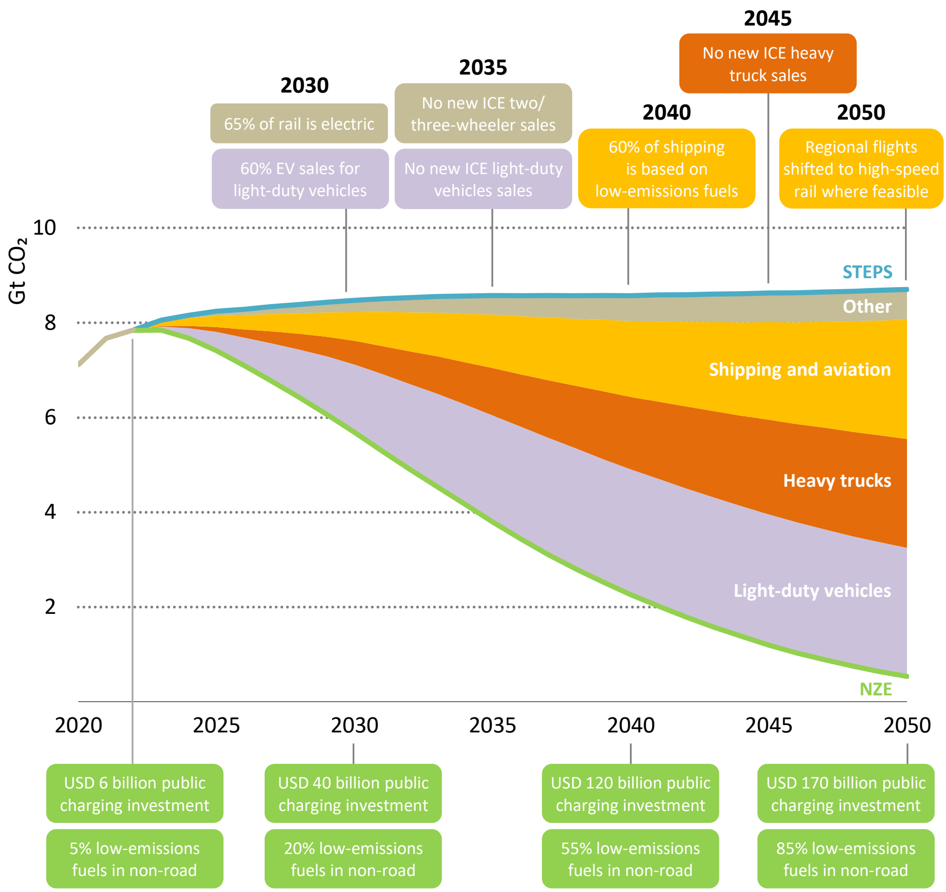
Electricity makes inroads by 2030, increasing its share in the chemical sub-sector's energy consumption from a bit more than 10% today to around 15% by 2030, and 35% by 2050. This is mostly driven by the increasing production of onsite electrolytic hydrogen in place of fossil feedstock for ammonia and methanol production in particular. Direct use of renewables, such as bioenergy, solar thermal and geothermal, provides around 10% of the sub-sector's consumption by 2050, while merchant hydrogen used as a fuel provides around 5%.

The **other industry** sub-sector includes a wide variety of industrial branches, most of which have lower energy intensity needs than steel, cement and chemicals. This sub-sector is almost completely decarbonised by 2050 in the NZE Scenario. Electricity already provides nearly 35% of total final consumption, and this rises to nearly 50% by 2030, and to two-thirds by 2050. Electricity is complemented by increasing use of modern solid bioenergy and biomethane, and other renewables including solar thermal and geothermal for low-temperature needs.

3.6 Transport

The global transport sector consumes a quarter of total final energy consumption today and is responsible for nearly 40% of the emissions from end-use sectors. Oil dominates in transport, accounting for 90% of consumption. From 2010 to 2019, increasing demand for passenger and goods mobility resulted in the transport sector seeing the largest growth in emissions of all end-use sectors. In 2021, global CO_2 emissions from the sector rebounded to 7.7 Gt CO_2, from 7.1 Gt CO_2 in 2020 as mobility demand recovered from the pandemic.

Figure 3.13 ▷ Emissions reductions and key milestones in transport in the NZE Scenario relative to the STEPS, 2020-2050



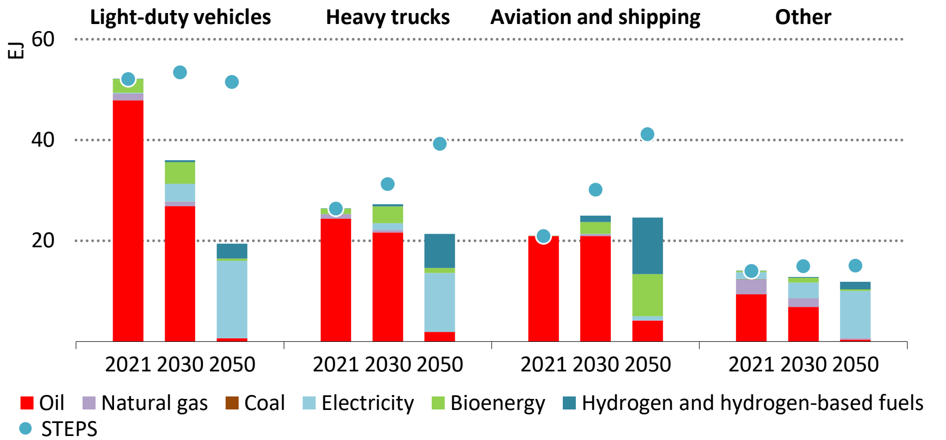
Electrification of road transport and rail brings rapid and massive emissions reductions; behavioural changes and low-emissions fuels are key in aviation and shipping

Notes: ICE = internal combustion engine. Light-duty vehicles include passenger light-duty vehicles and light commercial vehicles. Other includes two/three-wheelers, buses, rail, pipeline and non-specified. Non-road includes aviation, shipping and rail modes. Low-emissions fuels include biofuels and low-emissions hydrogen and hydrogen-based fuels.

Both passenger and freight activity are set to more than double by 2050 in the NZE Scenario, driven by higher mobility needs in emerging market and developing economies as their economies and populations grow and living standards increase. Energy demand growth is tempered in the NZE Scenario by improvements in technical and operational efficiency across all modes – road, aviation, shipping and rail – as well as by the deployment of highly efficient vehicles, i.e. electric vehicles (EVs), and policies to promote modal and behavioural shifts (Figure 3.13).

Decarbonising the transport sector in the NZE Scenario depends primarily on two changes. First is a switch to electricity, especially to the use of EVs[6] and hydrogen fuel cell electric vehicles in road transport. Second is a move to both blending and direct use of low-emissions fuels such as biofuels, hydrogen and hydrogen-based fuels, especially in aviation and shipping.

Figure 3.14 ▷ Final energy consumption in transport by source and mode in the NZE Scenario, 2021-2050



Direct electricity use is key to decarbonising road transport and rail; hydrogen and hydrogen-based fuels play a major role in aviation and shipping

Note: Light-duty vehicles include passenger light-duty vehicles and light commercial vehicles. Other includes two/three-wheelers, buses, rail, pipeline and non-specified. STEPS = Stated Policies Scenario.

In the NZE Scenario, the share of oil in transport final consumption drops to around 75% by 2030 and to 10% by 2050. Electricity is the key substitute for oil, accounting for nearly 50% of transport final energy consumption by 2050, but hydrogen and hydrogen-based fuels (30% of final consumption in 2050) and biofuels (almost 15%) also play important roles. Light-duty vehicles such as cars, vans and two/three-wheelers as well as most rail operations electrify rapidly, and heavy-duty vehicles including medium and heavy trucks follow suit on a longer

[6] EVs refer to full battery electric vehicles and plug-in hybrid electric vehicles.

timescale. Biofuels are blended into other fuels in growing quantities in road transport through to 2030, but are increasingly used instead in aviation and shipping beyond 2030 as electrification becomes the most cost-effective option for decarbonising the road sector. Direct use of hydrogen, and of low-emissions synthetic fuels such as synthetic kerosene and ammonia, increases rapidly to meet demand in long-distance modes of transport, mainly aviation and shipping (Figure 3.14). Despite the high costs of these energy carriers and the considerable energy losses incurred in their production, hydrogen and low-emissions synthetic fuels play a key role in reducing carbon emissions from long-distance modes thanks to their high energy density.

Globally **road vehicles** emitted 5.9 Gt CO_2 in 2021 – more than the entire energy-related carbon emissions of North America. Oil products accounted for around 90% of road transport energy consumption, with biofuels and natural gas accounting for almost all remaining demand. The share of electricity in road transport demand in 2021 was less than 1%.

In the NZE Scenario, the share of oil products in road transport demand decreases to 75% by 2030, with electricity accounting for 10%, biofuels for more than 10%, and hydrogen, hydrogen-based fuels and natural gas for the rest. New sales of internal combustion engine (ICE) cars, vans, two/three-wheelers and urban buses come to an end by 2035, intercity buses by 2040, and new sales of ICE heavy-duty vehicles (heavy and medium trucks) cease by 2045. EVs offer the most cost-effective low-emissions technology in most segments in both the short and long term, and they come to dominate in road transport. By 2030, 60% of all new car sales are electric, but ICE vehicles still account for nearly 80% of the stock of cars, meaning that fuel economy improvements and behavioural change remain critically important. The electrification of heavy-duty vehicles proceeds at a slower pace, with EVs accounting for almost 30% of sales by 2030. Hydrogen also plays a role, mainly for long-distance heavy freight trucks. Emerging market and developing economies initially focus on the electrification of two/three-wheelers and urban buses.

The rapid rollout of recharging infrastructure is essential to underpin the shift to EVs. In the NZE Scenario, around USD 35 billion of investment goes to support public EV chargers every year on average from 2022-30, and efforts are also made to scale up the availability of hydrogen refuelling stations in locations that are suitable for long-distance trucking such as industrial hubs. This requires tackling the financing gaps that exist in emerging market and developing economies for the deployment of charging infrastructure.

By 2050, the road transport sector is almost entirely decarbonised. Residual emissions amount to around 200 Mt CO_2 (3% of 2021 emissions) and are all attributable to oil product consumption in the remaining ICE heavy trucks on the road. Electricity is the main fuel for road transport, accounting for over two-thirds of total energy consumption and nearly 90% of total road activity by 2050. Hydrogen also plays an important part, and is responsible for almost one-quarter of energy consumption in the sector.

Aviation[7] is almost entirely reliant on oil today. As pandemic-related travel restrictions were lifted in most regions, surging demand for flights led CO_2 emissions from aviation to rise by over 20% year-on-year to 700 Mt in 2021, although they remained below 2019 levels.

The NZE Scenario sees lower growth of aviation activity (expressed in revenue-passenger kilometres) than the STEPS as policies to promote behavioural changes lead to shifts to high-speed rail and to a reduction in business trips (see section 3.8). Growth in aviation activity is kept down to around 2.5% per year to 2050 relative to 2019, and emissions fall to 200 Mt by then. Global use of jet kerosene decreases to around 90% of total aviation energy demand by 2030 and to around 20% by 2050. The use of sustainable aviation fuel (SAF) starts to accelerate in the 2030s. By 2030, over 10% of fuel consumption in aviation is SAF, most of which is biojet kerosene. By 2050, biojet kerosene meets almost 45% of demand and synthetic hydrogen-based fuels meet a further 25%. Investments in SAF production facilities scale up rapidly with support from governments in the form of blending mandates, low-emissions fuel standards and tax credits, while prioritising sustainability criteria.

The NZE Scenario sees commercialisation of hydrogen aircraft from 2035. By 2050, half of all regional and narrow body aircraft sold are hydrogen aircraft mainly serving short- to mid-haul routes, and direct use of hydrogen accounts for 8% of total energy demand in aviation. Growing use of hydrogen powered aircraft depends on technological advancements in storage tanks, on-board fuel delivery systems, and combustion engines or fuel cell technologies, as well as on investments in airport infrastructure for the storage and delivery of hydrogen.

The NZE Scenario also sees a role for battery electric aircraft. Current battery density and weight significantly restrict the range and size of such aircraft. However, advances in battery technologies are expected to open regional flights to battery electric aircraft. They meet 3% of aviation energy demand by 2050 in the NZE Scenario.

Maritime shipping is heavily reliant on oil, which meets virtually all its energy demand today. In the NZE Scenario, the fuel mix for the sub-sector undergoes a major transformation, and its global CO_2 emissions fall from 840 Mt CO_2 today to 110 Mt CO_2 by 2050. A number of fuels contribute to this decarbonisation progress. By 2050, ammonia meets around 45% of demand for shipping fuel. Bioenergy and hydrogen each meet a further 20% of demand, with the use of hydrogen in particular focussed on short- to mid-range operations. Electricity plays a minor role focussed on meeting demand from small ships and cruise ferries used for short-distance operations.

Ships have a lifetime of 20-35 years, which inhibits the uptake of new low-emissions technologies and contributes to oil still constituting almost 15% of shipping fuel demand by 2050. Although it is possible to retrofit ships to run on low-emissions hydrogen-based fuels,

[7] Aviation in this report includes both domestic and international flights. While the focus here is on commercial passenger aviation, other dedicated freight and general (military and private) aviation, which collectively account for more than 10% of fuel use and emissions, are also included in the energy and emissions accounting.

this is complicated by the need for major investments and co-ordinated efforts among fuel suppliers, ports, shipbuilders and shippers, especially when it comes to large transoceanic vessels. Efficiency measures such as wind kites and rotor sails also have an important role to play, since they help to reduce the need for fuel of any kind.

Rail is the most energy-efficient and least emissions-intensive mode of passenger transport, even though oil currently meets over half of all rail energy needs, and two-thirds of energy needs in freight rail. In the NZE Scenario, passenger rail demand expands significantly, in particular for urban metro rail and high-speed rail travel which mainly relies on electricity. Passenger activity on high-speed rail increases more than three-times by 2030 as travel demand is increasingly shifted from short-haul flights to rail as a lower emissions option. Rail freight demand also increases significantly. Despite this, global CO_2 emissions from rail fall from 90 Mt CO_2 in 2021 to almost zero by 2050 as all new tracks on high throughput corridors are electrified from now on and as electricity's share of rail energy demand rises from around 45% today to 65% by 2030, and almost 90% by 2050. Biodiesel accounts for a further 5% of demand in 2050, and hydrogen for an additional 2%, while conventional diesel use is reduced to only 3%. Fuel cell trains could potentially serve long-distance rail travel without refuelling, but are currently at a demonstration stage.

3.7 Buildings

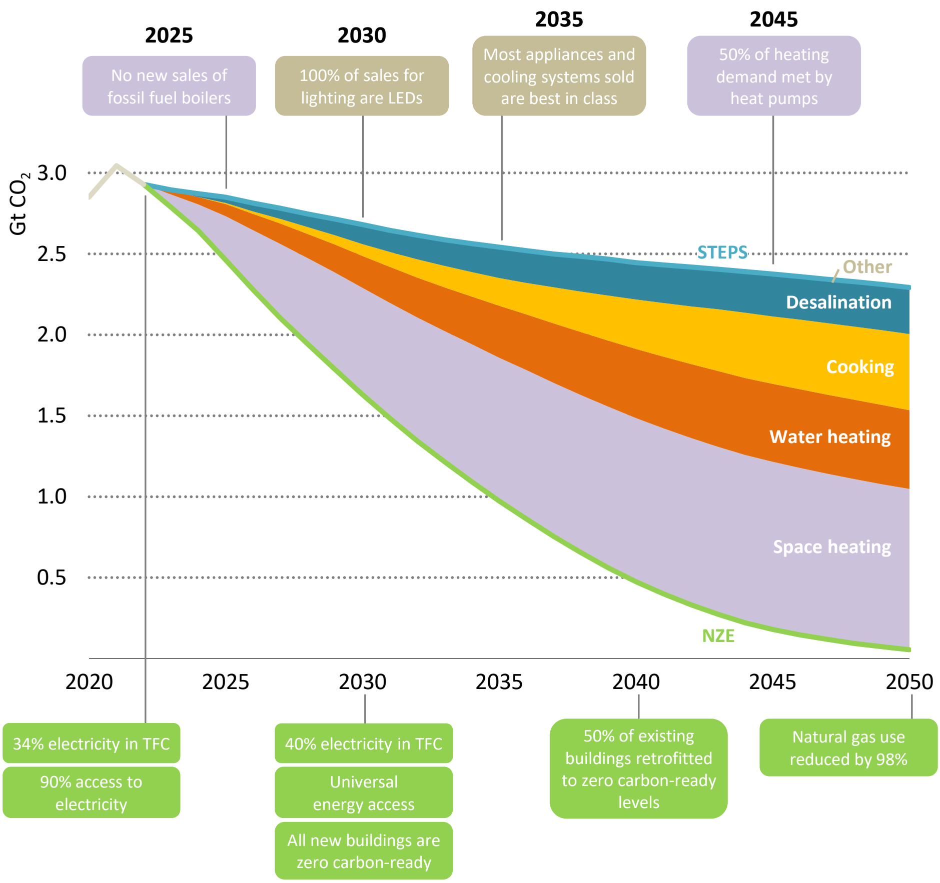
The buildings sector accounted for 132 EJ of energy consumption in 2021, or 30% of total global final energy consumption. The sector's 3 Gt CO_2 emissions accounted for 15% of total emissions from end-use sectors in 2021, but this share doubles if indirect emissions from electricity and heat production are included. Despite a gradual shift away from fossil fuels, direct emissions from the buildings sector have risen by 0.5% per year since 2010, driven by rising demand for energy services.

Activity levels in the buildings sector continue to rise. Access to electricity and clean cooking is improving in emerging market and developing economies, albeit too slowly to meet SDG goals and with recent reversals (see Chapter 5, section 5.6), and the ownership and use of appliances is expanding as incomes rise and populations expand. Floor area in the buildings sector worldwide is expected to increase 20% between 2021 and 2030, of which 80% is in emerging market and developing economies. The number of air conditioners in the global stock is set to increase by 50% by 2030, compounded by the increasing effects of climate change. In emerging market and developing economies alone, 590 million air conditioners are added by 2030 in the NZE Scenario. Given that buildings are responsible for more than half of total electricity consumption already today, tempering the impact of increasing equipment and appliance use on future electricity demand growth is of major importance to the decarbonisation of electricity generation.

At the same time, expanding the role of electricity in cooking, water heating and space heating is key to the decarbonisation of the buildings sector. Improving energy efficiency and increasing electrification and renewables use in buildings, however, is complicated by the long lifetimes of buildings and related infrastructure such as heat and electricity networks. Much also depends on the decisions of individual consumers.

In the NZE Scenario, despite the projected growth in service demand, direct CO_2 emissions from the buildings sector decline by 45% to 2030 and more than 98% by 2050 (Figure 3.15). Taken together, energy efficiency, electrification and behavioural change provide 80% of the emissions reductions in the buildings sector by 2030, and 70% by 2050.

Figure 3.15 ▷ Emissions reductions and key milestones in the buildings sector in the NZE Scenario relative to the STEPS, 2020-2050



Space heating delivers 50% of emissions reductions in buildings, driven by electrification and demand reductions from efficiency and behavioural changes

Notes: TFC = total final consumption; LEDs = light-emitting diodes. A zero carbon-ready building is highly energy efficient and uses either renewable energy directly or an energy supply that will be fully decarbonised by 2050 in the NZE Scenario (such as electricity or district heat). By 2025 in the NZE Scenario, any gas boilers that are sold are compatible with 100% low-emissions gases and in areas where fuel supply will be completely decarbonised before 2050.

Energy efficiency is the first pillar of the transition in the buildings sector; in the NZE Scenario it brings substantial benefits for affordability and consumer welfare. There is enormous scope for efficiency gains from improved envelopes for new and existing buildings, heat pumps, energy-efficient appliances, and energy and materials-efficient building design. Most of these technologies are available on the market, and some are already economically competitive, or on course to become competitive as technology costs decline.

In the NZE Scenario, efficiency measures are front-loaded, playing their largest role in curbing energy demand and emissions in the period to 2030. In the NZE Scenario, the energy intensity of the buildings sector needs to drop almost ten-times more quickly over the current decade than it did in the past. This means the energy consumed per square metre in 2030 is 45% less than in 2021.

The lifetime of the stock of buildings is typically very long, and the stock is expanding rapidly, particularly in emerging market and developing economies. In advanced economies, almost three-quarters of the buildings that will be in use in 2050 have already been built. In emerging market and developing economies the equivalent figure is much lower: 13% of the 2050 buildings stock will be constructed between today and 2030, and almost 40% in the 2030s and 2040s. Therefore, the NZE Scenario requires actions to simultaneously address emissions from both the existing and new buildings stock.

For all new buildings, mandatory zero carbon-ready building energy codes are introduced in all regions in the NZE Scenario no later than 2030 to avoid locked in emissions. For existing buildings, retrofit rates increase from less than 1% per year today to nearly 2.5% per year by 2030 in advanced economies, which means that around 10 million dwellings are retrofitted every year. This number rises to 20 million dwellings per year in emerging market and developing economies.

Strong retrofit rates result in 20% of the existing building stock being zero carbon-ready as soon as 2030, and more than 85% by 2050.[8] To achieve savings at the lowest cost and to minimise disruption, retrofits should be comprehensive. Deep renovations can be delivered through policies that require a gradual increase in renovation rates, starting with the worst performing buildings. Building envelope improvements in existing and new buildings account for the majority of heating and cooling energy intensity reductions in the NZE Scenario.

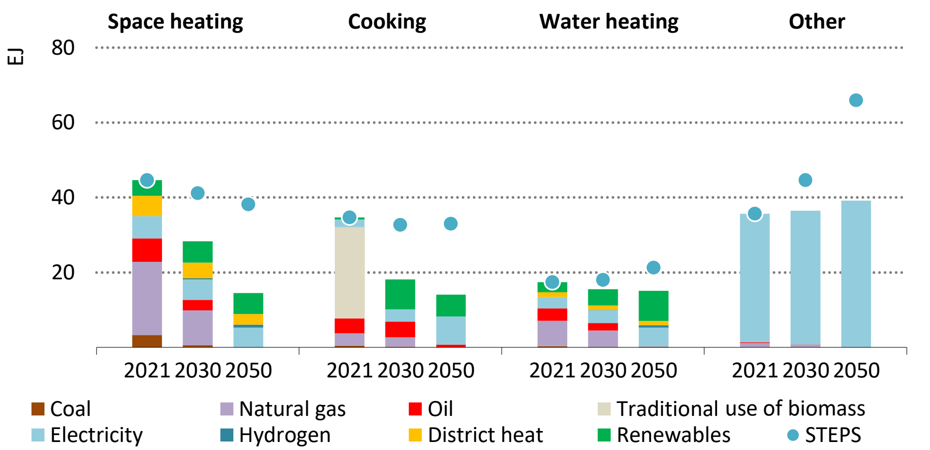
Energy demand in the sector depends on the efficiency of energy consuming equipment, as well as on the efficiency of the building envelope. In the NZE Scenario, over 80% of all appliances and air conditioners sold are the most efficient models by 2025 in advanced economies, and by the mid-2030s worldwide. Nonetheless, the upfront costs of key technologies to reduce direct emissions and improve energy efficiency, such as heat pumps, insulation and retrofits, create economic barriers to their adoption.

[8] A zero carbon-ready building is highly energy efficient and either uses renewable energy directly or an energy supply that can be fully decarbonised, such as electricity or district heat.

Behavioural changes are also important in the NZE Scenario, reducing energy demand by 8 EJ in 2030 through actions such as making temperature adjustments to space heating and cooling. The ability of behavioural changes to achieve demand reductions rapidly and at no cost means that they can help provide an emergency response to the current energy crisis in the short term and facilitate the net zero emissions transition in the long term.

Electrification and switching to low-emissions fuels is the second pillar of the transition in the buildings sector. Today electricity makes up 34% of total final energy consumption in the buildings sector, making it the largest fuel in its energy mix, followed by natural gas with 23%. All end-uses dominated today by fossil fuels are increasingly electrified in the NZE Scenario. Liquefied petroleum gas (LPG) still plays a limited role for cooking in some emerging market and developing economies in 2050, but 95% of cooking energy needs are met by electricity and modern bioenergy by then. Coal, oil and gas cease to be used for space and water heating almost entirely by 2050. Some 30% of homes are heated by natural gas today, but this drops to almost zero.

Figure 3.16 ▷ Total final consumption in buildings by source and end-use in the NZE Scenario, 2021-2050



Efficiency, fuel switching and behavioural change reduce energy consumption in buildings significantly compared to the STEPS, and the mix shifts to electricity and renewables

Note: Other includes energy demand from appliances, lighting, space cooling and desalination. STEPS = Stated Policies Scenario.

No new fossil fuel boilers are sold from 2025 in the NZE Scenario, except where they are to be operated with 100% hydrogen or synthetic hydrogen-based fuels, or are to be connected to fully decarbonised gas networks using low-emissions gases such as biomethane. Hybrid heat pumps, combining a standard air-to-water heat pump with a high efficiency gas boiler, play a limited role in the short term: in the longer term, they are used only where natural gas networks are maintained and use low-emissions gases. Electricity becomes the principal source of energy for decarbonised heating: homes using electricity for heating rise from 20% of the total today to 30% in 2030, and more than 50% in 2050, with high efficiency electric heat pumps becoming the primary technology choice.[9] Worldwide, the installation of heat pumps increases from 1 million per month today to around 8 million per month by 2030, and 14 million per month by 2050. Overall, the share of electricity in the buildings sector energy mix reaches almost 50% by 2030 and 67% by 2050, making it the most electrified of all end-use sectors.

Renewables used in buildings are mainly for water and space heating in the NZE Scenario, with solar thermal seeing the biggest increase. Renewables are also used for cooking, with various forms of modern bioenergy meeting 40% of cooking energy demand in 2050 (Figure 3.16). Overall, the direct use of renewable energy rises from about 6% of buildings energy demand in 2021 to almost 30% in 2050, with about two-thirds of the increase taking the form of solar thermal and geothermal energy. District heating networks and low-emissions gases such as biomethane, hydrogen, and synthetic hydrogen-based fuels play a bigger role in 2050 in regions with high heating needs, dense urban populations and existing natural gas or district heat networks.

Box 3.3 ▷ Clean cooking access in the NZE Scenario

In 2021, 2.4 billion people worldwide had no access to clean cooking technologies, down from 2.9 billion in 2010. The net decrease was mainly due to rapid improvements in developing Asia (in particular in China[10], India and Indonesia). These outweighed an increase of 200 million in the number of people without access in sub-Saharan Africa during the same period. Improvements have slowed significantly since 2019 because of the Covid-19 pandemic and the current energy crisis (see Chapter 5).

In emerging market and developing economies, the rate of improvement in access was on average 1.7 percentage points each year between 2015 and 2019. In the NZE Scenario, this rate improves by 2.7-times on average between 2022 and 2030 (Figure 3.17). However, there are major regional divergences: to make progress as rapidly as projected in the NZE Scenario, sub-Saharan Africa needs to improve its historical rate of progress by 15-times and in developing Asia by only 1.5-times, mainly reflecting strong improvements already seen in China, Indonesia and India.

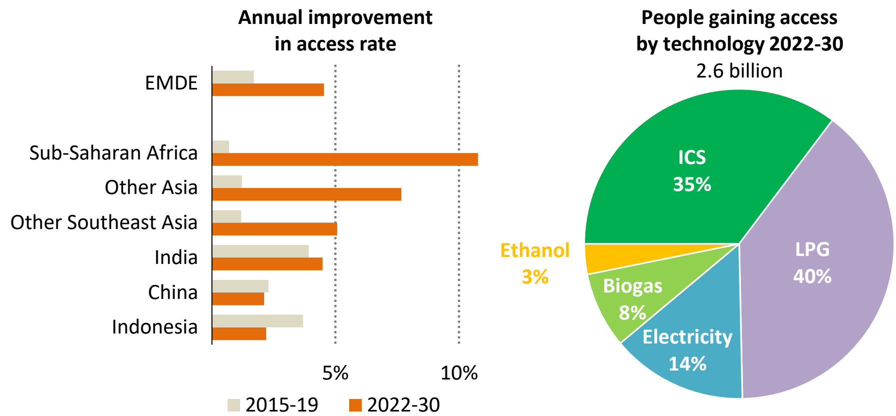
The NZE Scenario provides a pathway to reach the SDG 7.1 goals, but it requires determined action be taken quickly. Improved biomass cookstoves (ICS) provide access to 35% of those who gain it in the NZE Scenario and play a major role in ensuring that the

[9] The IEA will release a report on heat pumps and their role in energy security and transitions in November 2022.

[10] The World Health Organisation recently published revised historical data for clean cooking access in China based on information from recent surveys (WHO, 2022). This suggests that progress in China has been faster than estimated in previous reports.

poorest (mainly in rural areas) are able to make use of an affordable and readily available fuel. Liquefied petroleum gas provides access to almost 40% of those that gain it with the rest of the gap being closed by electricity (14%), biodigesters (8%) and ethanol (3%).

Figure 3.17 ▷ Annual improvement in access rate to clean cooking and by technology in the NZE Scenario, 2015-2030



Clean cooking access in emerging market and developing economies needs to improve 2.7-times faster between 2022 and 2030 than on average in recent years

Notes: EMDE = emerging market and developing economies; ICS = improved biomass cook stoves (ISO Tier > 1); LPG = liquefied petroleum gas.

Key themes

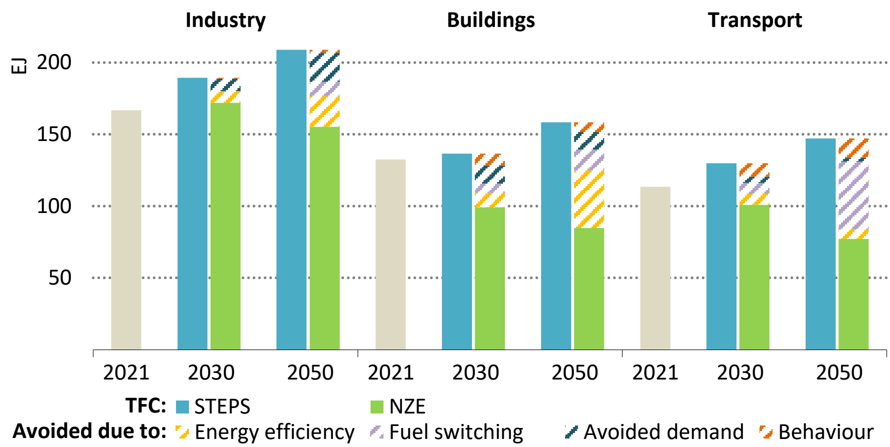
3.8 Avoiding growth in energy demand

Overview of measures

The decarbonisation pathway in the NZE Scenario cannot be achieved without the rapid and large-scale adoption of measures that limit growth in energy demand. Absent such measures, deployment of clean energy sources would be outpaced by fast rising demand for energy services. Measures include energy efficiency, fuel switching (notably electrification) and behavioural changes, and together they cut demand by 110 EJ relative to the STEPS in 2030 (Figure 3.18). They ensure that the energy intensity of GDP falls by 4% per year on average over the next eight years. Reductions in energy demand also play an important role in energy security and affordability.

In industry, around half of the reductions in energy use in 2030 are due to measures which avoid demand in the NZE Scenario compared to the STEPS, such as gains in materials efficiency. Most of the remaining reductions come from energy efficiency measures supported by a mixture of technical innovation, standards and regulations, including a systematic preference for best-in-class electric motors and other equipment, and digital energy management systems. There is also a role for changes in behaviour by consumers to consume less and recycle more, thereby reducing demand for industrial products, especially primary steel and plastics.

Figure 3.18 ▷ Total final consumption in the STEPS and demand avoided by measure in the NZE Scenario



IEA. CC BY 4.0.

Energy efficiency, behavioural changes and other mitigation measures in the NZE Scenario cut total final energy demand by almost 40% compared to the STEPS in 2050

Notes: Fuel switching includes electrification. Avoided demand includes materials efficiency gains, circular economy effects, and structural and economic effects, such as the response of consumers to higher prices.

In buildings, energy efficiency measures in the NZE Scenario avoid around one-quarter of the excess energy demand in the STEPS in 2030 and just over one-half of this in 2050. Fuel switching, largely from fossil fuel space heating to electric heat pumps, shaves a further one-fifth from this energy demand gap. The remainder is avoided by behavioural changes that moderate demand, notably for space heating and air conditioning.

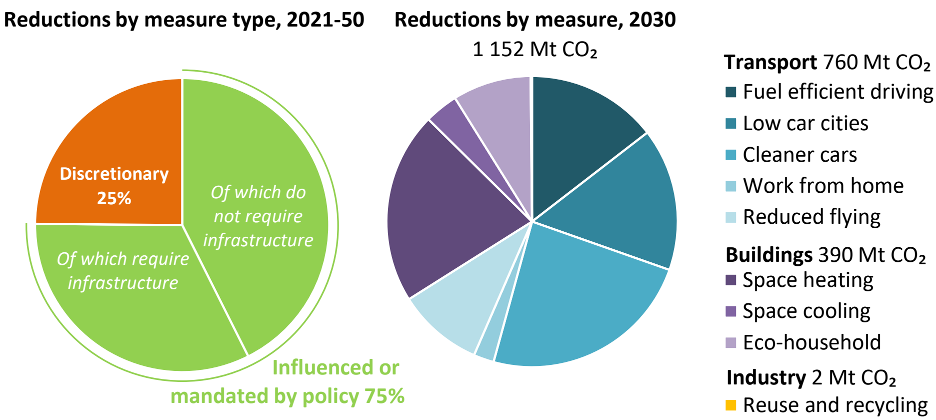
In transport, behavioural changes have a bigger impact than any other measure in 2030, accounting for one-third of the difference in energy demand between the STEPS and the NZE Scenario. These changes are particularly important in aviation, where there is little technical potential for fuel switching and limited room in the near term for energy efficiency gains beyond those in the STEPS. For road transport, fuel switching measures (mainly to EVs) and energy efficiency improvements underpinned by stringent fuel economy standards play an important role to curb growth in energy demand in 2030. But energy savings from electrification really come into their own after 2030, and there is a more than fourfold improvement in the average fuel economy of a car on the road in 2050 relative to today.

Focus on behavioural changes

The NZE Scenario incorporates a number of behavioural changes in the way consumers use energy services.[11] In part these function in the same way as energy efficiency and other technical options to reduce energy demand. Yet there are also important distinctions.

- Behavioural changes can tackle emissions from the existing stock of emissions-intensive assets without the need to wait for stock turnover and the advance of clean energy technologies. For example, while over 60% of cars sold in the NZE Scenario are EVs in 2030, almost 80% of cars on the road are still ICE vehicles by that time and many of them will continue to be driven for years to come. By contrast, behavioural changes that lead people to drive less or in a more fuel-efficient manner, e.g. more slowly, cut emissions from all vehicles without any transitional period. For that reason behavioural changes can also provide rapid responses when necessary to energy security concerns (IEA, 2022b).
- In some areas such as aviation, technical options are unlikely to exist at the scale required to reduce emissions to net zero by 2050. Behavioural changes which curb activity therefore have a critical part to play in reducing demand and minimising the need to rely on negative emissions technologies, which may be costly or fail to materialise at the requisite scale. In 2050, the behavioural changes in the NZE Scenario reduce the requirement for negative emissions technologies by around one-third, or 820 Mt CO_2.

Figure 3.19 ▷ CO_2 emissions reductions due to behavioural changes in the NZE Scenario



Behavioural changes cut CO_2 emissions, but most depend on targeted policies and some require new infrastructure

[11] Behavioural changes are active changes by end-users of energy-related services that reduce excessive or wasteful energy consumption. This means, for example, that the purchase of clean energy technologies, such as an EV, is not considered as a behavioural change.

By 2030, behavioural changes in the NZE Scenario reduce CO_2 emissions by around 1 150 Mt (or 9% of total emissions reductions) compared to levels in the STEPS (Figure 3.19). Between 2021-50 around three-quarters of cumulative emissions reductions from behavioural changes stem from measures directly shaped or mandated by government policies, such as congestion charging or speed limit reductions; around one-half of these require the support of infrastructure, such as high-speed rail networks. The remaining reductions are associated with discretionary behavioural changes which could be encouraged by information and awareness campaigns, such as product labelling and home energy consumption reports.

Buildings account for just over one-third of the total CO_2 emissions reductions from behavioural changes in 2030. For example, adjusting thermostats to 19-20 °C in winter and air conditioning to a maximum of 24 °C in summer reduces CO_2 emissions by almost 300 Mt (when including the indirect CO_2 emissions associated with electricity generation and heat production).

Transport accounts for just under two-thirds of the reductions in CO_2 emissions from behavioural changes in 2030 in the NZE Scenario. For road transport, measures to promote fuel-efficient driving, including reducing speed limits on motorways to 100 kilometres per hour (km/hour) and eco-driving,[12] reduce CO_2 emissions by 170 Mt in 2030. Other measures encourage working from home three days per week in jobs where it is possible to do so and increased carpooling.[13] Action is taken to phase out the use of ICE cars in large city centres, and reduce speed limits to 20 km/hour to discourage car use and make it easier and more enjoyable to cycle or walk. A shift towards cleaner cars is brought about by corporate targets to end the use of ICE cars in commercial ride-hailing fleets, e.g. Uber, and by policies to discourage ownership of sport utility vehicles (SUV) including by banning their use in city centres.

In aviation, a combination of frequent flyer levies, a 50% reduction in business-related long-haul trips in favour of teleconferencing and a shift to high-speed rail for regional flights cuts CO_2 emissions by 110 Mt in 2030 in the NZE Scenario relative to the level in STEPS.

S P O T L I G H T

Future of flying in the NZE Scenario

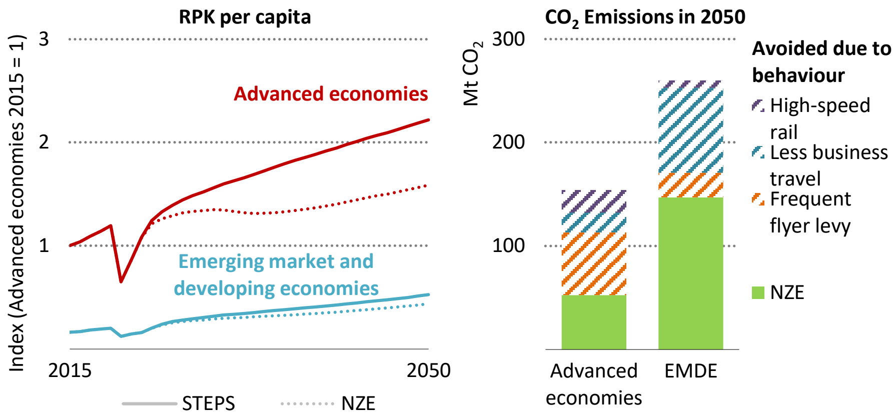
Technical options to decarbonise aviation are deployed at unprecedented speed in the NZE Scenario. For example, the share of sustainable aviation fuels rises to over 10% in 2030 from next to nothing today, reaching 70% in 2050, and the energy efficiency of new aircraft improves by 2% each year on average to 2050. Despite these efforts, rapid demand growth means that aviation would be one of the largest emitters of residual CO_2 in 2050 absent additional measures to limit demand growth (Figure 3.20). As a result of

[12] Note: Eco-driving involves pre-emptive stopping and starting and early up-shifting.

[13] We estimate that around one-fifth of jobs worldwide can be done at home (IEA, 2020).

the use of cleaner technologies coupled with these additional measures, demand in emerging market and developing economies increases by 3.5% per year on average between 2019-50 in the NZE Scenario (compared with 4.1% in the STEPS), and in advanced economies by 1.1% per year (compared with 2.2% in the STEPS).

Figure 3.20 ▹ Aviation activity growth per capita and emissions reductions due to behavioural changes in the STEPS and NZE Scenario



Policies are introduced in the NZE Scenario to curb the growth in aviation demand seen in the STEPS. Without these, emissions from aviation would be twice as high in 2050

Notes: RPK = revenue passenger kilometres, i.e. kilometres travelled by paying customers.

A number of levers mitigate demand growth in the NZE Scenario:

- **Frequent flyers**. There are very large variations in aviation demand between countries and income groups. It is estimated that 1% of the global population accounted for over half of all emissions from commercial aviation in 2018 (Gössling and Humpe, 2020). Our new analysis indicates that around 90% of the global population flies only once per year or not at all, whereas around 6% fly more than twice per year and just 1% fly more than five-times per year. Frequent flyer levies aim to reduce aviation demand in an equitable way (Büchs and Mattioli, 2022). They work by progressively taxing frequent flying, thereby curbing overall demand, while not making aviation unaffordable for the less well-off. A well designed levy could reduce aviation demand from the wealthiest 20% of the population by around 30%, while having little impact on those who fly once or twice a year (Chapman et al., 2021). Our analysis shows that this would reduce demand in 2050 by around 17% in advanced economies and 6% in emerging market and developing economies. In the NZE Scenario, frequent flyer levies reduce CO_2 emissions by around 90 Mt in 2050.

- **Business trips**. Based on analysis of passenger survey data, we estimate that around 20% of air travel in advanced economies is for business purposes. This rises to around 30% in emerging market and developing economies. In response to the Covid-19 pandemic, virtual business interactions have become more common, and many companies have invested heavily in enhancing the experience of remote meetings. In the NZE Scenario, teleconferencing substitutes for around one-in-two long-haul business trips in 2050, cutting CO_2 emissions by more than 100 Mt.
- **High-speed rail**. The opportunity to take high-speed rail instead of flying varies strongly by region.[14] Globally, in the NZE Scenario, sustained investment in new high-speed rail infrastructure combined with existing tracks enables around 17% of flights that serve routes shorter than 800 km to be shifted by 2050, saving around 30 Mt CO_2. Sustained investment in new high-speed rail infrastructure is critical to unlock the potential for rail to displace regional flights where possible. Some of the additional funding required to build this infrastructure could come from reductions in the funding needed for other infrastructure development, such as airport capacity expansions in advanced economies.

Many of the behavioural changes in the NZE Scenario target wasteful or excessive energy consumption, predominantly in wealthier parts of the world. Their main purpose is to reduce emissions, but some also act to reduce global inequalities in per capita energy consumption and CO_2 emissions, making the clean energy transition more equitable.

Policies that discourage car use in cities are one example. Such policies have an impact on private car ownership levels, particularly in wealthy households that own multiple cars.[15] In the NZE Scenario, car sales are around one-quarter above 2021 levels in 2030, but are around 10% lower than in the STEPS in that year (Figure 3.21).

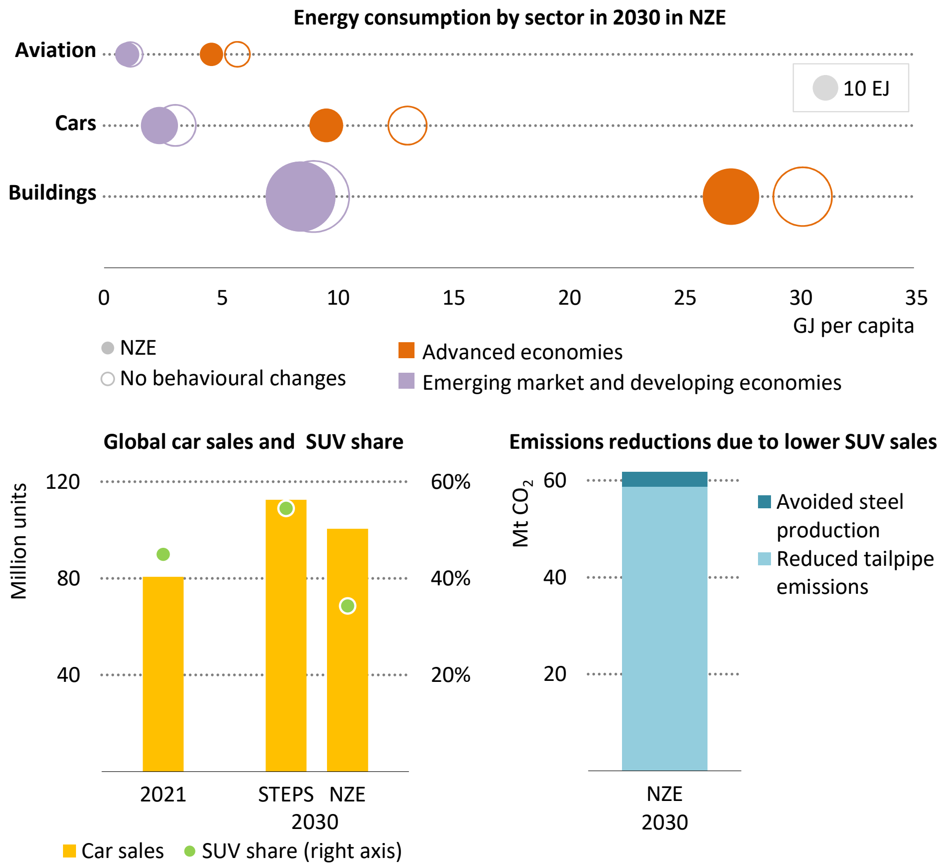
Policies that discourage ownership and use of SUVs is another example, and with a starker effect. Almost half of cars sold today are SUVs, and this rises to 55% in the STEPS by 2030. SUV ownership is highly concentrated: in 2021, almost five-times more SUVs were sold per capita in advanced economies than in emerging market and developing economies. In the NZE Scenario, the growing trend in SUV sales reverses and their market share falls to around 35% in 2030 and around 25% by 2050. Because SUVs are around one-quarter less fuel efficient than a standard car, the reduction in their popularity saves almost 60 Mt CO_2 in 2030 in the NZE Scenario. About 95% of the savings are associated with reduced direct emissions (tailpipe), with the remainder from reduced emissions in industry due to a drop in demand for steel. The benefits of discouraging SUV sales remain even as car fleets electrify in the NZE

[14] Air travel is assumed to be substituted by high-speed rail on existing or potential routes where trains can provide a similar travel time, and when demand is sufficiently large to enable economically viable operation, while new rail routes avoid water bodies and tunnelling through elevated terrains (IEA, 2021).

[15] Studies indicate that the provision of good public transport networks and access to ride-hailing services and shared mobility schemes can reduce ownership levels by 35%, with the biggest impacts on the ownership of multiple cars by the same household (IEA, 2021).

Scenario, not least because a stronger preference for smaller and lighter vehicles reduces the need for critical minerals for batteries, easing the burden on supply chains as they scale up to meet rapidly increasing EV demand (see section 3.10).

Figure 3.21 ▷ Energy consumption per capita in the NZE Scenario and car sales and SUV share in the STEPS and NZE Scenario, 2030



Behavioural changes in the NZE reduce emissions and make per capita energy consumption more equitable by tackling excessive energy consumption such as SUVs

Note: GJ = gigajoule; SUV = sport utility vehicle.

The behavioural changes in the NZE Scenario reflect regional differences in social norms and cultural values, as well as differences in geography, climate, urbanisation and the ability of existing infrastructure to support the changes. However, the speed and scale of behavioural changes is arguably more uncertain than that which characterises some other parts of the clean energy transition (for instance the deployment of solar PV, for which a clear trend has emerged in recent years). Consumer choices and habits often depend on trends that are hard to anticipate and can be subject to the influence of companies via marketing and advertising. In the NZE Scenario, governments introduce bold and consistent policies to encourage and make commercially viable those corporate strategies and business models which divert consumer demand away from wasteful or high-emitting consumption towards sustainable and low-emissions energy-related goods and services, for example by mandating the phasing out of frequent flyer programmes and promoting the implementation of similar schemes for rail travel. There would also be a role for policies to tackle activities linked to excessive and highly unequitable emissions, such as the use of private jets, which emit up to twenty-times more CO_2 than an average commercial flight for every passenger-kilometre flown (Mumbower and Sobieralski, 2022; Gössling and Humpe, 2020).

Box 3.4 ▷ Keeping the temperature rise below 1.5 °C: Role of diets

The NZE Scenario achieves net zero CO_2 emissions for the energy sector in 2050 without relying on offsets from other sectors. However, as about one-quarter of today's GHG emissions originate from outside the energy sector, mainly from agriculture, forestry and other land use (AFOLU), cutting these other emissions quickly is essential to have a reasonable chance of limiting the temperature rise to below 1.5 °C (IPCC, 2021).

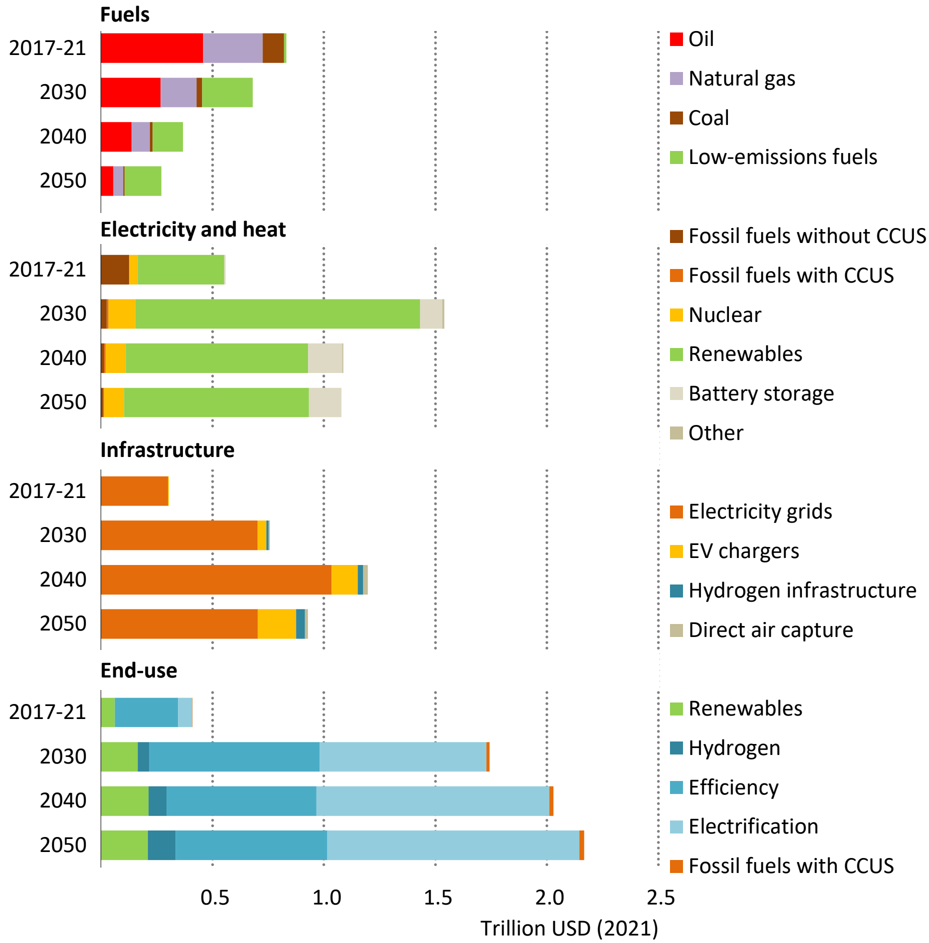
Around one-third of all food produced is currently wasted rather than eaten (WFP, 2020). It is not realistic to think that all food waste could be eliminated, but a significant reduction in food waste nevertheless could significantly reduce emissions from agriculture production. So could a move to healthier and more sustainable diets involving less meat, the global production of which has more than tripled since 1961, reaching around 340 Mt in 2018 (Ritchie and Roser, 2017). Plant-based foods tend to have a much smaller emissions footprint than meat: for example, the volume of GHG released per gramme of protein from peas is on average around 17-times less than for a gramme of protein from pork, and 110-times less than for beef (Ritchie and Roser, 2020). In collaboration with the International Institute for Applied Systems Analysis (IIASA), we have explored the possible consequences for GHG emissions of reducing food waste and shifting a portion of protein intake. We estimate that, if sustainable and healthy diets were adopted worldwide[16] and food waste halved, GHG emissions would be reduced by around 700 million tonnes of carbon-dioxide equivalent (Mt CO_2-eq) annually. Around 90% of this reduction would come from lower nitrous oxide and methane emissions in agriculture, with the remainder from reduced deforestation and the planting of new forests on agricultural land no longer needed for livestock feed production. About 240 million hectares (one-third the size of Australia) of pasture and cropland would be freed up, and fertiliser demand would be around one-fifth lower in 2050 than would otherwise be the case.

[16] This implies that animal calorie intake would not exceed 430 kilocalories per capita per day by 2030 following US Department of Agriculture recommendations for a healthy diet and that consumption in households with the highest levels of per capita consumption today would be reduced over time. Local societal and cultural preferences would determine what constitutes a so-called sustainable and healthy diet in different parts of the world.

3.9 What are the public and private investments needed to 2030?

The NZE Scenario requires a large increase in investment in clean energy. Energy investment accounted for just over 2% of global GDP annually between 2017 and 2021, and this rises to nearly 4% by 2030 in the NZE Scenario. This growth in investment is driven primarily by spending on clean energy technologies, which increases more than a factor of three over this period (Figure 3.22). Recent trends do not reflect the need for an increase of this magnitude: clean energy investment is expected to reach a record high in 2022 but this was only 25% larger than the 2017-21 average (IEA, 2022c).

Figure 3.22 ⊳ Global average annual energy investment by sector and technology in the NZE Scenario



Investment increases rapidly in electricity, infrastructure and end-use sectors; fossil fuel investments decrease and low-emissions fuel investments increase

Declining fossil fuel demand can be met in the NZE Scenario through continued investment in existing production assets without the need for any new long lead time projects. Annual spending on fossil fuels falls from its current level of around USD 830 billion to around USD 455 billion in 2030. This investment is needed to ensure that supply from existing fossil fuel projects does not fall faster than the decline in demand, and to reduce the emissions that occur along the supply chain. The rise in clean energy spending, including on low-emissions fuels, means that the share of fossil fuels in total energy investment falls from its current level of 35% to 10% in 2030.

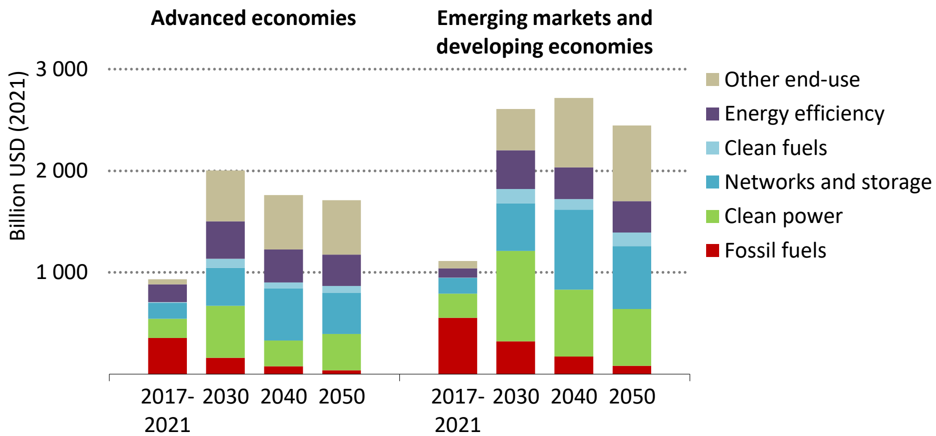
Investment in low-emissions fuels, including biofuels, low-emissions hydrogen and hydrogen-based fuels, increases from its current level of USD 18 billion to USD 235 billion in 2030. By 2050, low-emissions fuels account for over 65% of total investment in fuels, up from 1% in recent years.

Investment in electricity and infrastructure more than doubles, while investment in end-use sectors increase more than fourfold to 2030 in the NZE Scenario. Electricity generation from renewables sees one of the largest increases, rising from USD 390 billion today to around USD 1 300 billion by 2030. This level of spending in 2030 is equal to the highest level ever spent on fossil fuel supply (USD 1.3 trillion spent on fossil fuels in 2014). In order to support the increase in renewables deployment, spending on electricity grids increases from USD 320 billion today to just over USD 740 billion in 2030. Spending on renewables for use in buildings and industry increases nearly threefold to 2030.

Reaching net zero emissions requires an unprecedented acceleration in efficiency improvements and a significant reduction in energy intensity. In the NZE Scenario, this is achieved through the rapid electrification of transport, heating, cooling and industrial production and a massive wave of retrofits and spending on new energy-efficient buildings. As a result, the share of investment directed to energy efficiency and electrification moves from 17% of the total today to 32% in 2030 and 40% in 2050.

Investment trends vary significantly between countries and regions. The level of clean energy investment is at present significantly lower in emerging market and developing economies than it is in advanced economies. As a result, clean energy investment levels in emerging market and developing economies see a nearly fourfold increase by 2030 in the NZE Scenario, compared with a less than threefold increase in advanced economies (Figure 3.23). This dramatic growth is necessary to support economic development and industrialisation as well as provide access to electricity and clean cooking to the 774 million and 2.4 billion people respectively that still lack it. Investment also peaks later in emerging market and developing economies than in advanced economies as a result of the need to meet rising demand over a longer period.

Figure 3.23 ▷ **Energy investment trends by region in the NZE Scenario, 2017-2050**



Clean energy investment increases four-times in emerging market and developing economies by 2030 and less than three-times in advanced economies

Note: Other end-use includes investment in electrification and direct use of renewables or low-emissions technologies in end-use sectors.

Box 3.5 ▷ Sources of finance

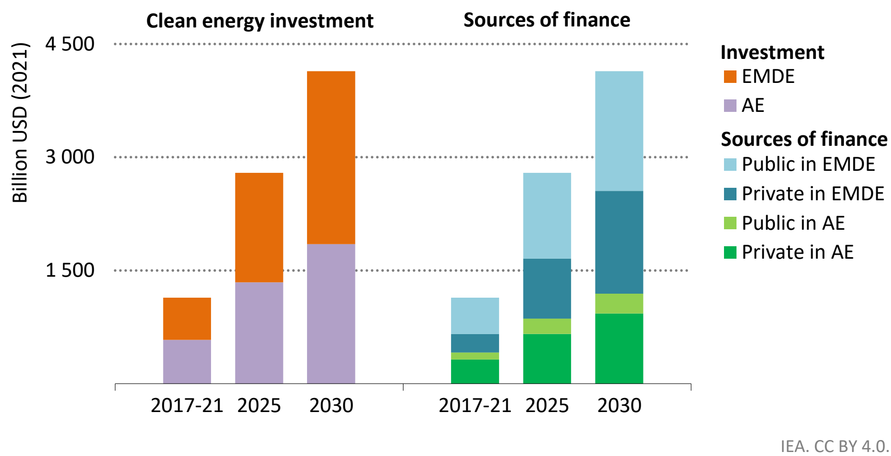
Financing the USD 4.2 trillion of clean energy investment needed in the NZE Scenario in 2030 will involve redirecting existing capital from fossil fuels towards clean energy technologies. However, that will not be enough on its own: there also needs to be a substantial increase in the overall level of investment in energy.

Private sources contribute around USD 3 trillion to clean energy investment in 2030 in the NZE Scenario (an over threefold increase from recent levels). This is mobilised by public policies that create incentives, set appropriate regulatory frameworks, and send market signals that unlock new business models. Reducing risks for investors will be essential to ensure successful and affordable clean energy transitions.

Public spending in clean energy technologies also rises, by slightly less than USD 800 billion from recent levels by 2030. This is needed to boost the development of new infrastructure projects, accelerate innovation in technologies that are in the demonstration or prototype phase today, and provide de-risking measures that mobilise private capital and reduce financing costs.

Public spending currently plays a larger role in emerging market and developing economies than elsewhere, accounting for nearly 60% of clean energy investment in recent years. In the NZE Scenario, policy reforms that ensure a pipeline of bankable projects, combined with an increase in targeted concessional public finance, help to reduce capital costs and incentivise private investors. By 2030, private capital accounts for nearly 60% of clean energy spending – behind the level of around 85% seen in advanced economies (Figure 3.24).

Figure 3.24 ▷ Clean energy investment and sources of finance in the NZE Scenario to 2030



Reaching the NZE Scenario investment levels requires a larger contribution from private finance than seen today, particularly in emerging market and developing economies

Note: AE = advanced economies, EMDE = emerging market and developing economies.

3.10 Can we ramp up low-emissions technologies fast enough?

The NZE Scenario requires an extraordinarily rapid deployment of clean energy technologies. The huge increase in their deployment in this scenario calls for rapid growth in the manufacturing of these technologies, as well as the production of essential material and mineral inputs. There are signs of recent progress, particularly in the case of those technologies that benefit from mass manufacturing and economies of scale, and many governments have committed during the current energy crisis to faster deployment of clean energy technologies. There is much more to do to reach the scale of deployment required by the NZE Scenario, however, and the next few years will be crucial.

In this section we examine current and announced production capacity and project pipelines for four clean energy technologies: batteries for transport, solar PV, electrolysers for hydrogen production, and CCUS. We also assess how projected production capacity and announced project pipelines match with the levels of deployment required in the NZE Scenario.

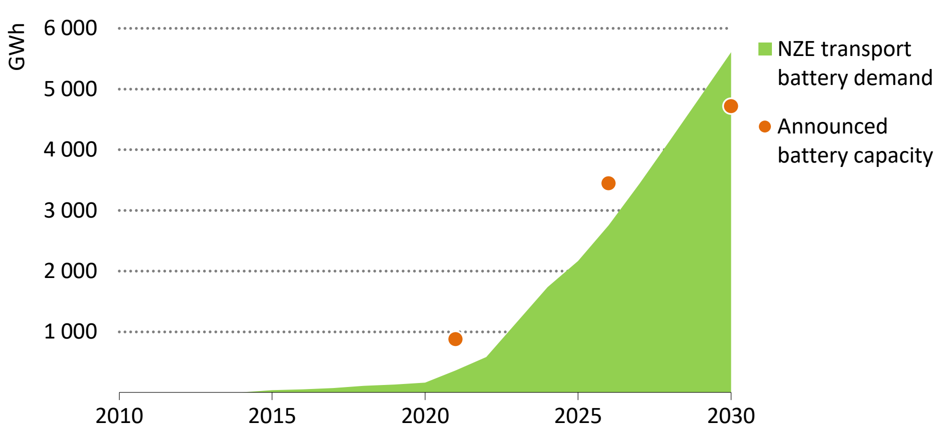
Batteries

Automotive lithium-ion battery demand was 340 gigawatt-hours (GWh) in 2021—more than twice the level in 2020. This increase was driven by the 120% increase in electric passenger car registrations in 2021. Battery demand for other transport modes, including medium- and heavy-duty trucks and two/three-wheelers, rose by more than 50%, less than the increase for passenger cars, but still huge.

China accounted for the largest share of global automotive battery demand in 2021 with almost 200 GWh of battery demand, up 140% from 2020. The United States saw demand more than double in 2021, albeit from a lower base. Demand growth in Europe was slightly slower than last year, but it still increased more than 70%. Prices for batteries have fallen by 86% over the last decade thanks to economies of scale and continuous innovation throughout the supply chain. Despite the recent commodity price surge, battery prices declined further in 2021, with the Bloomberg New Energy Finance annual battery price survey recording a 6% decrease from 2020. However, the impact of rising commodity prices has yet to fully materialise. If metal prices remain at the levels seen from January to September in 2022, then this could pose upward cost pressure on lithium-ion battery packs estimated at around 35% compared with 2021 levels.

Annual battery demand increases from 340 GWh in 2021 to 5 600 GWh by 2030 in the NZE Scenario. Battery demand is driven by electric cars which account for three-quarters of the projected total by 2030. Achieving such production levels requires the additional output of around 150 gigafactories of 35 GWh annual production capacity operating at full capacity.

Figure 3.25 ▷ Battery demand growth in transport in the NZE Scenario and announced battery manufacturing capacity expansion, 2010-2030



Announced battery manufacturing capacities for 2030 are close to – but still insufficient – to meet the surge in battery demand by 2030

Sources: IEA analysis and Benchmark Mineral Intelligence (2022).

However, the industry is well placed to respond to this surge in demand, having undertaken strategic early investments in battery plant capacity to prepare for projected demand growth (Figure 3.25). According to a recent study by Benchmark Mineral Intelligence, the battery production capacity announced by private companies for EVs in 2030 amounts to over 4 700 GWh (Benchmark Mineral Intelligence, 2022). This would be about 15% lower than the level of battery demand seen in the NZE Scenario in 2030. Battery production capacity will still be concentrated in China (70%), although more investments are now being planned in other regions, with a quarter of battery production capacity expected to be in Europe and the United States by 2030.

While battery production factories can be built in under two years, raw material extraction requires investment long before production reaches scale. Investments in new mines will need to increase quickly and significantly if supply is to keep up with the rapid pace of demand growth (Box 3.6).

There is scope for new investment to be supplemented by additional steps to minimise battery metals demand. Average battery sizes increased by 60% between 2015 and 2021, and – if current trends continue – they may increase by a further 45% by 2030. In the NZE Scenario, this trend is curbed by policies that discourage the production of vehicles with extremely large batteries, for example by linking purchasing incentives to vehicle weight. Robust deployment of such policies reduces battery demand by around 7% by 2030 in the NZE Scenario.

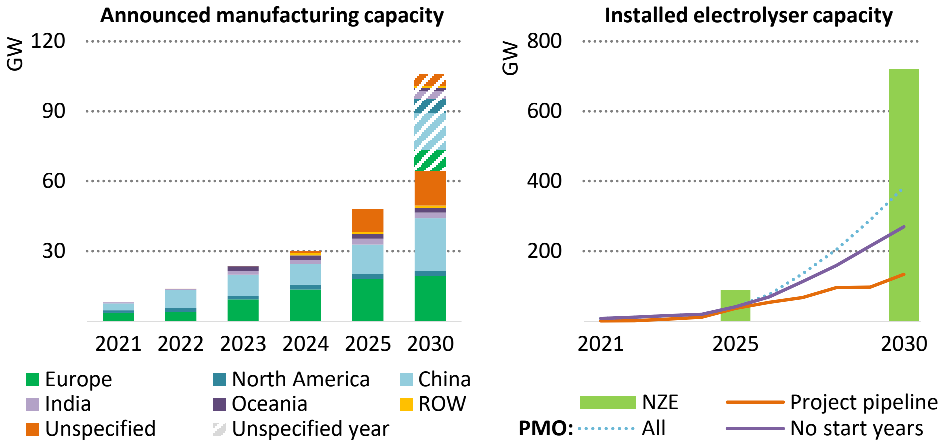
There is also scope for innovative battery chemistries to help minimise battery metals demand. Innovations are developed and commercialised more rapidly in the NZE Scenario than in the STEPS, and novel extraction and processing technologies are also brought forward. Moreover, if the current context of high commodity prices focusses innovation efforts on minimising the material footprint of batteries, preferences for battery chemistries could adapt accordingly, moving away from high-nickel cathode chemistries. In time, this could result in a further decrease in demand for key battery metals of around one-quarter compared to that in the NZE Scenario.

Electrolysers for hydrogen production

Almost all hydrogen today is produced from unabated fossil fuels. With global installed capacity of 510 megawatt (MW), electrolysers supplied only 0.1% of a total hydrogen demand of 94 Mt in 2021.

But now the industry is experiencing very dynamic growth (Figure 3.26). Global installed electrolyser capacity increased 70% in 2021, albeit from a low base. Around 460 electrolyser projects are currently under development. By the end of 2022, global installed capacity could reach 1.4 gigawatts (GW). By 2030, current capacity and announced projects would result in an installed capacity of around 134 GW. Taking into account more uncertain, very early stage projects, global installed capacity could reach 240 GW by 2030.

Figure 3.26 ⊳ Announced manufacturing capacity and installed electrolyser capacity projected on the basis of manufacturing capacity relative to the NZE Scenario, 2021-2030



Plans in the electrolyser industry are to ramp up hydrogen production very rapidly, but additional efforts are needed to reach the NZE Scenario 2030 level

Notes: PMO = Potential manufacturing output. Unspecified region includes manufacturing facilities for which the geographical location is unknown. Unspecified year includes manufacturing facilities for which the start year is unknown.

The prospects for a rapid scaling up of deployment are also reflected in the size of electrolyser projects. While the average plant size of new electrolysers starting operation in 2021 was 5 MW, the average size of new plants could be around 260 MW in 2025 and over 1 GW by 2030. Of the projects under construction or development today, 22 (5%) are above 1 GW.

Global demand reaches 180 Mt hydrogen by 2030 and 475 Mt hydrogen by 2050 in the NZE Scenario (of which 90 Mt in 2030 and 450 Mt in 2050 are low-emissions). Electrolysers meet a third of this demand in 2030 and 70% in 2050. This requires installed electrolyser capacity of 720 GW by 2030 and 3 670 GW by 2050. Electricity generation capacity is also needed to provide electricity for the electrolysers: over 1 000 GW of wind and solar PV are needed by 2030 for electrolytic hydrogen production in the NZE Scenario.

Alongside the expanding pipeline of projects for electrolysers, electrolyser manufacturers are already expanding their manufacturing capacity in anticipation of future growth. By 2030, global manufacturing capacity could reach 65 GW annually, and that could rise to 105 GW annually if plans with unknown start years are also taken into account. The cumulative output of projected manufacturing capacity with known start years would reach 270 GW by 2030 – an enormous increase over the current level of around 7 GW – but only a little more than one-third of the requirement in the NZE Scenario for 2030. Assuming that manufacturing capacity with an unknown start year becomes operational by 2030, the cumulative output could reach 380 GW, which is still little more than half of 2030 needs in the NZE Scenario.

Electrolysers also require minerals for their production, in particular nickel and platinum group metals, depending on the technology type. Key metal inputs for alkaline electrolysers are nickel (800 kilogramme per megawatt [kg/MW]), steel (10 000 kg/MW) and aluminium (500 kg/MW). With current metal prices, this results in costs of around USD 25 per kilowatt (kW), representing around 3.5% of total alkaline electrolyser costs. For proton exchange membrane (PEM) electrolysers, which use platinum (0.3 kg/MW) and iridium (0.7 kg/MW), the situation is somewhat different. Taking into account demands for steel, aluminium and titanium, the metal costs for PEM electrolysers, at USD 125/kW, currently account for around 12% of total electrolyser equipment costs, largely due to the cost of platinum and iridium. While it is hard to predict how future prices for these metals will evolve, efforts are underway to reduce the requirement for platinum group metals in PEM electrolysers. A reduction of specific iridium needs per MW by a factor of ten seems feasible in the next decade.

Solar PV

Solar PV provided over 3% of global electricity generation in 2021. Annual PV capacity additions reached 150 GW, making 2021 another record year. Of this, 95% was in the form of crystalline silicon modules, while thin-film PV technology accounted for the remainder.

Prices for PV modules have fallen by 80% over the last decade thanks to economies of scale and continuous innovation throughout the supply chain. As a result, solar PV has become the most affordable electricity generation technology in many parts of the world. In 2021, the average selling price of modules increased for the first time – by around 20% compared with 2020 – due to higher freight and commodity prices, in particular for polysilicon. While module prices remained at high levels in the first-half of 2022, continuous innovation to further improve material and energy efficiency is expected to drive further cost reductions.

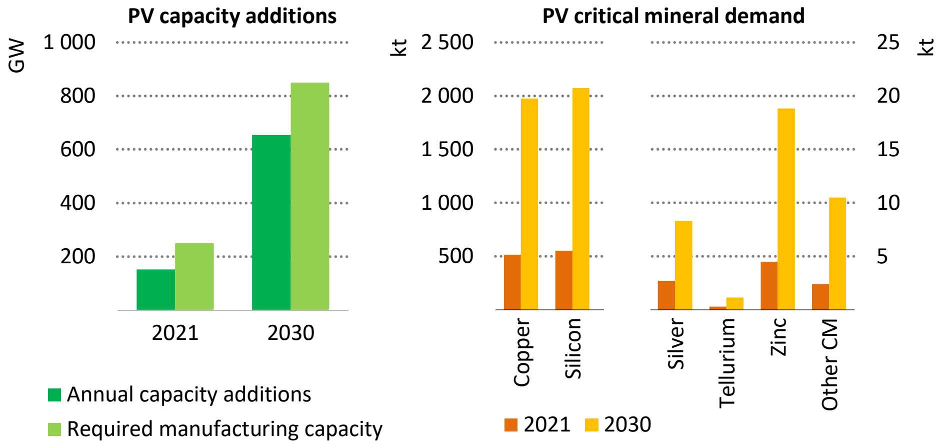
Raw materials account for 35-50% of the total cost of a solar PV module. For example, for crystalline silicon modules, silver and polysilicon together make up less than 5% of the module weight, but represent nearly two-thirds of material costs at 2021 prices. Material intensity improvements have already been realised in the past. For example, the polysilicon intensity for crystalline silicon modules was reduced by a factor of six between 2004 and 2020; silver intensity fell by one-third between 2009 and 2018. Further material intensity improvements are expected over the next decade, though at a slower pace.

Annual solar PV capacity additions more than quadruple from 150 GW in 2021 to 650 GW by 2030 in the NZE Scenario. Similar growth in relative terms has occurred in the past: solar PV capacity additions quadrupled in eight years from 37 GW in 2013 to 150 GW in 2021.

Global manufacturing capacity for solar PV modules stood at 250 GW in 2021. China dominates the global market today with a share of at least 80% across all steps of the supply chain. This share may soon rise further to 95% for polysilicon, ingot and wafer production (IEA, 2022d). Production capacity differs across the various parts of the PV supply chain. In

2021, there was much more capacity than needed for manufacturing wafers and cells (360 GW manufacturing capacity for wafers and 410 GW for cells), while polysilicon production capacity of 250 GW was the tightest along the supply chain: this meant that in effect it determined overall manufacturing capacity.

Figure 3.27 ▷ Solar PV capacity additions and mineral demand in the NZE Scenario, 2021 and 2030



Solar PV capacity additions expand by more than four-times from the 2021 level by 2030, while technology improvements mitigate growth in critical minerals demand

Note: kt = kilotonnes; CM = critical minerals.

To reach the deployment levels projected in the NZE Scenario, overall production capacities need to expand for the entire value chain to reach manufacturing capacity of more than 800 GW by 2030 (Figure 3.27). Taking into account expected manufacturing capacity additions of 150 GW, global polysilicon production capacity could reach 400 GW by the end of 2022, which is roughly half of the manufacturing capacity needed by 2030 in the NZE Scenario. Significant further manufacturing capacity additions are needed in the years to 2030 if deployment is to increase to the levels projected in the NZE Scenario. Estimates suggest that announced expansion plans could reach the levels of deployment seen in the NZE Scenario, although there is much uncertainty surrounding these announcements.

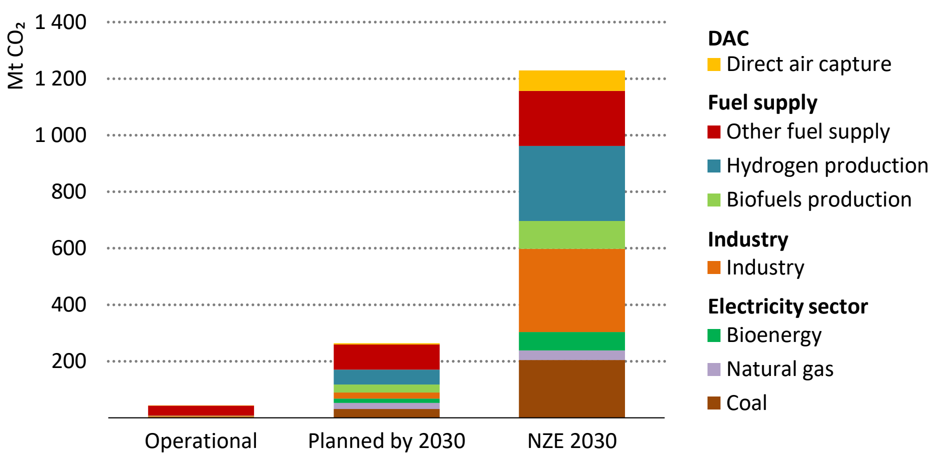
Material supplies will need to expand as well. In 2021, solar PV demand accounted for 11% of global silver production, over 6% of metallurgical-grade silicon and over 40% of all refined tellurium. In the NZE Scenario, demand for critical materials rises by 200-300% by 2030 compared to 2021, depending on the material. For silver, for example, this means that demand for solar PV manufacturing triples between 2021 and 2030, reaching levels in 2030 equivalent to 35% of global silver production in 2021, despite a projected one-quarter decline in silver intensity.

CCUS technologies

A rapid acceleration in the deployment of carbon capture, utilisation and storage is needed in the NZE Scenario to deliver deep emissions reductions across the industry, power and fuel transformation sectors and to remove CO_2 from the atmosphere through direct air capture (DAC) and bioenergy equipped with CCUS (BECCS).

Around 35 commercial CCUS facilities are in operation today with the collective capacity to capture almost 45 Mt CO_2 each year. This needs to increase to 1.2 Gt per year in 2030 and 6.2 Gt per year in 2050 in the NZE Scenario. In 2030, annual CO_2 capture from both new construction and retrofits amounts to around 270 Mt from hydrogen production, 300 Mt from coal-, gas- and biomass-fired power plants, and 300 Mt from industrial facilities, e.g. cement, steel, chemicals. On average, the NZE Scenario requires more than ten new CCUS-equipped facilities to be commissioned each month between now and 2030.

Figure 3.28 ▷ Global CO_2 capture by operating and planned source relative to the NZE Scenario, 2030



Despite the progress being made on CCUS, currently planned capacity for 2030 represents just 20% of the CCUS required in the NZE Scenario

Note: DAC = direct air capture.

Recent momentum provides cause for optimism that the next decade will see meaningful progress in deploying CCUS technologies. In 2021, governments around the world announced initiatives with around USD 20 billion in new funds specifically targeting CCUS, and further funds have been announced in 2022. The US Infrastructure Investment and Jobs Act provides approximately USD 12 billion across the CCUS value chain over the next five years and the US Inflation Reduction Act expanded the existing 45Q tax credit.[17] The 2022

[17] Section 45Q of the US Internal Revenue Code provides a tax credit for certain types of CO_2 use and for CO_2 injected for enhanced oil recovery or permanent geological storage.

federal budget in Canada introduced an investment tax credit for CCUS projects from 2022 to 2030 that covers industrial CCUS applications, hydrogen and DAC projects. In Europe, countries continued competitive funding opportunities for CCUS projects through regional funding programmes, such as the Connecting Europe Facility and the Innovation Fund, as well as national subsidy schemes, such as those in Denmark and the SDE++ in the Netherlands.

Driven by net zero emissions commitments, policy progress and an improved investment environment, the number of planned CCUS facilities has increased more than ninefold since 2018, when only around 30 new facilities were in the early stages of development. Plans for more than 130 new CCUS facilities were announced in 2021, and a total of 260 facilities are now in various stages of planning and development worldwide. If all of these projects proceed to operation, around 260 Mt CO_2 would be captured in 2030 (Figure 3.28). This represents a sixfold increase on current deployment yet only around 20% of what is required in the NZE Scenario.

Interest in capturing CO_2 directly from the atmosphere is expanding as governments and industry look for ways to meet their net zero emissions commitments. Since the start of 2020, almost USD 5 billion in public funding has been earmarked for DAC technologies, including USD 3.5 billion to establish DAC hubs in the United States, while leading DAC technology providers have raised over USD 1 billion in private capital.

DAC technologies play a growing role in the NZE Scenario, capturing around 70 Mt CO_2 in 2030 and around 600 Mt CO_2 in 2050. Their ability to capture CO_2 from the atmosphere that can then be permanently stored gives carbon dioxide removal technologies like DACS and BECCS a vital role in balancing emissions that are difficult to avoid. An alternative to permanent storage is for CO_2 captured by DAC or from BECC technologies to be used as a climate-neutral feedstock for a range of products that require a source of carbon, including synthetic aviation fuels. In the NZE Scenario, over 85% of BECC and DAC CO_2 is permanently stored, and under 15% is used as feedstock.

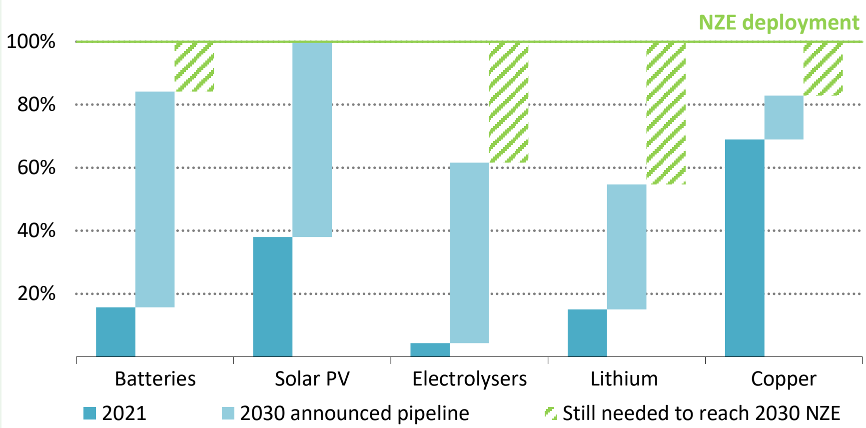
The 18 DAC plants currently operating worldwide are all small scale, with a combined CO_2 capture capacity of less than 0.01 Mt CO_2 per year. The first large-scale DAC plant of up to 1 Mt CO_2 per year is in advanced development and is expected to be operating in the United States by the mid-2020s. Plans for a total of 11 facilities are now in development, including in North America, Norway and the United Kingdom. If all planned projects go ahead, DAC deployment could reach more than 5 Mt CO_2 by 2030.[18] This is around 700-times today's capture rate, yet only less than 10% of the level projected in the NZE Scenario in 2030.

[18] This does not include a recent announcement by companies 1PointFive and Carbon Engineering to deploy 70 DAC facilities (each with a capture capacity of up to 1 Mt CO_2 per year) by 2035, which could significantly increase DAC deployment plans.

Box 3.6 ▷ Scaling up supply chains across sectors and regions

This section highlights the prospects for a rapid scaling-up of a number of clean technology supply chains, while also drawing attention to the gaps that need to be bridged to reach the levels of deployment seen in the NZE Scenario. Some clean technology value chains have announced expansion plans which would see them get close to the level of deployment in the NZE Scenario by 2030: the main examples are batteries and solar PV (Figure 3.29). Some are slated to see huge expansion, but still fall short of the required level by 2030: these include electrolysers.

Figure 3.29 ▷ Production or throughput capacity in 2021, assuming full implementation of announced project pipelines and NZE Scenario deployment levels in 2030



IEA. CC BY 4.0.

A number of clean technology value chains have announced supply capacity that approaches the level required in the NZE Scenario by 2030

Note: This figure assumes full implementation of announced project pipelines, including speculative projects. For all technologies, the figure shows annual production capacity in 2030 relative to the level of annual demand or capacity addition in the NZE in the same year.

Clean technology supply chains need to be developed with diversity, co-ordination and efficiency in mind:

- **Diversity:** Currently, many clean technology supply chains are geographically concentrated, particularly in China. For example, 75% of global production capacity for battery cells is located in China, and as much as 97% of global capacity for wafer manufacturing for PV cells (with around 14% of global wafer production taking place in a single Chinese factory). Such concentration raises the risks of supply chain disruptions. Maintaining the economic efficiency benefits of trade while diversifying supply chains will be critical to accelerate clean energy transitions.

- **Co-ordination:** Clean energy technologies are delivered via highly complex supply chains with numerous inputs and manufacturing steps. While some parts of the chain are moving ahead almost in line with the NZE Scenario, others are lagging. For example, while almost 85% of the battery manufacturing capacity needed in the NZE Scenario in 2030 is already in place or in the pipeline, the lithium supply chain faces a much bigger stretch. Announced capacity expansions and potential new projects would increase current production capacity three-and-a-half-times, but another tripling of current capacity would be required to meet the level seen in the NZE Scenario in 2030. Similarly, even though announced solar PV capacity growth is essentially sufficient to meet the NZE Scenario demand in 2030, achieving this rate of capacity additions may face bottlenecks on issues such as land acquisition, grid connections (notable also in the context of the projected shortfall in copper supply), and secure grid integration of this variable renewable energy source.
- **Efficiency:** A focus on supply chains does not imply that all solutions to bottlenecks must come from supply. For example, while current and announced production capacity for copper might be able to cover around 80% of the projected demand in the NZE Scenario, meeting the additional demand could be very challenging given the long lead times of projects and depletion of those reserves that are easiest to exploit. In such cases, measures to enhance recycling, reduce material use where possible and accelerate the deployment of substitutes could reduce pressure on the supply side to meet the huge increase in demand seen in the NZE Scenario.

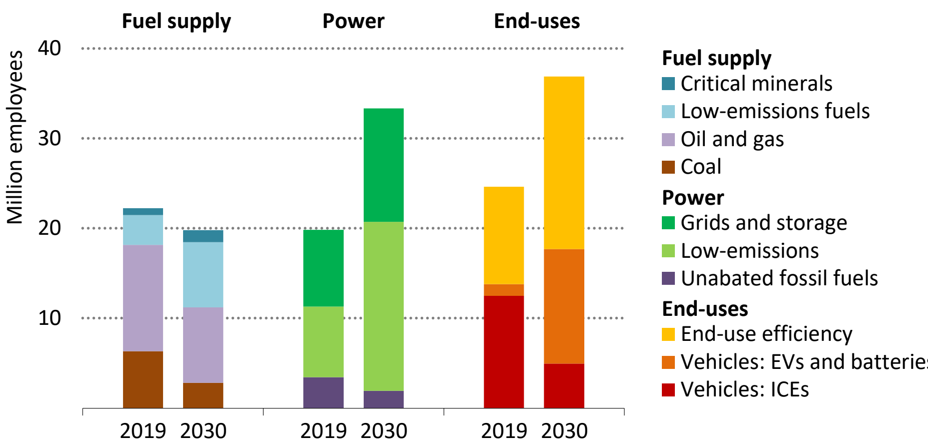
The complexity of – and current tensions in – global clean energy supply chains is one reason that the IEA is placing increased focus on this issue, which will be at the heart of the next *Energy Technology Perspectives* report forthcoming in 2023.

3.11 Energy employment: an opportunity and a bottleneck in the NZE Scenario

Rapid expansion of clean energy technologies in the NZE Scenario is accompanied by a commensurate expansion of the energy sector workforce. Energy sector employment increases from just over 65 million today to 90 million in 2030, taking into account both direct jobs in energy sectors and indirect jobs in the manufacturing of essential components for energy technologies and infrastructure. There are almost 40 million new jobs in clean energy by 2030, outweighing job losses in fossil fuel-related industries, and the share of energy sector employment related to clean energy increases from around half today to 80% by 2030. Achieving this growth in clean energy jobs within the decade will require strategic and proactive planning by industry, governments, and educational and training institutions in order to prevent shortages of skilled labour from becoming a bottleneck for energy transitions.

Despite some growth in bioenergy and hydrogen supply jobs, employment in the NZE Scenario shifts away from fuel supply and becomes more heavily concentrated in the power and end-use sectors (Figure 3.30). Fossil fuel supply jobs decrease by 7 million by 2030 in the NZE Scenario, with coal supply seeing the sharpest decline as mechanisation and decarbonisation efforts lead to further downsizing of the coal industry. Many skilled workers in the fossil fuel industry, in particular those in the oil and gas industries, have skills that are highly applicable to emerging clean energy sectors, though some will also still be needed to operate oil and gas assets that persist beyond 2030. Coal miners, particularly those in modern, mechanised mining operations, may have skills that would be useful in critical minerals production, although the scope for this transition may be limited by the relatively smaller volumes of minerals needed and by the different geographic locations of coal and mineral deposits. People-centred and just transitions policies will be vital to provide support for fossil fuel workers with limited transition prospects in energy or parallel industries.

Figure 3.30 ▷ Energy employment by technology in the NZE Scenario, 2019 and 2030



The share of energy sector employment related to clean energy increases from around half today to 80% by 2030

Note: EVs = electric vehicles; ICEs = internal combustion engines.

The power sector leads the way in the NZE Scenario in terms of job growth to 2030, with around 9 million additional jobs in power generation complemented by 4 million new jobs in power grids and electricity storage. Employment opportunities related to solar PV and wind power increase by around 10% each year to keep pace with steady growth in capacity additions, while power grids maintain 4% annual employment growth thanks to rising electrification rates and new investment in grid upgrades and expansion. Employment also increases substantially in vehicle manufacturing and in businesses concerned with improving the efficiency of equipment, industry and buildings.

In vehicle manufacturing, three-fifths of current jobs shift to EVs and their batteries. While EVs have fewer components and are less labour-intensive to assemble, additional jobs will be needed along the related battery supply chain, although they may not be in the same location as current manufacturing jobs. Efficiency improvements in the industry and buildings sectors require an additional 8 million workers to retrofit buildings, install more efficient heating and cooling and improve industrial process efficiency.

Energy sector employment spans several value chain segments.[19] Project construction and manufacturing are of particular importance for the delivery of new energy infrastructure, seeing the creation of over 10 million new jobs by 2030 in the NZE Scenario. Construction jobs are typically located where new projects are deployed. By contrast, manufacturing jobs are currently concentrated in the Asia Pacific region, where active industrial policies and well-established manufacturing competitiveness are enabling the emergence of significant clean energy manufacturing hubs that supply projects worldwide (IEA, 2022e). However, several countries including the United States and India are making efforts to bring critical supply chains onshore as they accelerate clean energy investment, and others may follow suit. The global distribution of manufacturing job gains in the coming decade depends on how countries balance diversity, resilience and affordability as clean technology supply chains develop and grow.

Shortages of skilled labour in clean energy construction projects are already starting to be seen, underlining the importance of strategic and proactive labour policies to build the workforce needed for the rapid expansion of clean energy technologies. Training and reskilling take time, and close collaboration between governments, companies, labour organisations, academia and training institutions would help to prevent hiring bottlenecks. Those with jobs that are edged out as decarbonisation proceeds should be offered retraining to enable them to work in fast growing low-emissions sectors of the economy. Efforts to improve the quality, inclusivity and wages of clean energy jobs would help to attract more workers, as would recognised qualifications or the certification of skills tailored to particular clean technology sectors.

[19] As grouped in the ISIC International Standard Industrial Classification revision 4 structure: https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf.

PART C

KEY ENERGY TRENDS

Part C of the World Energy Outlook takes an in-depth look at the impact of the current energy crisis and how policy responses and technology and investment choices may change the future of energy. It does this for all energy sources, sectors and regions to 2050, using the most up-to-date data. It also provides some guidelines for policy makers and other stakeholders that can help to safeguard energy security in an era of rapid change.

These chapters utilise scenario analysis to explore various potential pathways that the energy sector could take, how they may be achieved, and what may be the implications for energy security, energy demand and electricity, oil, gas, and coal markets as well as for low-emissions fuels.

OVERVIEW BY CHAPTER

Chapter 4 presents ten elements of a pragmatic agenda to ensure energy security during clean energy transitions and covers a range of risks that may arise. It includes traditional energy security concerns as the global energy sector evolves as well as new vulnerabilities that may emerge, and highlights the policies and approaches that can mitigate these risks.

Chapter 5 examines the outlook for energy demand. Alongside updated projections by scenario, it examines in detail the outlook for energy access as well as the increasing demand for space cooling. In addition, it details the prospects for oil use in road transport in light of the rapid rise in electric vehicles.

Chapter 6 focusses on the power sector. It looks in depth at the importance of system flexibility for electricity security, the essential role of networks to accelerate emissions reductions from electricity generation, and the increasing needs of critical minerals for clean electricity systems.

Chapter 7 assesses the outlook for liquid fuels. It looks in detail at the use of oil in plastics, the extent to which new conventional oil projects are needed to balance oil markets in the scenarios, and the immediate and longer term challenges facing the refining sector.

Chapter 8 tackles the outlook for gaseous fuels. It considers in detail the current crisis and its potential impacts on domestic production and on pipeline and LNG flows in Europe and beyond. It also considers the prospects for low-emissions hydrogen, and the future role of natural gas in emerging market and developing economies in Asia.

Chapter 9 explores the outlook for solid fuels. It highlights some key findings of the updated projections for coal and solid bioenergy as a precursor to the forthcoming *World Energy Outlook Special Report, Coal in the Global Net Zero Transition.*

Energy security in energy transitions

A pragmatic agenda for secure and rapid change

S U M M A R Y

- High and volatile fossil fuel prices in the wake of Russia's invasion of Ukraine underscore the risks inherent in today's energy system and the importance of energy security to our economies and daily lives. Energy transitions offer the chance to build a safer and more sustainable energy system that reduces exposure to fuel price volatility and brings down energy bills, but there is no guarantee that the journey will be a smooth one. Traditional security threats remain, even as new potential vulnerabilities emerge. This chapter proposes the following **ten guidelines** to help buttress energy security in the "mid-transition", when the clean energy and fossil fuel systems co-exist and are both required to deliver reliable energy services.
- **Synchronise scaling up a range of clean energy technologies with scaling back of fossil fuels.** Investing in clean energy is key to avoid future crises while reducing emissions. In the Net Zero Emissions by 2050 (NZE) Scenario, around USD 9 is spent on clean energy by 2030 for every USD 1 spent on fossil fuels. Cutting investment in fossil fuels ahead of scaling up investment in clean energy pushes up prices but does not necessarily advance secure transitions. High fossil fuel prices could make it 10-25% more expensive for fossil fuel importers to meet climate goals.
- **Tackle the demand side and prioritise energy efficiency**. The energy crisis highlights the crucial role of energy efficiency and behavioural measures in helping to avoid mismatches between demand and supply. Since 2000, efficiency measures have reduced unit energy consumption significantly, but the pace of improvement has slowed in recent years. Policies that accelerate the rate of retrofits are crucial as over half of the buildings that will be in use in 2050 have already been built.
- **Reverse the slide into energy poverty and give poor communities a lift into the new energy economy**. As a result of the pandemic and the energy crisis, 75 million people have lost the ability to pay for extended electricity services and 100 million for clean cooking solutions. In emerging market and developing economies, the poorest households consume nine-times less energy than the wealthiest but spend a far greater proportion of their income on energy. Turning these worsening energy poverty trends around is essential for secure, people-centred energy transitions.
- **Collaborate to bring down the cost of capital in emerging market and developing economies.** The cost of capital for a solar photovoltaics (PV) plant in 2021 in key emerging economies was between two- and three-times higher than in advanced economies and China. Tackling related risks and lowering the cost of capital in emerging and developing economies by 200 basis points reduces the cumulative financing costs of getting to net zero emissions by USD 15 trillion through to 2050.

- **Manage the retirement and reuse of existing infrastructure carefully.** Some parts of the existing fossil fuel infrastructure perform functions that will remain critical for some time, even in rapid energy transitions. They include gas-fired plants for electricity security - in the European Union peak requirements for natural gas rise to 2030 even as overall demand goes down by 50% - or refineries to fuel the residual internal combustion engine car fleet. Unplanned or premature retirement of this infrastructure can have negative consequences for energy security.
- **Tackle the specific risks facing producer economies**. Diversification will be crucial to mitigate risks. Some countries are investing part of their current windfall oil and gas profits in renewables and low-emissions hydrogen. Potential export earnings from hydrogen are no substitute for those from oil and gas, but low cost renewables and carbon capture, storage and utilisation (CCUS) can provide a durable source of economic advantage by attracting investment in energy-intensive sectors.
- **Invest in flexibility – a new watchword for electricity security.** Reliable electricity is central to transitions as its share in final consumption rises from 20% today to 40% in the Announced Pledges Scenario (APS) in 2050 and 50% in the NZE Scenario. Increasing variability in electricity supply and demand means that the requirement for flexibility quadruples by mid-century in both scenarios. Battery storage and demand-side response become increasingly important, each providing a quarter of the flexibility needs in 2050 in the APS.
- **Ensure diverse and resilient clean energy supply chains**. Mineral demand for clean energy technologies is set to quadruple by 2050 in both the APS and NZE Scenario, with annual revenues reaching USD 400 billion. High and volatile critical mineral prices and highly concentrated supply chains could delay energy transitions or make them more costly. Minimising this risk requires action to scale up and diversify supplies alongside recycling and other measures to moderate demand growth.
- **Foster the climate resilience of energy infrastructure**. The growing frequency and intensity of extreme weather events presents major risks to the security of energy supplies. IEA analysis of the risks facing four illustrative assets shows that the potential financial impact from flooding could amount to 1.2% of their total asset value in 2050, and in one case would be four-times higher than this without flood defences in place. Governments need to anticipate the risks and ensure that energy systems have the ability to absorb and recover from adverse climate impacts.
- **Provide strategic direction and address market failures, but do not dismantle markets.** Governments need to take the lead in ensuring secure energy transitions by tackling market distortions – notably fossil fuel subsidies – as well as correcting for market failures. However, transitions are unlikely to be efficient if they are managed on a top-down basis alone. Governments need to harness the vast resources of markets and incentivise private actors to play their part. Some 70% of the investments required in transitions need to come from private sources.

10 guidelines for secure energy transitions

Clean energy investment and energy efficiency are key to a secure exit from today's crisis

1. Synchronise scaling up a range of clean energy technologies with scaling back of fossil fuels
2. Tackle the demand side and prioritise energy efficiency

Global energy security cannot be achieved without everyone on board

3. Reverse the slide into energy poverty and give poor communities a lift into the new energy economy
4. Collaborate to bring down the cost of capital in emerging market and developing economies

The transition away from oil and gas needs to be handled with care

5. Manage the retirement and reuse of existing infrastructure carefully, some of it will be essential for a secure journey to net zero
6. Tackle the specific risks facing producer economies

New vulnerabilities emerge as the world builds a new clean energy system

7. Invest in flexibility, a new watchword for electricity security
8. Ensure diverse and resilient clean energy supply chains
9. Foster the climate resilience of energy infrastructure

Governments have to take the lead, but cost-effective transitions also need well-functioning markets

10. Provide strategic direction and address market failures, but do not dismantle markets

Introduction

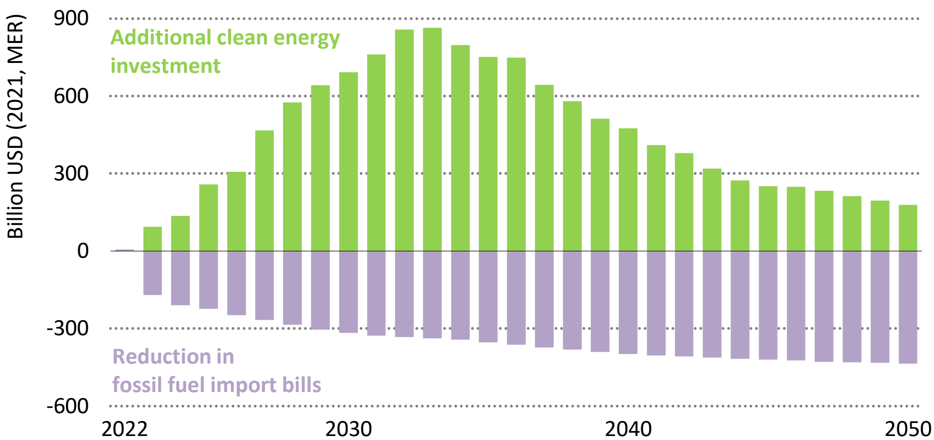
Energy security is not just about having uninterrupted access to energy, but also about securing energy supplies at an affordable price. It is a topic of perennial importance, and is once again high on the policy agenda as a result of the global energy crisis sparked by Russia's invasion of Ukraine. The surge in energy prices has been on a large enough scale to worsen considerably the global economic outlook, causing difficulties for households and industrial operations alike, and leading many governments to recalibrate their policy priorities (see Chapter 2, Box 2.4).

The immediate policy focus is understandably on dealing with the impacts of high energy prices on consumers and coping with the disruption of energy supplies. Many countries are taking action to: make the most of existing power plants, e.g. Japan's restart of nuclear reactors; diversify sources of supply, e.g. European imports of liquefied natural gas (LNG); accelerate the deployment of clean energy technologies, e.g. through the European Union REPowerEU Plan and the US Inflation Reduction Act; or enact programmes to protect consumers from high prices, e.g. by setting price caps, expanding targeted support or cutting fuel taxes. In some cases, actions have involved trade-offs between short-term security benefits and emissions reduction goals, for example when relying more on coal-fired power plants for electricity generation.

Nonetheless, the need to move towards net zero emissions to ward off catastrophic climate change remains as important as ever. In the **Net Zero Emissions by 2050** (NZE) **Scenario**, traditional risks surrounding oil and gas supplies ease as demand for fossil fuels falls, but they do not vanish. Huge additional investments are required to scale up clean energy provision, and they are accompanied by large reductions in fossil fuel import bills in many regions (Figure 4.1). Efficiency gains also mean that household energy bills in 2030 in this scenario are also lower than in the **Stated Policies Scenario** (STEPS). As highlighted in the *IEA 10-Point Plan to Reduce the European Union Reliance on Russian Natural Gas*, moving towards a more sustainable energy system provides a clear answer to predicaments such as the current crisis (IEA, 2022a).

While achieving net zero emissions goals ultimately brings energy security benefits, it should not be taken for granted that pathways to get there will be smooth. Energy transitions require adding new clean energy infrastructure while reducing reliance on existing carbon emitting infrastructure, and managing the co-existence of these systems is challenging (Grubert and Hastings-Simon, 2022). Nor should it be assumed that there will be no new energy security risks in a net zero emissions world. New areas of concern may emerge as massive deployment of clean energy technologies puts strains on supply chains, notably for critical minerals, while a reorientation of global energy trade flows could bring about new geopolitical tensions. Rising reliance on electricity generated from variable renewables calls for an ever higher degree of power system flexibility that could pose risks if not carefully managed. A lack of preparation for the challenges stemming from a changing climate, inadequate energy systems resilience and looming cyber threats could expose consumers to more frequent supply disruptions and price spikes.

Figure 4.1 ▷ **Clean energy investment and reduction in fossil fuel import bills in developing economies in Asia in the NZE Scenario relative to the STEPS**



Significant additional investment in clean energy is required in the NZE Scenario, but this delivers steadily lower import bills over time

Note: NZE = Net Zero Emissions by 2050 Scenario; STEPS = Stated Policies Scenario; MER = market exchange rate.

The need to look at a broad range of energy security issues during energy transitions was a core pillar of new mandates given to the IEA at its Ministerial meeting in March 2022. The Ministerial Communiqué recognised the need for the IEA to remain vigilant in an increasingly complex energy security environment. Building on core principles, notably the benefits of diversified energy sources, supplies, routes and means of transport, the communiqué reflects on evolving security issues for oil, gas and electricity markets and infrastructure as well as new areas such as climate resilience, clean energy supply chains and critical minerals.

In this chapter, we present ten key elements of a pragmatic agenda to safeguard energy security during energy transitions. This agenda is not focused on the current energy crisis, although many of the items are relevant to it. Nor is it designed to provide a comprehensive overview of all aspects of energy security, although it covers a wide range of potential hazards. Rather, the intention is to explore specific energy security risks that arise as the world moves through a much needed transformation of the energy sector, and to examine policies and approaches that mitigate these risks. As such, we focus on how some traditional energy security concerns might evolve as we move through transitions and on new vulnerabilities that might emerge. The overarching aim is to map ways to avoid clean energy transitions running into problems that could lead to extreme price volatility, social disruptions, consumer discontent or supply chain bottlenecks.

Ten essentials for secure energy transitions

A major push on scaling up investment in clean energy technologies (section 4.1) and reducing demand and improving energy efficiency (section 4.2) are fundamental to achieving secure energy transitions, and also offer the lasting solutions to the immediate energy crisis. Energy transitions require an inclusive approach if they are to be secure. This means reversing the slide into energy poverty and giving poor communities a lift into the new energy economy (section 4.3). It also means avoiding the emergence of new dividing lines in energy by facilitating faster change in emerging market and developing economies. Collaborating to bring down the cost of capital in the developing world is essential to unlock timely, cost-effective clean energy investment (section 4.4).

The energy transition involves building a clean energy system while winding down existing fossil fuel supply and emissions, but some parts of the fossil fuel system remain vital for energy security, and there is a need to manage the retirement and reuse of existing infrastructure carefully (section 4.5). Producer economies that export oil or gas (and that rely heavily on hydrocarbon income) remain important to global energy security even as reliance on these fuels diminishes; their long-term stability requires that they diversify their economies and adapt their energy systems to the new market and policy environment (section 4.6).

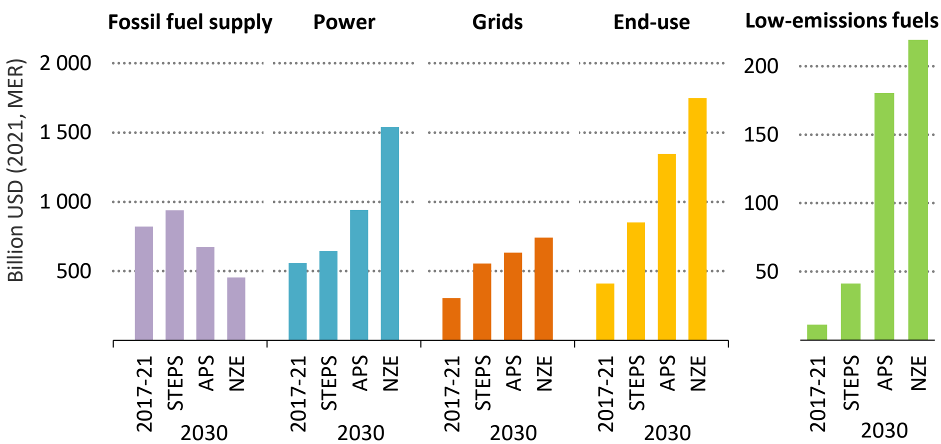
New vulnerabilities may also emerge as the world builds a new clean energy system. The increasing role of electricity in final consumption puts a premium on investing in system flexibility (section 4.7). Diverse and resilient clean energy supply chains, including those for critical minerals and metals, are essential to avoid costly or delayed energy transitions (section 4.8). Since the climate is already changing, both existing and new infrastructure will need to factor in climate resilience (section 4.9). All this implies a crucial role for governments, who are taking on increasingly expansive roles to accelerate transitions but also need to retain the benefits of competitive, reliable energy markets based on transparent rules (section 4.10).

4.1 Synchronise scaling up a range of clean energy technologies with scaling back of fossil fuels

> *Boosting investment in clean energy rather than new long lead time fossil fuel supply provides a more lasting solution to today's energy crisis while cutting emissions. Reductions in fossil fuel investment need to be sequenced carefully to avoid sharp spikes in fuel prices.*

The world has not been investing enough in energy. Since 2017, annual clean energy investment has averaged USD 1.2 trillion, well below the investment levels for clean energy seen in the STEPS in 2030, and annual investment in fossil fuels has averaged USD 0.8 trillion, similar to the investment levels that feature in the Announced Pledges Scenario (APS) in 2030 (Figure 4.2). In other words, recent investment levels in clean energy technologies have been far below what is needed to bring about a peak and decline in fossil fuel demand, yet investment in fossil fuel supply has been geared towards a world of stagnant or even declining demand for these fuels. This underlying mismatch has made the energy system more vulnerable to the sorts of shocks that came in 2022 with Russia's invasion of Ukraine.

Figure 4.2 ▷ Annual average investment in fossil fuel supply, clean power, infrastructure, end-uses and low-emissions fuels by scenario



IEA. CC BY 4.0.

The world is not investing enough in energy. Fossil fuel investment is geared to stagnant or falling demand, while clean energy investment is not rising fast enough.

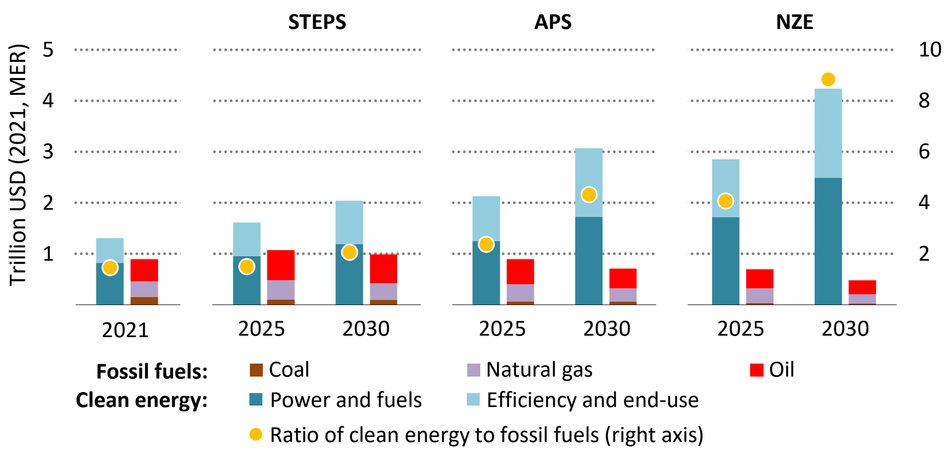
Note: MER = market exchange rate; APS = Announced Pledges Scenario.

In the STEPS, fossil fuel demand rises in the coming years, requiring new upstream conventional projects to avoid a shortfall in supply in the mid-2020s (see Chapter 7). In the APS, global demand for fossil fuels soon peaks and starts to decline. This means that there is less need for new conventional upstream projects, but some remain essential to ensure a smooth match between supply and demand by the late-2020s.

In the NZE Scenario, governments rapidly introduce policies to reduce emissions from existing fossil fuel infrastructure and to scale up investment in clean energy technologies by a factor of three by 2030. The clean energy investment surge in the NZE Scenario means that demand for fossil fuels declines with sufficient speed that it is possible to satisfy oil and gas demand without approving new long lead time upstream conventional projects, although continued investment in existing assets is still necessary (see Chapter 1). Annual fossil fuel investment in the NZE Scenario in 2030 falls to around USD 450 billion, half of the levels seen over the past five years. Reducing fossil fuel investment to these levels in advance of – or instead of – the threefold scale up in clean energy spending would not lead to the same outcomes as in the NZE Scenario. It would instead lead to high and volatile fossil fuel prices during energy transitions (Spotlight).

Russia's invasion of Ukraine could lead to a substantial and prolonged reduction in energy supplies from Russia, and any immediate shortfalls in fossil fuel production from Russia need to be replaced by production elsewhere, even in a world working towards net zero emissions by 2050. But governments looking to protect against the current disruption in energy markets can do so in ways that do not risk undermining or slowing the energy transition. A dramatic scaling up of energy efficiency and clean energy is key to lasting structural solutions to the energy crisis. It is also key to getting on track towards net zero emissions. Governments have a unique ability to act in this regard: they can provide strategic vision; policy signals; incentives for consumers; and public finance that catalyses private investment and can spur innovation.

Figure 4.3 ▷ Investment in clean energy and fossil fuels by scenario, 2025 and 2030



Around USD 9 is invested in clean energy for every USD 1 invested in fossil fuels in 2030 in the NZE Scenario

Note: MER = market exchange rate.

Reductions in fossil fuel investment need to be sequenced so they do not run ahead of the huge scaling up in clean energy technologies that is required to get to net zero emissions. Many companies and financial organisations have set goals and plans to scale down investment in fossil fuels, but it makes little sense to consider these in isolation: much more emphasis is needed on their goals and plans for the scaling-up of investment in clean energy technologies, and on what governments can do to incentivise this. For every USD 1 spent globally on fossil fuels in the NZE Scenario in 2030, USD 5 is spent on clean energy supply and another USD 4 on efficiency and end-use. (Figure 4.3). This provides a useful guideline for understanding the alignment of financial flows of investor and company portfolios with achieving net zero emissions globally by 2050.

Emissions from fossil fuel extraction, processing and transport account for more than 15% of energy-related greenhouse gas (GHG) emissions today and need to be minimised as quickly as possible. Reducing these emissions is also the primary way in which fossil fuel industries can limit the potential impact of future climate policies on their operations. Oil and natural gas with lower emissions intensities will be better positioned than higher emitting sources as clean energy transitions speed up, may incur lower tax burdens, and are likely to be increasingly preferred for continued production during transitions.

The extraordinary financial windfall for the oil and gas sector from today's high prices could provide a major boost to clean energy investment. Global net income from oil and gas production is anticipated to reach nearly USD 4 trillion in 2022, which is double the level in 2021. If the global oil and gas industry were to invest this additional income in low-emissions fuels, such as hydrogen and biofuels, it would fund all of the investment needed in these fuels for the remainder of this decade in the NZE Scenario. It would go even further if used to catalyse spending by both private and public sources on clean energy more broadly. For oil and gas producing economies, this could be a once-in-a-generation opportunity to diversify their economic structures to adapt to the new global energy economy that is emerging.

SPOTLIGHT

Do high fuel prices help or hinder the process of change?

Investment in clean energy technologies and fossil fuels in the NZE Scenario is calibrated to minimise stranded assets and avoid energy market volatility. Wholesale fossil fuel prices fall to low levels as they are increasingly set by the operating costs of the marginal project.[1] If supply were to transition faster than demand, with a drop in fossil fuel investment preceding a surge in clean energy technologies, this would lead to much higher prices – possibly for a prolonged period – even if the world is moving towards net zero emissions. There are parallels with the situation in markets today, and responses to the current crisis provide useful insights into what high fossil fuel prices could mean for energy transitions.

Economics: Increases in the prices of the most polluting fuels improve the economic advantages of cleaner alternatives (including energy efficiency measures). They act in a similar way to a carbon dioxide (CO_2) price in this respect.[2] The oil price increase between 2021 and the first six months of 2022 is equivalent to a USD 70 per tonne of CO_2 price on oil use; the natural gas price increase seen in Europe is equivalent to a price of USD 350/t CO_2. But high fossil fuel prices are no substitute for climate policies. Fuel prices

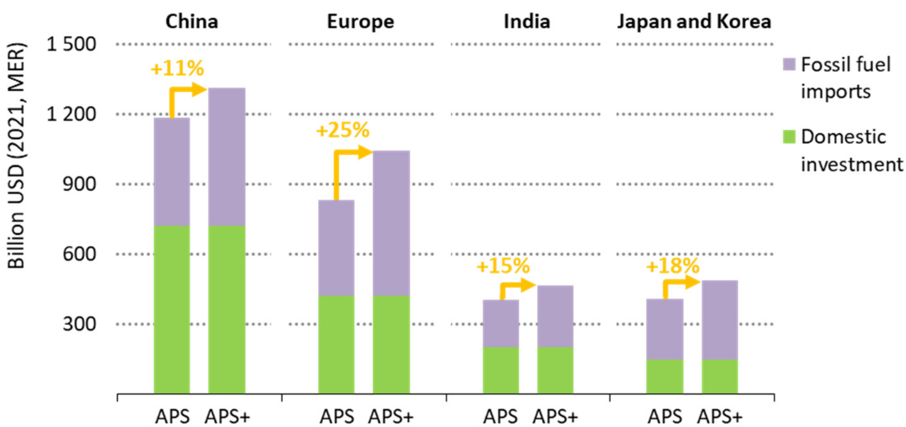
[1] Ongoing operating costs include the cost of extraction, extraction taxes, cost to reduce scope 1 and 2 emissions, and CO_2 taxes from any residual emissions.

[2] A key difference, however, is that the increased revenues from higher fossil fuel prices are collected by the producing country or company, while revenues from higher CO_2 prices are collected by the consuming country.

do not reflect the carbon content of the fuels and they can incentivise shifts towards more polluting fuels, e.g. from natural gas to coal. In response to the current crisis, for example, some countries have delayed planned coal power plant closures to reduce reliance on natural gas, and new investments in coal supply have been announced in China and India.

Political economy of transitions: Countries may see high fuel prices as a spur to accelerate transitions, as for example seen in the European Union REPowerEU Plan and the US Inflation Reduction Act, and a powerful boost to innovation, as happened during the 1970s oil price crises. However, high fuel prices also create the risk that affordability and security concerns reduce the attention and money that policy makers devote to emissions reductions. If importing countries end up spending much more on their fuel import bills, this could squeeze funding to support clean energy transitions (Figure 4.4). Fossil fuel exporters would receive windfalls as a result of such extra spending, but there is no guarantee that these would be a net boost for transitions. This might reinforce hydrocarbon-dependent development models rather than promote the need for reform.

Figure 4.4 ▷ Annual average investment and fossil fuel imports in the APS with projected prices and with high fossil fuel prices, 2021-30



High fossil fuel prices would squeeze funds available to support transitions and make it 10-25% more expensive for fossil fuel importers to achieve their climate targets

Notes: MER = market exchange rate. APS+ = APS with high fossil fuel prices, which assumes that countries reduce fossil fuel use and emissions in line with the APS, but with fossil fuel prices remaining around current levels (oil - USD 100/barrel; natural gas - USD 15-25 per million British thermal units; coal - USD 170-250 per tonne of coal equivalent).

Social implications: High fossil fuel prices are regressive and hit the poor hardest. They often lead to price interventions such as fossil fuel subsidies that are rarely well designed or targeted to the most vulnerable. This underlines the importance of ensuring that climate policies help poor households, including with the higher upfront costs of clean energy investments (such as efficiency and clean electrification). If climate policies do not do this, they risk being socially divisive, especially in a high price environment, with richer segments of the population able to adjust to changing circumstances and the poor left behind. This would make just transitions very difficult to achieve, and it would also risk undermining support for climate policies.

The net impact of high fossil fuel prices and policy changes made in response to the current energy crisis is to increase near-term emissions in the STEPS slightly compared with the projections in the *WEO-2021*. This demonstrates that while high prices can reduce demand and emissions, they will not necessarily do so, and should not be viewed as a viable or desirable substitute for climate policy.

4.2 Tackle the demand side and prioritise energy efficiency

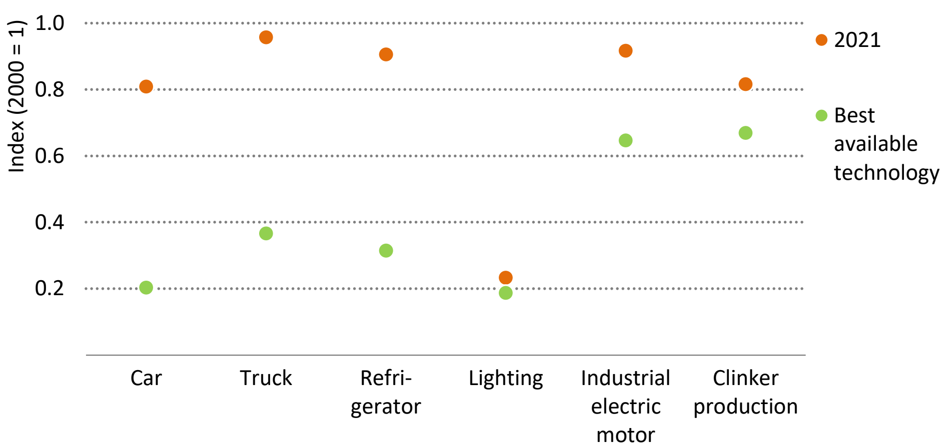
Efficiency is an indispensable tool for multiple policy aims, easing pressures on consumers and their vulnerability to high and volatile fuel prices, cutting reliance on fuel imports and driving progress towards climate goals while supporting jobs and growth.

The current energy crisis has put the spotlight on energy demand for both governments and the public, not least of all in Europe. By dampening energy demand, energy efficiency plays an indispensable role in lowering energy bills for households and businesses and shielding consumers from volatile fuel prices. It also brings energy security benefits, especially at a time when the world is moving towards a decarbonised energy system, by reducing strains on fuel markets and the need for costly and uncertain investments in new supply.

The uncertainties around long-term fossil fuel demand and supply-side fossil fuel investments mean that demand-side responses are now more important than ever to keep the energy system in balance. Today's tight oil product markets, especially for diesel and kerosene, provide a good example of the energy security gains from improved efficiency. Tight markets usually push up prices for these products and trigger investment in new refining capacity, which then stabilises price levels. Some new refining facilities are slated to be added in the coming years, most of which were planned well before the Covid-19 pandemic. However, with clean energy transitions posing uncertainty about long-term oil demand, further new investment might not take place as it has in the past. If demand for these products follows the trajectory in the STEPS, it could lead to tight supplies for many years to come. In the APS, however, planned new capacity additions in the next few years match the level of demand growth partly because more robust efforts on energy efficiency dampen demand (see Chapter 7, section 7.3).

In the 1970s, energy efficiency played a major role in the response to oil price shocks. Countries adopted a broad portfolio of efficiency policies that not only reduced demand but also spurred technology improvements in all end-use sectors, resulting in long-term efficiency gains. In the United States, for example, the average fuel consumption of new cars declined from 18 litres per 100 kilometres (km) in the early 1970s to 11 litres per 100 km ten years later. Building codes started to include energy targets/mandates during the crisis: France and New Zealand added mandatory insulation measures in 1974 and 1977 respectively, while in 1978 California paved the way for other US states with the introduction of minimum energy efficiency requirements for appliances. Since then, technology has continuously improved in all sectors, with notable demand reductions in the buildings sector for lighting and refrigeration (Figure 4.5). For example, the phase-out of incandescent light bulbs in almost all countries and the rapid uptake of light-emitting diodes (LEDs) (with payback periods of less than a year in most regions) means that the energy consumption for a light bulb used in 2021 was on average between four- to eight-times less than one used in 2000.

Figure 4.5 ▹ Unit energy consumption for selected equipment in 2021 relative to 2000



Thanks to energy efficiency, unit energy consumption has declined significantly since 2000, but there is plenty of scope to do more

Note: Unit energy consumption refers to: fuel economy for cars and heavy freight trucks measured in litres per kilometre travelled; annual electricity consumption for refrigerators in kilowatt-hours; lumens per watt for lighting; average efficiency of the electric motor fleet in industry; energy intensity of clinker production (a key component in cement and concrete).

Energy efficiency measures adopted since 2000 saved a total of 125 exajoules (EJ) up to 2021, or around 30% of current total final consumption. Around 45% of these savings are attributable to energy efficiency gains in industry, largely a result of strict minimum energy performance standards (MEPS) for electric motors. A further 35% of the savings were from transport, with the fuel economy of cars having improved by 20% since 2000 and of trucks by 5%. Electrification is rising rapidly in transport leading to additional efficiency gains. Almost all refrigerators, freezers and air conditioners are now subject to MEPS in advanced economies, which have contributed in a major way to improve energy efficiency in end-uses. Emerging market and developing economies are making progress with about 80% of refrigerators and air conditioners – a rapidly expanding end-use – covered by MEPS. Where in effect, these standards also had major impacts to reduce consumer energy bills compared to what they would have been without energy efficiency improvements.

Recently, however, the pace of efficiency improvements has slowed. Between 2017 and 2020, energy intensity has improved on average by 1% per year, down from 2.1% between 2011 and 2016 (IEA, 2022b). The rate of improvement further slowed to 0.5% in 2021. Reversing the trends seen over the past few years is key to ensuring secure energy supplies while reducing emissions. In the STEPS, energy intensity improves by 2% per year from 2021 to 2030, around twice the average rate achieved over the last two decades. In the APS, it improves by 3% per year.[3] By 2030, around 44 EJ (10% of total final consumption) is avoided in the STEPS due to energy efficiency and electrification measures. In the APS, this rises to 59 EJ (13% of total final consumption), with notable improvements in emerging market and developing economies.

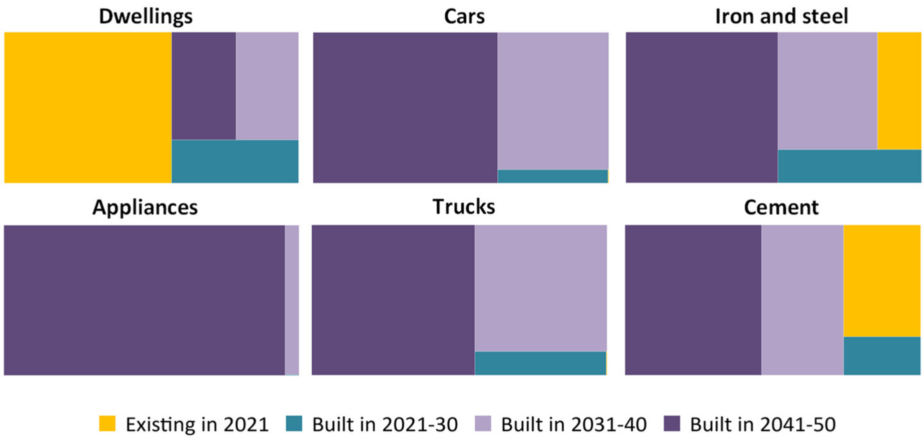
Stock turnover remains a primary challenge in improving energy efficiency across all end-uses (Figure 4.6). More than a third of the cars, trucks and heavy industrial facilities that will be in use in 2050 are expected to be added in the next two decades. So how these assets are made or built will have enduring implications for future energy intensity, CO_2 emissions and energy security. This underscores the value of effective policy interventions to ensure that energy efficiency is foundational in new assets. In addition, it is also necessary to take action to improve the energy efficiency of the existing stock, particularly in some key sectors. Buildings are a case in point, with some 55% of the buildings that will be in use in 2050 already in place. Recent IEA analysis of what works well has led to the identification of best practices that include putting in place "one-stop" renovation offices and free audit programmes (IEA, 2022c).

Behavioural measures also have an important part to play in tandem with energy efficiency measures, not least because they can make a significant impact in the short term. In response to a possible cut-off of Russian gas, European countries are implementing measures to encourage consumers to save energy. The IEA 10-Point Plans, published in the immediate aftermath of Russia's invasion of Ukraine, highlights energy efficiency and specific behaviour changes as key to reduce Europe's reliance on fossil fuel imports from Russia (IEA, 2022a; IEA, 2022d). Several of the IEA recommendations have found strong support in the European

[3] Energy intensity is calculated using GDP in purchasing power parity (PPP) terms to enable differences in price levels among countries to be taken into account. In the IEA scenarios, PPP factors are adjusted as developing countries become richer.

Union member states. For example, Germany, Belgium, Luxembourg and Denmark implemented regulations to accelerate replacement of natural gas boilers with heat pumps. Germany, Austria, France, Portugal, Ireland and Spain implemented measures to make public transport cheaper, in line with the IEA recommendation to reduce transport oil demand (IEA, 2022d).

Figure 4.6 ▷ Global stock by vintage for selected sectors, 2050



Efficiency policies over the next few years will play a crucial part in determining future energy intensity and GHG emissions

Finding ways to encourage energy users to change behaviour is not always easy, and what works in one place may not be effective in another, since cultural norms and consumption patterns vary widely. Nevertheless, there are many potential approaches and ample scope for well targeted messages and effective communication. Policy makers can learn from behavioural science and employ digital tools, nudges and incentives to stimulate energy saving behaviour.

Good communication is vital as consumers often have limited visibility about pressures on the system. For example, South Africa has provided real time information about electricity shortfalls via a "power alert" message, which is communicated via the internet and television between 17:30 and 20:30, to inform the public of immediate measures to reduce peak loads. Providing actionable data can help consumers take informed decisions. In California, for example, communication with citizens via apps, SMS and email is used to lower energy demand at peak times, when the system is under the most strain.

Setting energy saving defaults is also an effective way to encourage efficiency while minimising consumer resistance. For example, India has mandated a 24 °C default cooling temperature for all new air conditioners to reduce over cooling behaviour. Consumers can adjust the settings, but many stay at the default, leading to significant energy savings. Bringing all existing energy efficiency programmes and relevant subsidies under one administrative agency can help overcome inertia. Ireland's Reduce Your Use campaign and the UK Simple Energy Advice are cases in point. Both offer a clear list of existing grants, incentives and tax rebates in one place (IEA, 2022e).

An energy crisis provides an opportunity to ramp up and take new actions to prompt energy efficiency and behavioural changes. Experience in Japan suggests that such actions can yield sustained benefits. A combination of public awareness campaigns and technical assistance programmes in the aftermath of a devastating earthquake in 2011 reduced peak electricity demand that summer by 15% compared with the previous year. Thanks to the continued focus on energy efficiency, this reduction has largely been sustained to date. Electricity demand has stayed below pre-earthquake levels which helped avoid outages when there were strains on the electricity system.

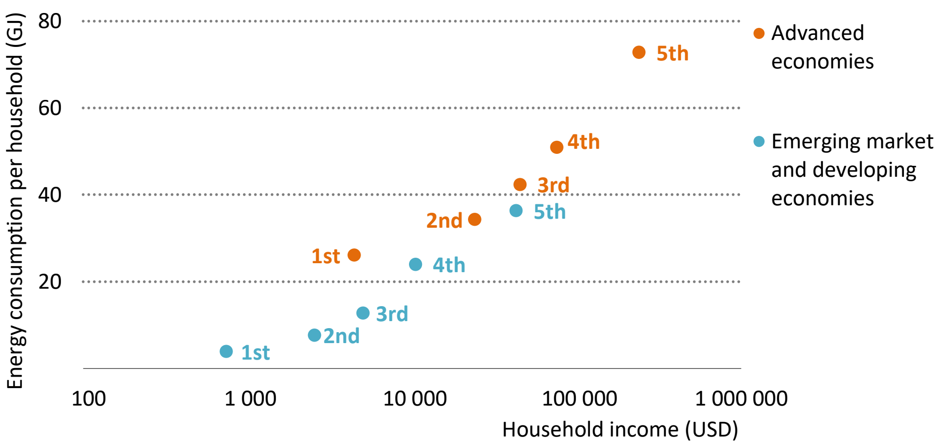
4.3 Reverse the slide into energy poverty and give poor communities a lift into the new energy economy

As a result of soaring energy prices, millions of people risk losing the most fundamental form of energy security by becoming unable to afford basic energy services. Targeted policy support is vital to ensure that disadvantaged and vulnerable communities have improved access to affordable, secure and sustainable modern energy.

The surge in energy prices has put a disproportionate burden on low income households and exacerbated energy insecurity. As a global average, households typically spend around 7% of income on energy, half for energy used in the home for a variety of end-uses such as heating, cooling, lighting and cooking. However, this does not capture the reality that poor households spend a far higher share of their income on energy than wealthy ones, even though the poorer ones consume less energy. New IEA analysis for this *Outlook* finds that the lowest quintile of households by income in advanced economies consume on average just a third of the energy used in households in the highest quintile (Figure 4.7). In emerging market and developing economies, the poorest households consume nine-times less modern energy than the wealthiest households, with millions of poor households still lacking any access to modern energy. These differences would be even wider if oil use for transport were included.

The least well-off often live in less efficient buildings and use older, inefficient appliances and equipment for services such as cooking and heating. Improving the efficiency of such homes tends to be difficult, as they may be rentals and face the landlord/tenant barrier as well as difficulty in making the upfront investment in retrofits and other efficiency measures. Therefore, achieving a similar level of comfort and basic energy services typically requires more energy in poor households, driving up costs or obliging them to forego these services. Moreover, the poorest households in emerging market and developing economies often have no choice but to use low quality and polluting fuels combined with inefficient equipment to meet energy needs, inflating their energy bills. In some cases they may purchase charcoal (and other cooking fuels) in informal markets, which expose them to low grade products and seasonal price volatility.

Figure 4.7 ▷ Residential consumption of modern energy per household by income quintile, 2021



The poorest households use nine-times less energy than the wealthiest ones, but spend a much larger share of household income on energy

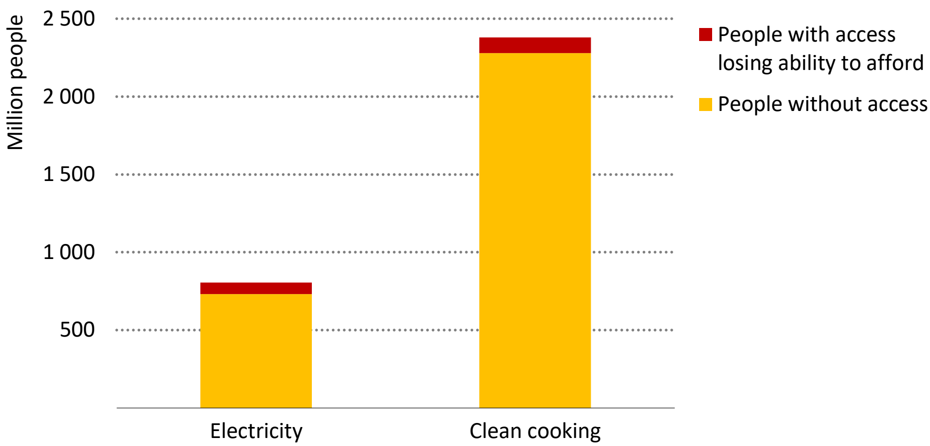
Notes: GJ = gigajoules. Quintiles are sequenced by total household income within all advanced economies or all emerging market and developing economies. Countries on the wealthier end of these categories tend to be concentrated in the higher quintiles, and similarly lower income countries within these broad categories are concentrated in lower quintiles. Excludes oil use for transportation.

Source: IEA analysis based on World Inequality Database (2022).

These factors disproportionately expose the poorest households to energy price spikes. We estimate that worldwide the number of people living in households spending at least 10% of their income on energy used in the home increased by 160 million between 2019 and 2022 (assuming similar levels of household energy use in both years). While oil use for transport is not considered in this estimate, high and volatile oil prices are also triggering rapid rises in retail prices, and this may lead to households that already have low per capita energy consumption levels being forced to reduce energy consumption even further.

This is already causing problems for people that recently acquired access to electricity and modern sources of energy for cooking (see Chapter 5, section 5.6). An estimated 75 million people that were able to afford an extended bundle of electricity services are likely to substantially cut energy use as a result of strains on household incomes. As a result of higher prices for liquefied petroleum gases (LPG), an estimated 100 million people have had to switch from LPG for cooking to traditional stoves (Figure 4.8). This is a clear manifestation of extreme energy insecurity caused by the Covid-19 pandemic and the energy crisis.

Figure 4.8 ▷ Number of people without access to modern energy and losing the ability to afford modern energy in sub-Saharan Africa and developing Asia, 2022



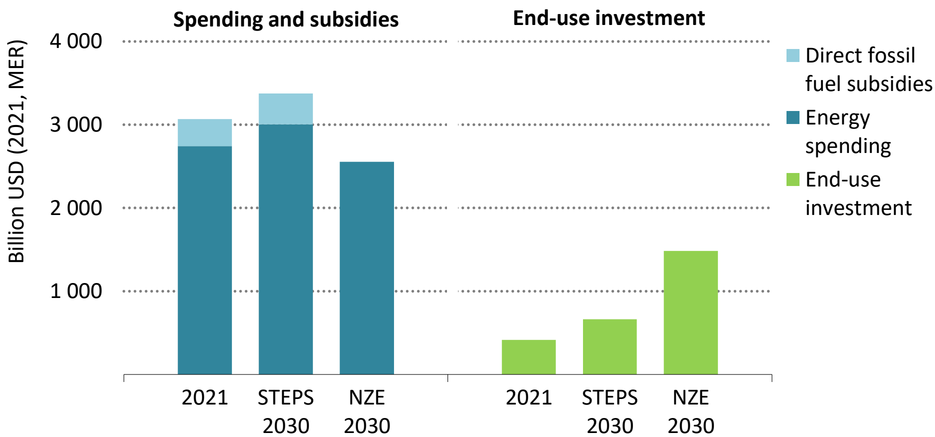
IEA. CC BY 4.0.

75 million people recently lost the ability to pay for an extended bundle of electricity services and 100 million people can no longer afford to cook with LPG

Notes: People losing the ability to afford modern energy is defined here as those with access that are reducing their use of modern fuels due to the combined effects on household income and energy prices resulting from the Covid-19 pandemic and the current energy price spikes. For electricity, this is the number of people in households where the cost of an extended bundle of electricity services has risen above a region-specific threshold of their income. An extended bundle of electricity services includes four lightbulbs operating for four hours per day, a fan for six hours per day, a radio or television for four hours per day and a refrigerator. For clean cooking, this is the number of people that cook with LPG whose expenditure on fuel has risen above a region-specific threshold as a percentage of their income based on international LPG prices in June 2022. These thresholds vary between 5% and 10% of household income depending on the region for both electricity and LPG cooking.

In the transition to cleaner energy, ensuring affordability for poor households will be critical to gaining widespread public acceptance and avoiding a social backlash. During the current crisis, governments have intervened in a variety of ways to try and protect consumers from the impact of high prices. The least efficient intervention is where direct fossil fuel consumption subsidies, below market energy prices, are offered indiscriminately to all consumers. These subsidies diminish or remove entirely the incentives to improve efficiency, and disproportionately benefit wealthier households and businesses. They also burden government finances at a time when fiscal leeway is important to accelerate clean energy transitions. In the STEPS, a failure to push ahead with direct fossil fuel subsidy reform could see subsidies for household energy use and personal mobility rise by 15% to USD 370 billion by 2030 (Figure 4.9).

Figure 4.9 ▷ Consumer energy spending, subsidies and end-user investment for efficient, low-emissions equipment in the buildings and transport sectors in the STEPS and NZE Scenario by 2030



Poorly targeted subsidies in the buildings and transport sectors come at the expense of much-needed structural changes in energy use

Note: MER = market exchange rate.

In the NZE Scenario, more emphasis on energy efficiency and fuel switching lowers consumer energy spending in 2030 compared to the STEPS. However, poor households still require financial support if they are to spend less than 10% of their income on household energy. This scenario sees direct fossil fuel subsidies eliminated. However targeted forms of affordability support may play a role, such as energy rebates, social tariffs or bill repayment assistance. Energy- or carbon-based taxes more than offset the value of these supports in the NZE Scenario. This helps to channel government financial support to those most in need while reducing overall energy subsidy burdens substantially. It also frees fiscal resources to support the upfront costs required to improve end-use energy efficiency. The reduction in subsidy burdens in 2030 in the NZE Scenario relative to the STEPS could support households bear up to half of the additional upfront investment costs for efficiency and fuel switching.

Table 4.1 ▷ Selected affordability and support measures specific to low income households

	Targeted	Progressive	Effective	Implementable
Affordability support for energy use				
Price caps, discounts or direct fuel subsidies	Low	Low	Moderate	Moderate
Low income tariffs	Strong	Moderate	Moderate	Strong
Energy rebates and direct transfers	Strong	Strong	Moderate	Moderate
Financial support to manage upfront costs				
Tax credits for retrofits/upgrades	Low	Low	Moderate	Strong
On-bill repayment or ESCO models	Low	Moderate	Moderate	Moderate
Low income rebates	Strong	Strong	Moderate	Strong
Shifting onus to reduce energy cost				
Minimum efficiency level requirements for renting	Low	Strong	Strong	Low
Transferring repayment for upgrades with the property	Low	Moderate	Strong	Moderate
Investing in enabling infrastructure				
Public, multi-unit EV charging	Moderate	Moderate	Moderate	Strong
Improving mass transit access	Moderate	Moderate	Moderate	Moderate
Efficient new construction of low income housing	Strong	Strong	Strong	Strong

Strong Moderate Low

Notes: ESCO = energy service company; EV = electric vehicle. Targeted refers to the ability of the policy measure to be directed to a selected subset of the population. Progressive implies that the price support benefits low income individuals more than others. Effective refers to the ability of the policy measure to enable low income individuals to use the energy needed and benefit from energy cost-saving measures. Implementable refers to the ease with which these policy measures can be put in place, as well as to the costs incurred by governments.

This transformation is easier said than done, and progress has been mixed in recent years. One challenge is garnering public support in the face of opposition from those who stand to lose access to direct fuel subsidies. Another is developing the capacity to target welfare payments. In some cases this depends on better social security infrastructure as well as improved data on energy use and household income. As these challenges are overcome, energy subsidies can shift over time towards better focused support, which ideally should be targeted, progressive, effective and implementable (Table 4.1).

4.4 Collaborate to bring down the cost of capital in emerging market and developing economies

The high cost of capital is a major obstacle to deploying clean energy infrastructure in many emerging and developing economies. Mitigating economy-wide and sector-specific risks is essential to unlock timely, cost-effective investment.

The most recent evidence presented in the *World Energy Investment 2022* (IEA, 2022f) shows that, after remaining flat for several years, global clean energy spending is finally picking up and is expected to exceed USD 1.4 trillion in 2022. However, almost all of the growth is taking place in advanced economies and China. Moreover, over 90% of the USD 1.1 trillion earmarked for clean energy as part of post-pandemic stimulus packages is contained in the plans of advanced economies. Despite having two-thirds of the global population, clean energy investment in emerging market and developing economies, excluding China[4], account for less than one-fifth of the total.

This shortfall in investment in emerging market and developing economies is cause for alarm. If there is no accessible pathway towards low-emissions inclusive growth for these economies, then either growth will be high carbon, or it will be constrained by a lack of energy. Both of these possibilities are associated with immense risks. Clean energy investment is attractive from an economic perspective, especially during the current period of high and volatile fossil fuel prices. It is also the most cost-effective way for the world to avoid future emissions: IEA analysis has shown that the average cost of emissions avoidance in emerging market and developing economies is around half the level in advanced economies (IEA, 2021a). So why are these investments not taking place?

One of the key barriers hampering clean energy investment in emerging market and developing economies is the high cost of capital. The cost of capital is a measure of the risk associated with projects in different jurisdictions; it expresses the expected financial return, or the minimum required rate, for investing in a company or a project. This expected return is closely linked with the degree of risk associated with a company or project cash flows (IEA, 2021b). A high cost of capital hampers prospects for investment, particularly for capital-intensive investments, including renewables that require large upfront capital costs but have very low operating expenditures.

One obstacle to assessing this issue has been a lack of available data on the cost of capital at the project and corporate level, especially for emerging market and developing economies. This acts as a barrier to investors looking to direct capital into these regions, and also undercuts the possibilities of evidence-based conversations with policy makers on the main perceived risks and ways to mitigate them. In recognition of wide data gaps, a Cost of Capital

[4] Emerging market and developing economies in this section exclude China.

Observatory was launched in September 2022 by the IEA, the World Economic Forum, ETH Zurich and Imperial College London to increase the visibility and availability of data on financing costs in the energy sector and to inspire investor confidence.

Table 4.2 ▷ Indicative weighted average cost of capital of utility-scale solar PV projects, 2021

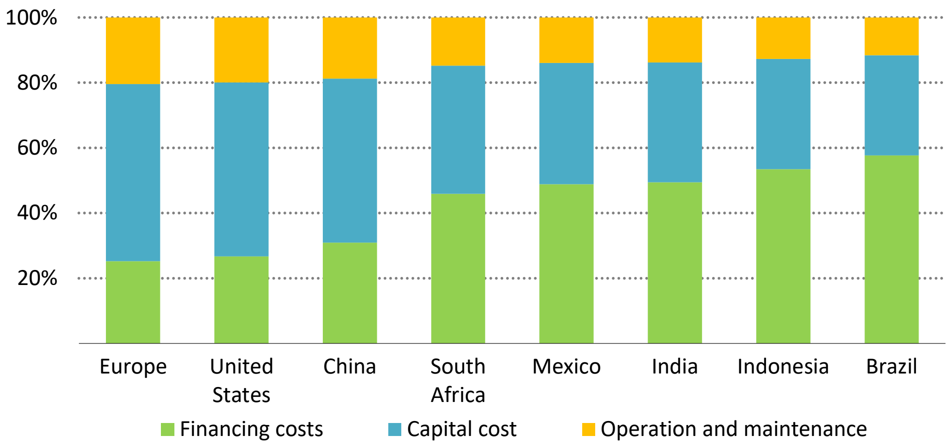
	Cost of debt (after tax)	Cost of equity	Share of project debt	WACC (nominal, after tax)
Europe	2.5% - 3.0%	6.0% - 11.0%	75% - 85%	3.0% - 5.0%
United States	3.0% - 3.5%	5.0% - 7.0%	55% - 70%	3.5% - 5.0%
China	3.5% - 4.0%	7.0% - 9.0%	70% - 80%	4.0% - 5.5%
Brazil	11.5% - 12.0%	15.0% - 15.5%	55% - 65%	12.5% - 13.5%
India	8.0% - 9.0%	12.5% - 13.5%	65% - 75%	9.0% - 10.5%
Indonesia	8.5% - 9.5%	12.0% - 12.5%	60% - 70%	9.5% - 10.5%
Mexico	8.0% - 8.5%	12.0% - 12.5%	60% - 70%	9.5% - 10.0%
South Africa	8.0% - 9.0%	12.0% - 14.0%	65% - 70%	9.5% - 11.0%

Notes: WACC = weighted average cost of capital. Values are expressed in local currency. The values for Brazil, India, Indonesia, Mexico and South Africa are based on the survey of the Cost of Capital Observatory, https://www.iea.org/data-and-statistics/data-tools/cost-of-capital-observatory.

Our analysis, based on a survey of investment practitioners and experts in various countries, revealed that the cost of capital for a typical solar PV plant in 2021 was between two- and three-times higher in emerging market and developing economies than in advanced economies and China (Table 4.2). This was driven not only by higher country risk, which is reflected in higher rates for sovereign bonds, but also by higher sectoral risks that translate into higher premia for debt and equity, and by a lack of bankable projects. The risks include regulatory risk, off-taker risk and land acquisition risk. Regulatory risk arises from a suboptimal or unpredictable energy policy, the lack of robust infrastructure planning or inefficient market designs. Off-taker risk stems from the financially distressed position of distribution companies, which are often the principal off-takers for developers: this can lead to delays in the signature of power purchase agreements and in payments under those agreements, weighing on financing costs. Land acquisition risk comes from lengthy and complex permitting processes and the absence of available grid infrastructure. The lack of bankable projects is often associated with lower market depth and experience in financing clean energy projects.

Higher costs of capital and rising borrowing costs threaten to undercut the economic attractiveness of clean energy investment in emerging market and developing economies, even in countries that possess rich renewable resources. Financing costs accounted for around half of the total levelised costs of a solar PV plant that reached final investment decision in these regions in 2021, notably higher than the 25-30% equivalent in advanced economies and China (Figure 4.10). This inevitably affects inward investment levels.

Figure 4.10 ⊳ Composition of levelised cost for a utility-scale solar PV plant with final investment decision secured in 2021



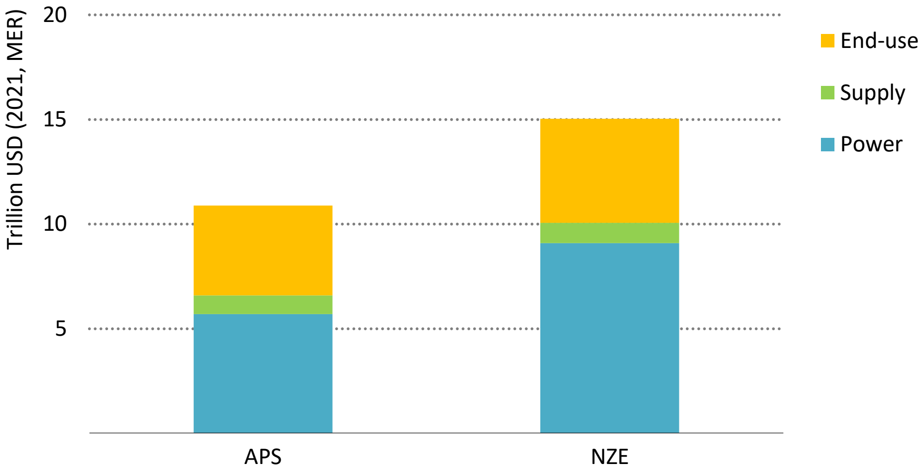
Financing costs are around half of total levelised costs in emerging market and developing economies, which is significantly more than in advanced economies and China

The current macro-economic context weighs further on the prospects for lowering the costs of capital. A growing number of central banks are currently opting for contractionary monetary policies to tackle inflation, and the US dollar is looking strong. In this kind of environment, borrowing costs tend to rise faster in emerging market and developing economies than in advanced economies because of higher economic uncertainty and investor preference for creditworthy issuers against projects with higher return and risk profiles.

Concerted efforts to lower the costs of capital in emerging market and developing economies could bring major energy security benefits by unlocking capital flows to support clean energy projects in those countries. The IEA, together with the World Bank and the World Economic Forum, proposed a series of priority actions based on more than 40 on-the-ground case studies (IEA, 2021a). Additional financial and technical support, including concessional capital, private sector capital and inflows from international carbon markets, will all be crucial. For example, financial support from Brazil's national development bank (NDB) was key to the provision of low cost, locally denominated loans to renewable power projects, at a time when market-based interest rates were relatively high. As the sector matured, the bond market rose too and the role of the NDB shifted from direct financing to catalysing capital.

Improving access to domestic capital through more robust banking and capital markets is as important as international measures. Governments and regulators have an important role in mitigating risks by providing revenue stability or other guarantees to enhance the cash flows of clean energy projects, incentivising the participation of private capital and putting state-owned enterprises on a sound financial footing. This applies especially to projects to expand and modernise electricity grids. The issue of limited bankability projects could be tackled with detailed least-cost plans for infrastructure deployment and regional integration.

Figure 4.11 ⊳ Cumulative reduction in clean energy financing costs in emerging market and developing economies by lowering costs of capital in the APS and NZE Scenario, 2023-2050



Lowering costs of capital by 200 basis points could reduce the cumulative clean energy financing costs in emerging and developing economies by up to USD 15 trillion to 2050

Note: MER = market exchange rate.

If the costs of capital were to be lowered by 200 basis points[5] in emerging market and developing economies, this would reduce the financing costs for clean energy by a cumulative USD 11 trillion over the period to 2050 in the APS and by USD 15 trillion in the NZE Scenario (Figure 4.11). These reductions correspond to 20% of total clean energy investment requirements, including financing costs.

[5] One basis point is equal to 1/100th of 1%, or 0.01%. 200 basis points are equal to 2%. 200 basis points correspond to roughly 15-20% of current cost of capital on an after-tax basis.

4.5 Manage the retirement and reuse of existing infrastructure carefully, some of it will be essential for a secure journey to net zero emissions

Unplanned, chaotic or premature retirement of existing fossil fuel infrastructure could have negative consequences for energy security as well as for people. New and old systems will exist side-by-side during the transition, and effective management of their interactions is essential.

Shutting down fossil fuel infrastructure as quickly as possible is often assumed to be a primary task of clean energy transitions, but this assumption needs some qualifications. The speed at which fossil fuel infrastructure can safely be retired depends crucially on the speed at which clean energy technologies are deployed and fossil fuel demand declines. Moreover, even in the NZE Scenario in 2050, when no CO_2 is emitted on a net basis, fossil fuel use does not fall to zero. Around 100 EJ of fossil fuels per year are still consumed in 2050 in this scenario, either in conjunction with CCUS, or in sectors where clean technology options are scarce, or for non-energy purposes, notably as feedstock for the chemical industry. Another key point is that some existing infrastructure can be reused and repurposed to support the clean energy economy. While much of the infrastructure for the clean energy economy has to be built anew, electricity grids remain the backbone of electricity security, and natural gas networks could be used to transport biomethane (without any modification) and hydrogen (with modifications). Parts of oil refineries could be recast as bio-refineries. Some sites previously used to store natural gas, notably salt caverns, could be repurposed to store hydrogen.

The energy security perspective is important, as consumers have very low tolerance for unreliable or very expensive energy. Even in very rapid energy transitions, fossil fuels and their infrastructure perform certain functions that will remain critical to the reliable operation of the energy system as a whole, and the infrastructure in question will need to be maintained. The task for policy makers is to identify what needs to be maintained and managed, and why, and then to ensure that the necessary work is carried out. Premature or unplanned removal of these assets could be disruptive: three examples are highlighted.

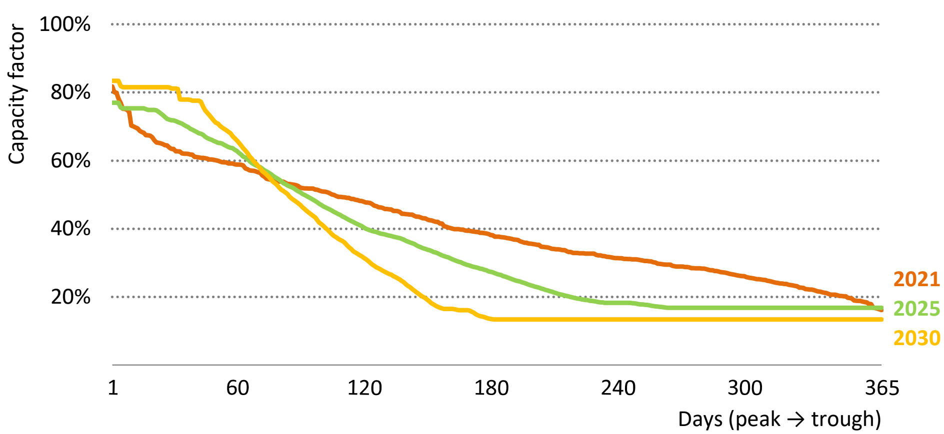
Role of natural gas-fired power in providing flexibility

In energy transitions, the role of natural gas-fired power in many energy systems has to adapt. Average utilisation rates fall over time and the main task for gas-fired power plants becomes the provision of flexibility, ramping output up and down in response to the needs of the system, rather than providing large volumes of electricity on a more consistent basis. The average utilisation of gas-fired plants in the APS worldwide falls from 40% today to 31% by 2035, and to 18% in the NZE Scenario.

There are already signs that investors are readying gas for this role. Open-cycle gas turbines are better suited than closed-cycle gas turbines to business cases calling for flexibility and firm capacity procurement, despite being less efficient. Among the gas-fired plants that reached final investment decisions in 2021, the share of open-cycle gas turbines increased to 22%, twice the level in 2016.

As transitions progress towards net zero emissions, this role for gas-fired power needs eventually to be supplanted by other forms of flexibility that do not result in emissions. These include supply-side options such as low-emissions gases (biogases and hydrogen) as well as demand-side measures, long duration energy storage and higher levels of interconnection between systems. However, these alternatives take time to be available at scale. Meanwhile some other existing forms of flexibility – notably coal-fired power – decline quickly, and the requirement for flexibility rises rapidly as variability increases on both the supply and demand sides (see section 4.7). More extreme variations in weather patterns may add to this variability in the years ahead, and thus to the requirement for flexibility. For these reasons, the importance of gas-fired power for electricity security actually *increases* in many countries before falling again, especially in systems with significant seasonal variations in demand. In the European Union, natural gas demand for power generation halves to 70 bcm in 2030 in the APS. However, peak requirements for natural gas go up over the same period even though overall or aggregate demand goes down (Figure 4.12).

Figure 4.12 ▷ Load duration curve for natural gas-fired power generation in the European Union in the APS



Sorting gas-fired generation from the highest to lowest utilisation rates over a year reveals a vital balancing role, even as the annual contribution of gas to power demand declines

Against this backdrop, maintaining reliable electricity systems requires that natural gas will be deliverable and gas-fired power plants remain available in times of stress for the system, notably when high electricity and gas demand coincides with low availability of variable renewables. This cannot be taken for granted.

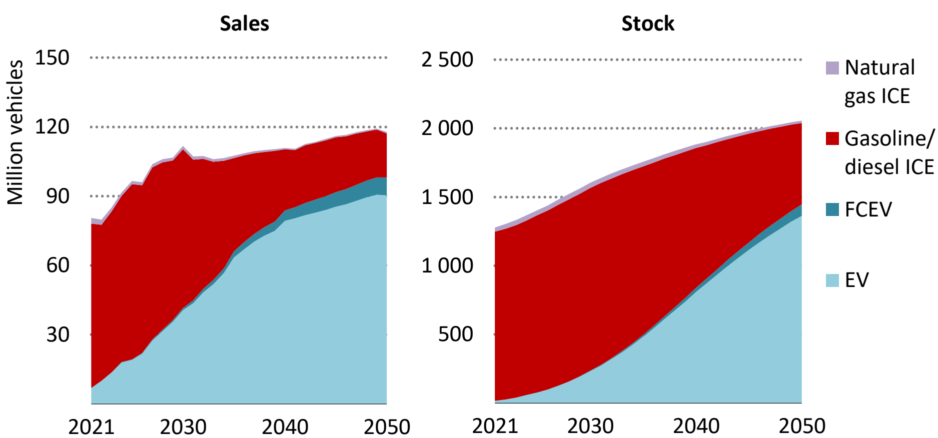
- Lower utilisation can mean lower profitability, and gas-fired power plants may close if markets do not appropriately remunerate the flexibility and other services that they provide.
- Pressure on operators has been exacerbated by extremely high and volatile prices, which have led to discussions about capping revenues for gas-fired capacity, and raised broader questions about the role of gas in transitions (see Chapter 8).
- Deliverability requires that networks and storage are still capable of managing peak levels of gas demand (see discussion on gas infrastructure).

Against this backdrop, it is vital for governments to ensure that the design of electricity markets recognises the value of flexibility from gas-fired plants as well as other sources of flexibility, and that gas-related contingencies are included in regular adequacy assessments conducted by countries relying on this source of flexibility.

Refining and product supply for the residual ICE vehicle fleet

The rise of electric mobility necessarily involves an extended period during which vehicles using gasoline or diesel will be operating side-by-side with electric vehicles (EVs), with each requiring well-functioning infrastructure to deliver the fuel and electricity they need. Analysis of changes in the transport sector understandably focuses on the shift to EVs in new car sales, which is proceeding rapidly in some markets. Even in those markets, however, it will take time for the entire stock of vehicles to change (Figure 4.13).

Figure 4.13 ▷ Stock and flow of passenger cars by type in the APS



Even in scenarios that feature rapid reductions in sales of ICE cars, oil use in road transport does not disappear quickly

Notes: FCEV = fuel cell electric vehicle; ICE = internal combustion engine; EV = electric vehicle, which includes battery electric and plug-in hybrid models.

In markets where ICE vehicles sales are banned, oil demand for transport does not disappear immediately. For example, the European Union consumes just under 5 million barrels per day (mb/d) of oil products today for road transport. In the APS, this falls to just over 2 mb/d in 2035, the year when ICE vehicle sales cease for passenger cars and light commercial vehicles. Ten years later it stands at 0.6 mb/d, with freight making up an increasing share of residual consumption. A similar pattern is visible at the global level in the NZE Scenario, where all sales of ICE passenger cars and two/three-wheelers cease in 2035, but there is still a sizeable tail of these vehicles on the road by mid-century.

As with gas-fired power, these transitions worsen the economics of traditional refinery operations (see Chapter 7). Refiners do not just have to cope with a change in overall levels of demand, but also with changes in the composition of demand, and both have major implications for business models. Our transition scenarios all show an increase in the share of lighter products (often used in petrochemicals, a sector where demand is relatively robust) alongside a reduction in the output of traditional refined products used in the transport sector, such as gasoline and diesel.

Today, refiners typically earn most of their profit from selling gasoline, diesel and jet fuel. Prices for petrochemical feedstocks – the main sources of demand growth – often trend lower than crude oil prices. In theory, lower profits in one area could be compensated by higher prices for products in high demand such as naphtha and LPG. While it is conceivable that the revenues of these products may increase to some degree, it is hard to envisage a rise that fully compensates for the reduction in road transport fuels sales. As we have seen in recent years (and also in the mid-1980s), low margins prompt rationalisation of refinery capacity and closures. This is a natural response to changing market conditions, but it comes with risks to security of supply: the retirement of refineries may leave gaps in product supply or result in more vulnerable supply chains for the delivery of certain products to consumers.

There is a need for dialogue between governments and refiners on how to manage this reduction in traditional refining activity, and for steps to be taken to monitor national and international supply chains for vulnerabilities that may require attention or action. There may be a case in some instances for governments to work with refiners to chart a way forward in the interests of energy security. Australia, for example, is providing support to its last two refineries to stay open, in return for accelerated commitments to switch to producing low sulphur fuels.

Right sizing and repurposing gas networks

A third area requiring close attention is natural gas networks. This is a particularly difficult area, because the networks sit at the intersection of different visions of how transitions should play out. On one side there is the "electrify everything" approach, in which electricity not only increases its share substantially in final consumption (as it does in all our scenarios) but becomes the dominant or even the sole vector for most consumers. This route requires a massive build-out of clean electricity generation and infrastructure, and the role of existing gas networks in this vision is marginal – the main policy issue is how to manage their decline.

On the other side are those arguing that most current natural gas pipelines can eventually be repurposed to carry low-emissions gases, whether biogases or low-emissions hydrogen, so grids need to be maintained (and in some cases expanded).

Starting points for this debate differ. Nearly all countries have an extensive electricity grid for delivering power to consumers, but the extent of gas infrastructure varies considerably.[6] Where it has been built, in many cases the gas network provides a larger and more flexible energy delivery mechanism than the electricity network. In Europe and the United States, gas networks deliver between 50-100% more energy on average to end-consumers than electricity grids.

Switching from gas to electricity brings major efficiency gains, but replacing gas entirely with electricity would bring practical challenges, especially if it proves difficult to expand the electricity network quickly due to permitting issues or public opposition. There is an energy security rationale for maintaining overlapping infrastructure and, indeed, most countries that have considered how to realise rapid and wholesale emissions reductions are looking at a future in which electricity and gas networks play complementary roles.

However, these roles are often not well defined in practice, and this creates risks. Without a well co-ordinated approach to the provision of power, gases and heat, the different networks are unlikely to evolve in a harmonious way. For example, there is a distinct possibility of gas infrastructure suffering "death by a thousand cuts" as individual consumers migrate to using electricity. Those making the move are likely to be better-off households in a position to make the upfront investment in electrified heating systems. This could in turn have distributional implications as poorer consumers, along with some industries, would continue to rely on existing infrastructure and, under existing tariff structures, would need to shoulder a higher share of its fixed costs.

To avoid these kinds of outcomes, there is a need for early and co-operative resource planning among electric and gas utilities and network operators, mediated by governments to ensure that the outcomes are consistent with rapid, secure transitions that minimise costs to consumers. This kind of ongoing dialogue, informed by changing technology and deployment trends, can contribute to developing a coherent vision of where gas networks have long-term viability (and where they need to be decommissioned), and how gas and electricity grids can work together to contribute to rapid reductions in emissions.

[6] The role of gas networks is determined in many cases by the need for winter heating; in countries where seasonal fluctuations in demand are lower (including many developing economies), gas networks tend to be smaller in size.

4.6 Tackle the specific risks facing producer economies

Countries that rely heavily on fossil fuel revenues face particular challenges and potential strains in energy transitions, with major potential knock-on effects for energy security – and emissions – if they are unsuccessful in moving to the new energy economy.

Producer economies today face a complex set of strategic choices. The need for change is unavoidable, and development prospects for any country or company pursuing business-as-usual will be bleak, but there are also downsides for those that move away from current business models without a clear strategy for what comes next.

The world's hydrocarbon producers and exporters have faced many periods of volatility in the past, but few that have matched the wild swings seen in prices since 2019. In the past, these fluctuations have typically been correlated closely with changes in government spending in oil and gas dependent economies, with a boom in spending when prices are high, and a bust when they fall. These pro-cyclical patterns of spending have had destabilising effects on domestic consumption, private investment and the economy as a whole.

In recent years, there has been a slew of announcements of new strategies that aim to break this cycle and promote more resilient economies, some taking the form of roadmaps for diversification, such as the Vision 2030 in Saudi Arabia launched in 2016, and others focusing on reforms to smooth spending cycles, such as the decision by the United Arab Emirates to introduce five-year budgets. The surge in oil prices and revenues in 2022 provides an opportunity to take stock and ask the question: is this time different?

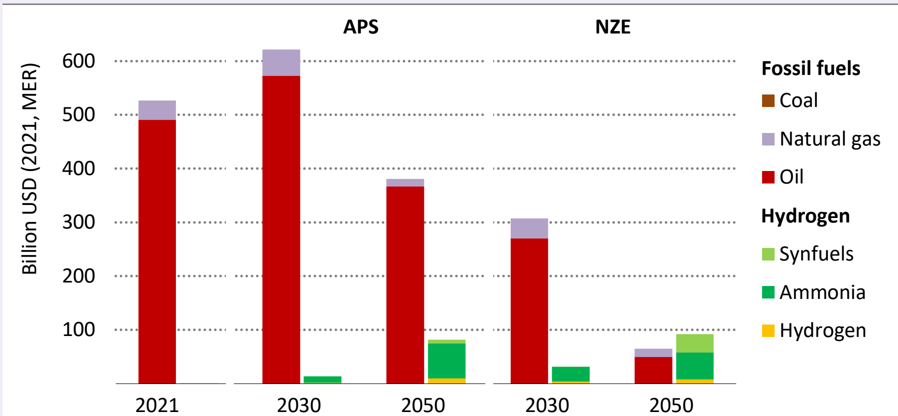
It is likely too soon to tell definitively, and the answer may depend on how long oil and gas prices stay at high levels and whether windfall revenues introduce a complacency that stifles reform. However, there are a number of provisionally positive signs. For instance, Saudi Arabia's 2022 budget is based on an oil price of around USD 75/barrel, below the prevailing price. This is coupled on the expenditure side by a 6% decrease in planned spending, reflecting a cautious approach that is geared to replenishing its financial buffers. In Iraq, where oil revenues have broken historical records this year, windfalls are likewise being saved, though this mostly reflects the political impasse that has prevented the country from passing a budget, and has therefore forced it to constrain expenditure to the same level as last year.

There are some signs of change too in the way that increased revenues are being spent in the energy sector. Spending on oil and gas infrastructure has increased, with upstream investment above 2019 levels. But so too has spending on renewables, even among the more fiscally constrained producers: in 2021, renewables investment in the Middle East and North Africa rose by 60% from 2019 levels, and 2022 is likely to see a further rise. Algeria, for instance, launched a tender for 1 gigawatt (GW) of solar PV capacity in mid-2022, while Iraq announced an ambitious target to produce a third of its electricity with renewables by 2030 and is conducting talks with European, Middle Eastern and Chinese partners on renewables projects with a combined capacity of 5 GW. In Saudi Arabia, a USD 5 billion project to develop a renewable hydrogen sector was agreed in mid-2020. Oman has made clear its intention to use the current period of increased export revenue to boost investment in its zero-carbon hydrogen sector, which it sees as essential to its efforts to decarbonise existing energy-intensive industries.

Box 4.1 ▹ Could hydrogen exports replace hydrocarbon income in the Middle East?

Energy transitions present obvious challenges to development models dependent on oil and gas, and therefore have huge implications for the hydrocarbon-rich economies of the Middle East (Figure 4.14). But could these countries have comparative advantages in providing the fuels of the future as well? The idea is attracting a lot of attention, with low-emissions hydrogen providing a beguiling vision of continuity for some producers, based on ample reserves of natural gas, plenty of options for geological storage of CO_2, and outstanding potential for renewables to produce hydrogen by electrolysis.

Figure 4.14 ▹ Export revenue from oil and gas versus hydrogen in the Middle East in the APS and NZE Scenario, 2021-2050



Exports of hydrogen and hydrogen-rich fuels are no substitute for the revenues coming from fossil fuels, though they could provide a durable source of economic advantage

IEA analysis confirms the competitive edge that many Middle East countries have as producers of hydrogen, but also that hydrogen exports are not going to be more than a partial substitute for current hydrocarbon revenues. In the STEPS, hydrogen is projected to earn around USD 15 billion in revenues by mid-century, which is only around 1% of combined oil and gas revenues in the same scenario. In the APS, hydrogen export revenues are expected to rise to levels equivalent to one-fifth of the revenues from oil and gas over the same period. It is only in the NZE Scenario that revenues cross over and hydrogen becomes more lucrative for the Middle East – albeit at significantly lower levels than those seen historically for hydrocarbons.

Export earnings for hydrogen as a fuel are not likely to be more than a very partial replacement for oil and gas exports (Box 4.1). This is hardly surprising, given that many countries have the potential to produce hydrogen and that there are therefore very limited resource rents on offer; the projected market size for hydrogen also remains well below that of oil and gas today. Nonetheless there are very good reasons for countries with a comparative advantage in low-emissions hydrogen to move in that direction. Export earnings for fuels, however, are not the big prize on offer. The major long-term opportunity is rather the ability of today's hydrocarbon exporters to become global leaders in the manufacture – and export – of low-emissions industrial products and chemicals.

Several producers are studying ways to ensure that their energy transition efforts are integrated into their economic diversification strategies, including by assessing how existing supply chains, expertise and support industries might be repurposed for clean energy technologies such as low-emissions hydrogen. First movers stand to benefit not only from exports of clean energy but also from the value created domestically by the establishment of new clean energy industries. Oman, for example, is working to identify the potential to use low-emissions hydrogen in industry, which currently accounts for half of its natural gas consumption.[7] As well as potentially creating anchor consumers for low-emissions hydrogen, this approach could allow Omani industries to become competitive in markets where carbon border adjustment mechanisms begin to reward the lowest emitting producers. Such mechanisms including those that impose a price based on the emissions intensity of production, or consumer pressure for low-emissions goods, may lead other prominent producer economies that have focussed diversification efforts on encouraging energy-intensive industries to follow Oman's example (Spotlight).

S P O T L I G H T

New criteria for the location of energy-intensive industries?

Energy-intensive industries such as refining, chemicals, steel and iron, cement and aluminium production could be deeply affected by energy transitions and possible accompanying price volatility. In Europe, high natural gas and electricity prices since September 2021 have already reduced the region's aluminium production capacity by nearly half (Eurometaux, 2022). The financial position of companies could be further affected by a variety of carbon pricing schemes, including carbon border adjustment

[7] Including chemical feedstock and energy sector own use.

mechanisms. All this is putting rising pressure on energy-intensive industries to find ways to reduce their emissions. Each energy-intensive sector and technologies vary, but deep emissions reductions are typically associated with switching to low-emissions electricity, using low-emissions fuels (which could be produced with renewables, as with electrolytic low-emissions hydrogen) or adopting CCUS.

Factors that influence decisions about the location of a plant traditionally include proximity to consumers, access to raw materials and a skilled workforce, and tax and other financial incentives. These elements remain important, but additional criteria may emerge in a world transitioning to clean energy. These could include access to low-emissions electricity, scope to make use of renewable resources and proximity to CO_2 storage sites. Future investment in energy-intensive industries is likely to favour regions with outstanding clean electricity and CCUS potential in particular.

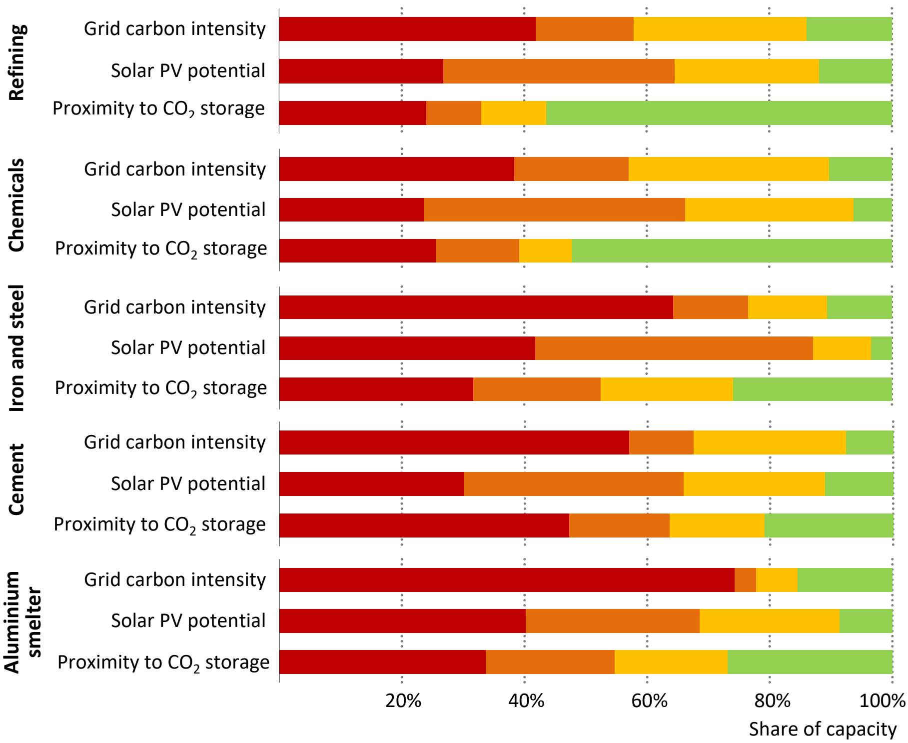
Our detailed geospatial analysis suggests that sustainability and carbon considerations have not featured prominently in past decisions regarding the location of energy-intensive industries. Today some 40-70% of plants are located in regions where the carbon intensity of the grid is very high (above 600 tonnes of carbon dioxide per-gigawatt-hour [t CO_2/GWh]). Only around a third of plants are located in regions with high solar PV potential[8] (the share is lower for the iron and steel sector). Around 70% of capacity in key regions, e.g. China, the European Union and the United States, however, is located within 100 km of potential storage for CO_2 (and 35% is located within 10 km) although it does not necessarily mean that CCUS will be technically and commercially feasible in any given location (Figure 4.15). To put these distances into context, the average distance over which CO_2 is currently transported by pipeline between existing CCUS facilities is around 180 km.

While the endowment of renewable resources and potential sites for CO_2 storage are more or less fixed, there is still a lot that individual countries can do to foster an attractive low-emissions environment for energy-intensive industries. The carbon intensity of the grid could be reduced significantly by scaling up the deployment of low-emissions power generation sources. Technology innovation means that solar power generation is now affordable even in regions with less favourable resource potential, and wind power is also becoming more affordable in a number of countries. The viability of CCUS could be boosted through a range of targeted measures, e.g. regulatory levers, public procurement, low-emissions product incentives and tax credits. Supporting industrial clusters with shared CO_2 transport and storage infrastructure is also proving to be an effective development strategy. New business models separating the components of the CCUS value chain and developing multi-user transport and storage networks that industrial facilities can access (CCUS hubs) could also help. Other possible measures include ensuring accessibility to renewables-based electricity, for example via power

[8] Above 4.2 kilowatt-hour per kilowatt peak.

purchase agreement contracts, and nurturing innovative technologies. As global efforts to reduce emissions expand, building an environment conducive to decarbonisation is likely to emerge as a key strategy to attract large-scale industrial investment.

Figure 4.15 ▷ Current distribution of energy-intensive industries by grid carbon intensity, solar potential and proximity to CO_2 storage



Proximity to cheap renewables and geological storage are set to emerge as key factors in determining the future location of energy-intensive industries

Notes: t CO_2/GWh = tonne carbon dioxide per gigawatt-hour; kWh/kWp = kilowatt-hour per kilowatt peak. The proximity assessment for CO_2 storage sites has been done for selected regions only, i.e. China, European Union and United States. Some facilities, such as aluminium smelters, have dedicated power supply facilities separate from the grid and are thus less affected by grid carbon intensity.

Sources: IEA analysis based on European Commission (2022); Global Solar Atlas (2022); US DOE (2018); S&P Global (2022).

4.7 Invest in flexibility – a new watchword for electricity security

Modern economies depend on electricity, putting the spotlight on measures to ensure the reliable and flexible operation of a system that features higher variability in both supply and demand, and on steps to ensure resilience against new cybersecurity threats.

Electricity is at the heart of modern economies, supporting many fundamental aspects of daily life across the economy. It accounts for about 20% of total final consumption today, and this is set to increase in all scenarios, reaching 28% in the STEPS in 2050, 40% in the APS and about 50% in the NZE Scenario. The rising share of electricity in final consumption puts electricity security firmly in the overall energy security picture, along with oil and natural gas.

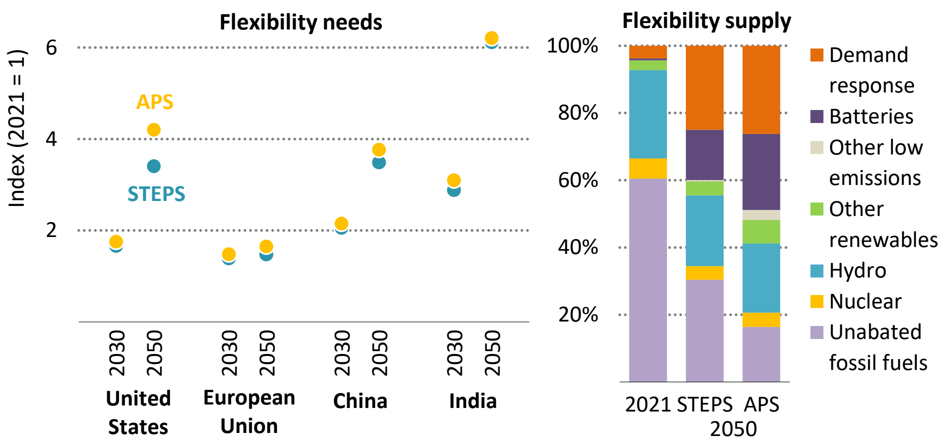
Electricity security means having a reliable and stable supply of electricity which is able to meet demands at an affordable price. Electricity supply has always required the capability to meet demand continuously, down to the scale of seconds or less, in order to maintain system stability. This is currently achieved by means of a set of managed power generators connected to demand centres through grid lines. However, power systems are becoming more complex, and variability is increasing in terms of both supply and demand. Electricity's central role in modern life means that shortages or outages have the potential to do immense damage and impose billions of dollars of costs per day on national economies; these costs will only increase as electricity comes to account for an ever larger share of overall energy consumption.

Maintaining electricity security in the power systems of tomorrow calls for new tools and approaches. Power generators will need to be more responsive and agile, consumers will need to be more connected and adaptable, and grid infrastructure will need to be strengthened and digitalised to support more dynamic flows of electricity and information. Power systems will also need to adapt to both changing climate and weather patterns and changing consumer behaviour.

The expansion of electricity into new sectors is one of the changes making the task of maintaining electricity security more challenging. The progressive electrification of road transport, heating, industrial processes and electrolytic hydrogen production will reshape load curves and has the potential to make demand more variable. The increasing use of electric heat pumps and air conditioners, for example, will make demand more temperature-sensitive, while the proliferation of EVs increases the risk of rapid variations in demand caused by uncontrolled charging (although it also creates additional opportunities for demand-side response via smart charging or vehicle-to-grid technology). The variability of electricity demand is set to increase in all countries and in all scenarios, with the level of variation being higher in the APS than in the STEPS, and most of all in the NZE Scenario.

The rising share of variable wind and solar PV electricity generation adds to the need for future flexibility on the supply side. Changes in electricity demand and supply profiles together are set to increase the call on the providers of power system flexibility.[9] All these factors indicate that flexibility will be a new watchword for electricity security. In the STEPS, global power system flexibility needs more than triple by 2050.[10] In the APS, they double in the period to 2030 and increase 3.5-fold by 2050, while in the NZE Scenario, they more than quadruple between today and 2050 (Figure 4.16).

Figure 4.16 ▷ Flexibility needs and supply by region and scenario



Flexibility needs rise in all scenarios and vary substantially by country; a broad range of technologies and approaches is required to ensure electricity security

Most of the flexibility required to maintain power system reliability today is provided by dispatchable thermal power plants and hydropower. Sharply rising flexibility needs and changes in the composition of the power plant fleet – with the phase-out of large unabated coal-fired thermal power stations in many regions – see the share of flexibility demand served by thermal power plants drop to roughly a third in the STEPS and a quarter in the APS, down from around two-thirds today.

This increases the need for alternative sources of flexibility to maintain grid stability and security of supply. Reinforced power grids and additional interconnections can help even out fluctuations in the supply of weather-dependent variable renewables, within and between countries and regions; they can also connect additional providers of flexibility to the system. Certain grid assets, such as high voltage direct current interconnections, can also provide flexibility services like fast ramping or voltage control directly.

[9] Flexibility is defined as the ability of a power system to reliably and cost effectively manage the variability of demand and supply across all relevant timescales. It ranges from ensuring the instantaneous stability of the power system to supporting long-term security of supply.

[10] Flexibility needs are represented by the hour-to-hour ramping requirements after removing hourly wind and solar PV production from hourly electricity demand, divided by the average hourly demand for the year.

All three scenarios show battery storage emerging as an important flexibility option in power systems characterised by high shares of variable renewables. The pace of deployments picks up dramatically: global battery storage capacity increases nearly 50-fold in the STEPS, rising to more than about 1 000 GW by 2050. In the APS this is 80% higher, reaching about 2 300 GW by2050, with over 420 GW already installed by 2030. In the APS, batteries provide close to a quarter of the flexibility needed in 2050 in advanced economies and only slightly less than that in emerging market and developing economies. Other storage technologies also play important roles: pumped hydro is the largest source of electricity storage today and is set to increase further over the next ten years (IEA, 2021c). Hydrogen and ammonia are emerging as solutions for the seasonal storage of renewable electricity (IEA, 2021d).

Demand-side response is another emerging option for the provision of electricity system flexibility. It helps to align consumption with the available supply, reducing the need for other sources of flexibility. The progressive electrification of further end-uses is set to provide additional opportunities for load shifting, with EVs and electric heating playing a major part. In 2050, demand-side response provides roughly a quarter of power system flexibility in both advanced economies and emerging market and developing economies in the STEPS and APS. Tapping this potential, however, will require further changes to regulatory frameworks and significant investments in digital infrastructure (Box 4.2).

Box 4.2 ▻ Enhancing resilience in the face of increasing cybersecurity risks

Electricity systems are becoming increasingly digitalised, bringing many benefits to electricity consumers, utilities and the system as a whole. However, increasing connectivity and automation and the rising number of connected devices and distributed energy resources are raising risks to cybersecurity. Threat actors are also becoming increasingly sophisticated both in terms of their destructive capabilities and ability to identify vulnerabilities. Although electric utilities and cybersecurity experts note the high and growing threat of cyberattacks, quantitative indicators of this growing threat are not available since most cybersecurity incidents are never publicly reported (or even reported to authorities).

Several cyberattacks on electricity systems have been documented over the past decade, including attacks on the power grid in the Ukraine in 2015 and 2016 that resulted in major outages (IEA, 2021e). Recent attacks on electric utilities in India and Ukraine were thwarted and did not result in outages. While disruptions to electricity systems as a result of cyberattacks have so far been relatively small compared to other causes, a successful cyberattack could trigger an operator’s loss of control over devices and processes, causing physical damage, service disruption and millions of dollars in damages.

Electric utilities face several challenges to address growing cybersecurity risks, including a lack of strategic attention, a tendency to harbour institutional silos, a limited set of resources and personnel, and a lack of information sharing between organisations. While preventing all cyberattacks is not possible, electricity systems can and must become more resilient to cyber attacks. This means designing systems in ways that enable them to withstand attacks and quickly absorb, recover or adapt, while preserving the continuity of critical infrastructure operations.

Policy makers, regulators, utilities and equipment providers all have important parts to play in ensuring the cyber resilience of the entire electricity value chain. The role of policy makers, however, is particularly central. They are best placed to take the lead in raising awareness of the issues, and working continuously with stakeholders to identify, manage and communicate emerging vulnerabilities and risks. Policy makers are also ideally placed to facilitate partnerships and sector-wide collaboration, develop information exchange programmes and support research initiatives across the electricity sector and beyond. Effective collaboration can help to improve understanding of the risks that each stakeholder poses to the electricity system and vice-versa.

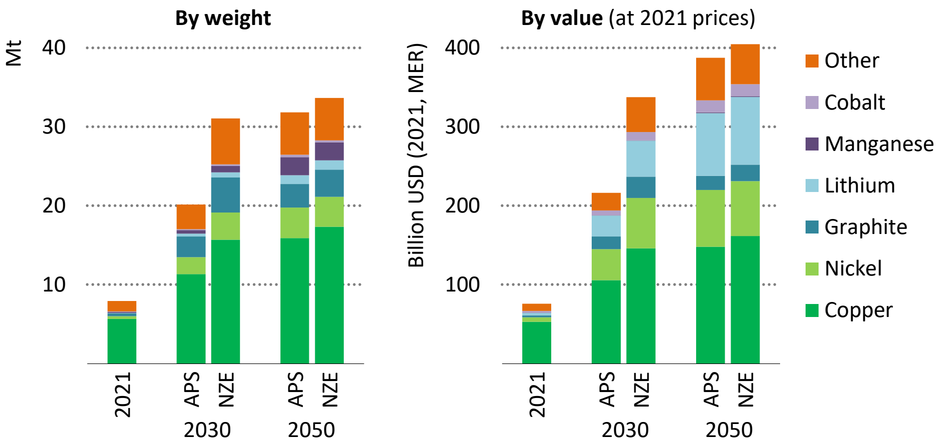
Different countries have taken various policy and regulatory approaches: some have adopted highly prescriptive approaches while others have chosen framework-oriented, performance-based models. Regardless of the approach taken, cyber resilience policies need continuous review and adaptation, particularly as further decentralisation and digitalisation of the electricity sector shifts the risk exposure to the grid edge. Effective policies now need to look beyond bulk utilities and consider the entire electricity chain, including supply chains.

4.8 Ensure diverse and resilient clean energy supply chains

High and volatile critical material prices and highly concentrated clean energy supply chains could delay energy transitions and make them more costly. Policies to promote diversified supply as well as demand-side innovation are essential.

Clean energy transitions require a strong focus not only on traditional elements of international energy security relating to the supply of fossil fuels, but also on the supply of the minerals, materials and manufacturing capacity needed to deliver clean energy technologies. As clean energy transitions accelerate, demand for critical minerals from the energy sector is set to soar. In the APS, demand for critical minerals for clean energy technologies is 2.5-times higher by 2030 and quadruples by 2050 (Figure 4.17). In the NZE Scenario, an even faster deployment of clean energy technologies implies four-time higher demand for critical minerals in 2030 and 2050 than today. In the NZE Scenario, lithium sees the fastest rise among the key minerals, with demand surging by 26-times between today and 2050 while demand for cobalt (6-times), nickel (12-times) and graphite (9-times) also rises rapidly. At 2021 prices, the value of the minerals used in clean energy technologies increases over fivefold, reaching around USD 400 billion by 2050 in the APS and in the NZE Scenario.

Figure 4.17 ▷ Critical mineral demand by weight and value for clean energy technologies by scenario



Critical mineral demand for clean energy technologies quadruples already by 2050 in the NZE Scenario, with particularly high growth for EV-related minerals

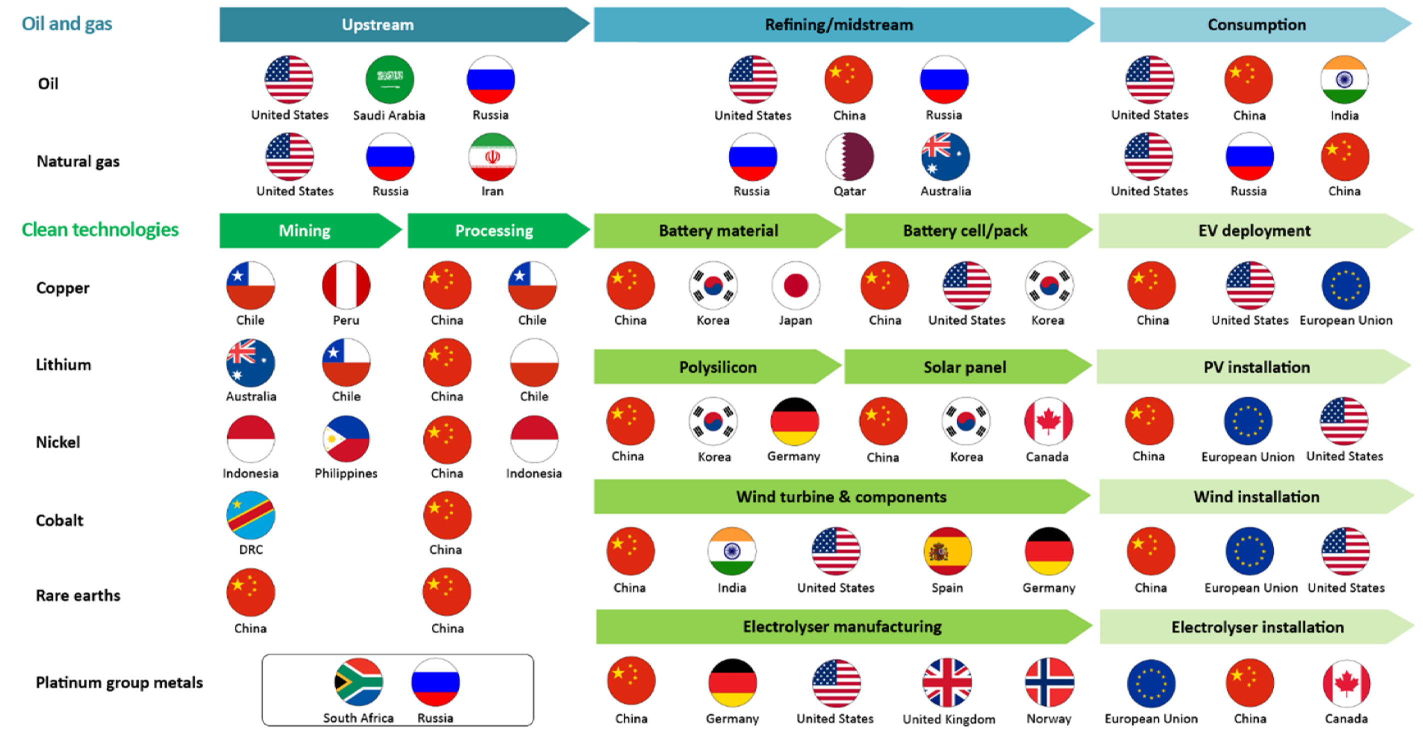
Notes: Mt= million tonnes. 2021 prices are used to calculate the monetary value of critical minerals.

As energy sector dependence on minerals grows, so too will the importance of securing adequate supplies of sustainable and affordable critical minerals. There are important distinctions to be made between critical mineral security and oil or gas security: a price spike for oil affects all consumers driving oil-fuelled cars; a shortage or price spike in critical minerals affects only the production of new EVs or solar panels for the market. As recent price increases make clear, however, supply chain disruptions and rising mineral costs threaten to increase the cost of clean energy technologies and slow their deployment.

Higher mineral prices mean that critical minerals now account for a significant and rising share of the total cost of clean energy technologies, contributing to an uptick in costs since 2020, which reversed a longstanding trend of cost reductions (see Chapter 2). Getting these costs back on a continued downward trajectory requires more robust and resilient mineral supplies, alongside a redoubling of efforts to reduce costs by other means, including through technological innovation, recycling, efficiency improvements and economies of scale.

The risk of supply chain disruptions and volatile prices is exacerbated by the fact that clean energy technology supply chains are highly concentrated. Critical minerals extraction is geographically concentrated, with a single country accounting for over half of global production of several key minerals, notably graphite (China, 79%), cobalt (Democratic Republic of the Congo [DRC], 70%), rare earth elements (China, 60%) and lithium (Australia, 55%). The level of concentration is even higher for processing operations, with China dominating across the board.

Figure 4.18 ▷ Indicative supply chains for oil and gas and selected clean energy technologies



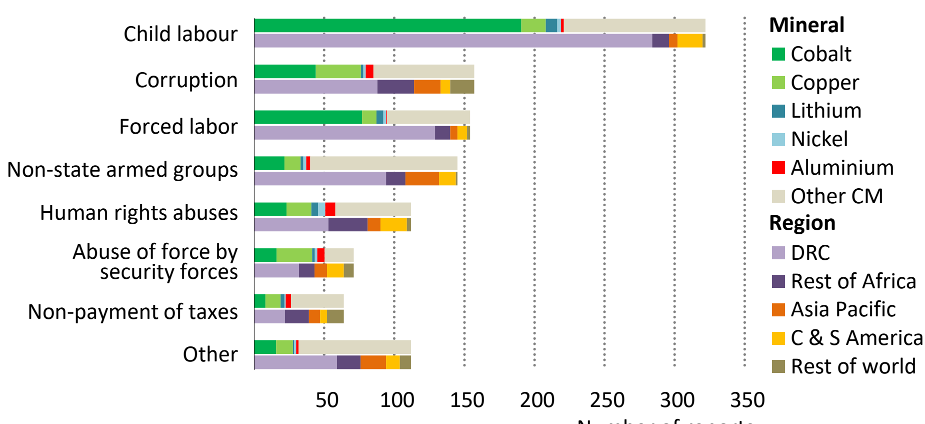
Transition to a clean energy system brings new energy trade patterns, countries and geopolitical considerations into play

Notes: DRC = Democratic Republic of the Congo. Largest producers and consumers are noted in each case to provide an indication, rather than a complete account.

Clean energy technology manufacturing and assembly are also highly concentrated, with China accounting for three-quarters of the manufacturing and assembly of solar PV modules and EV batteries (Figure 4.18). The capital-intensive nature of manufacturing and its technical complexities also mean that it also tends to be dominated by a small number of companies. Just three companies accounted for 65% of global battery cell production in 2021, for example.

Alongside risks from high prices and supply chain issues, there are also significant risks associated with the environmental, social and governance (ESG) impacts of mining projects. Ensuring an adequate supply of minerals for clean energy transitions requires concerted efforts to address and minimise the ESG impacts of mining and mineral processing, such as human rights violations, bribery and corruption, tailings management, water use, air pollution, CO_2 emissions and loss of biodiversity. Clean energy transitions must be carried forward using minerals that prioritise the mitigation of these impacts to align with sustainable and people-centred transitions that policy makers and the public are increasingly demanding.

Figure 4.19 ▷ Public reports of governance-related risks by mineral supply chain and region, 2017-2019



ESG risks could impact mineral supply chains across every region, particularly for cobalt and copper

Notes: CM = critical minerals; DRC = Democratic Republic of the Congo; C & S America = Central and South America. Other critical minerals include chromium, graphite, lead, manganese, molybdenum, niobium, platinum, silicon, silver, tantalum, tin, titanium, tungsten, uranium, vanadium, zinc and zirconium.

Source: IEA analysis based on OECD (2021).

ESG-related incidents may also give rise to short-term mineral supply disruptions with implications for supply chains and prices (Figure 4.19). After specific incidents of corruption or human rights abuses come to light, governments may intervene to stop production at projects where illegal activities are going on. Efforts to bring such sites into compliance may also lead to temporary shutdowns that impact production. These types of risks are especially prominent in the cobalt supply chain in the DRC, where artisanal and small-scale mining is prevalent and where significant allegations of child labour, forced labour and other human rights abuses have been made (OECD, 2019).

Investing in projects with high standards of treatment for communities and the environment is essential to improve the resilience of supply chains, as is credibly and transparently addressing concerns with higher risk projects. In a world with ambitions to reach net zero emissions by mid-century, the demand for ethically sourced and sustainably produced materials is likely to grow rapidly, along with increasing demand for supply chain transparency and traceability. If supply is unable to keep pace with this growing demand then companies may end up competing for a limited pool of these "green materials", leading to bottlenecks in supply chains.

There are also risks in other value chains. Far-reaching energy transitions imply burgeoning demand for low-emissions industrial products such as green steel, green aluminium, green plastics and near-zero cement. However, as things stand, there is uncertainty over how quickly this demand will materialise and at what scale, and no guarantee that these ambitions will be matched by adequate supply. Production costs for many of these low-emissions products generally are not competitive with their traditional counterparts, and some technologies such as green steel or near-zero cement are still at the demonstration stage. If demand materialises and industry ambition does not scale up in time, the tight supply of green materials could push up their prices in the coming decades.

Early demand signals along with comprehensive policy support are important to send a clear market signal to suppliers. Incentivising investment in green materials will help to boost supply and prevent consumers from switching to high emitting materials. This is a matter for companies as well as governments, and a growing number of joint governmental and corporate sectoral initiatives are now seeking to increase the use of green materials. For example, the First Mover Coalition, including more than 50 participating companies such as Volvo, Eiffage and Moller-Maersk, is sending a demand signal for near-zero aluminium, chemicals, concrete and steel. These initiatives are also establishing a strong link between improving the overall emissions intensity of heavy industries and the ESG performance of raw material mining and supply.

From a policy perspective, a comprehensive and co-ordinated approach is required to develop and expand global clean energy technology supply chains that are secure, resilient and sustainable. This requires both the scaling-up and diversification of supplies as well as the implementation of measures to moderate growth in demand. An increasing number of projects have recently been announced to develop domestic supply chains for critical minerals and clean energy equipment. While these would help diversify supply chains, international trade also has a vital part to play to enable cost reductions and promote efficiency.

Policy should also support further technological innovation, which has already shown its ability to relieve some of the pressure on primary supplies while also reducing costs. For instance, silver and silicon use in solar cells over the past decade has been reduced by 40-50%, while recent low cobalt EV batteries contain 75-90% less cobalt than earlier versions, although they use twice as much nickel. Reuse and recycling also have a part to play in reducing the need for primary supplies, while shifting consumer preferences and behaviour could play a significant role in reducing mineral demand from EVs (Box 4.3). Following a new mandate from IEA member governments in March 2022, the IEA is expanding its work to help ensure reliable and sustainable international supplies of critical minerals through market monitoring, policy tracking and facilitating international collaboration on technology innovation, supply chain resilience, recycling, and environmental and social standards.

Box 4.3 ▷ Security benefits of shifting consumer preferences and behaviour

Shifts in consumer preferences and behaviour could play an important role in reaching net zero emissions by 2050, while also offering opportunities to reduce mineral demand, particularly in transport. For example, consumers tend to prefer larger batteries in EVs than they actually need, reflecting both range anxiety and a growing preference for larger and more powerful vehicles such as sport utility vehicles. Between 2015 and 2021, average battery sizes in light-duty EVs increased by 60%. If these trends continue, battery sizes could increase by up to a further 30% by 2030.

Targeted measures to promote EVs with smaller batteries (including plug-in hybrid electric vehicles [PHEVs]) could help to reduce mineral requirements, while lighter vehicles could improve operational energy efficiency and yield safety benefits (Shaffer, Auffhammer and Samaras, 2021). Measures could include differentiating subsidies by battery size (or taxing heavier vehicles in the longer term), accelerating the deployment of charging points to reduce range anxiety and promoting technology innovation aimed at increasing the energy density of batteries. If the current average range of electric cars is maintained – resulting in 20-25% smaller batteries than our base case assumptions between 2030 and 2050 – mineral demand from EV batteries could be around 20% lower in 2030 in the NZE Scenario, equivalent to two years of current demand from EV batteries.

Increasing the utilisation of each EV could also reduce mineral demand by reducing the need for additional new EVs while providing the same level of mobility. While conventional mantra posits that the more EVs sold, the better for the climate, in reality, the emissions benefits of EVs are accrued through its utilisation, not simply its purchase. This means that attention also needs to be given to the utilisation rate of vehicles (and for PHEVs, its electric use factor). Encouraging higher and more efficient utilisation of each EV could achieve the same (or larger) emissions reductions with fewer new EVs, helping to alleviate strains on material supply in the near term. Support for car-sharing could pay dividends here: vehicles used for car- and ride-sharing typically have much higher utilisation rates than privately owned vehicles, and a single shared car could potentially displace up to 20 private cars (Jochem et al.,2020). Policy measures and investments in public transport and infrastructure could at the same time encourage a shift away from private cars to shared mobility services, active transport and public transport (see Chapter 3, section 3.8). In the NZE Scenario, these measures result in a reduction of almost 20% in new passenger car sales in 2050 compared with the STEPS, avoiding nearly 3 million tonnes (Mt) of material demand for batteries, equivalent to around three years of current demand.

4.9 Foster the climate resilience of energy infrastructure

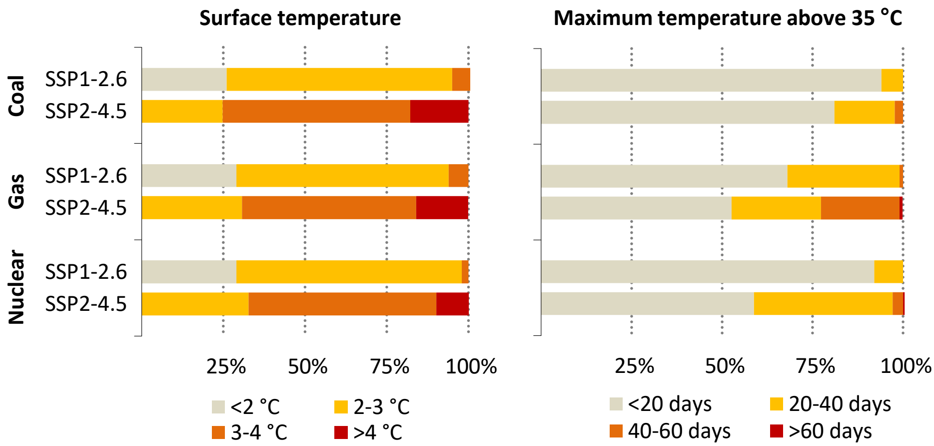
The growing frequency and intensity of extreme weather events presents major risks to energy infrastructure and supply, so governments need to act to ensure that the system has the ability to anticipate, absorb, accommodate and recover from adverse impacts.

There are growing signs that climate change is driving more frequent extreme weather events as well as systemic changes in climatic conditions. Average global temperatures have continued to rise over the past few decades, and heatwaves have become a regular feature during the summer period in a variety of regions. Many countries are experiencing marked changes in rainfall, while tropical cyclones and wind storms are getting more intense. Our analysis suggests that over 85% of IEA member and association countries[11] are already exposed to a medium or high level of climate hazard risks. If emissions remain unabated, the world is likely to experience more frequent and intense climate-related anomalies.

This poses serious risks to energy infrastructure and threatens reliable energy supplies. For example, a warmer climate reduces the efficiency of power plants. Maximum electricity output from a natural gas-fired plant (combined cycle) begins to decline above a temperature of 15 °C, while the efficiency of a solar panel generally degrades by 0.3-0.5% per degree above a temperature of 25 °C. Standard wind power installations are usually designed for a 25 °C environment and may be shut down above 45 °C to protect critical components from additional wear and tear. Thermal power generation has to be curtailed if water temperatures rise above regulatory thresholds in countries such as the United States, France and Germany. In the United States, 13 out of 18 incidents involving power curtailment at coal-fired power plants between 2000 and 2015 were related to water temperature needed for cooling purposes. In an Intergovernmental Panel on Climate Change (IPCC) scenario that leads to a higher long-term temperature outcome, the number of thermal power plants exposed to temperature levels exceeding these thresholds is materially higher than in a scenario with low-temperature outcomes (Figure 4.20) (IPCC, 2021).

[11] IEA Association countries include Argentina, Brazil, China, Egypt, India, Indonesia, Morocco, Singapore, South Africa, Thailand and Ukraine. Ukraine joined as an Association country on 19 July 2022, and so is not included in this analysis.

Figure 4.20 ▷ Share of installed power plant capacity exposed to global temperature rise under various IPCC AR6 scenarios



Failure to reduce GHG emissions could expose a large number of fossil fuel and nuclear plants to severe heat stress, endangering reliable electricity supply

Note: Results show long-term climate projections (2080-2100) compared to preindustrial levels based on two IPCC scenarios representing different temperature outcomes (SSP1: 2.6-2 °C and SSP2: 4.5-3 °C).

Source: IPCC (2021).

Increasing water shortages in dry regions are another source of concern. The production of many fuels and minerals such as shale resources, coal mining, copper and lithium mining, biofuels, and hydrogen production, currently require a considerable amount of water. A projected decrease in water availability at major production sites could disrupt supply. Hydropower is also very sensitive to water availability. Hydro generation could decline significantly in regions where water flows are likely to decrease, such as southern Europe, North Africa and the Middle East. Thermal power plants could be interrupted by shortages that affect the water they rely on for cooling. In France, the Chooz nuclear power plant was closed for around two months when a severe drought hit in 2020, and several other plants had to reduce their output in 2022 due to the lack of cooling water. Increasing water stress could also hinder the deployment of CCUS technology: a plant equipped with CCUS requires over 50% more water than one without it. Extreme droughts also pose risks to energy supply chains that rely on the transport of fuels and materials. In 2022, for example, droughts caused by severe heatwaves in Europe exacerbated low water levels in key rivers such as the Rhine River that transport significant volumes of coal, chemicals and other materials.

Changes in wind patterns may reduce the output from wind farms and cause electricity grid failures. The latest IPCC report suggests that global mean wind speed is likely to decrease, with the potential decline being highest in the regions where current major wind power generators are located, e.g. western United States, northern Europe and East Asia (IPCC, 2021). Wind power generation is proportional to the cube of the wind speed, which means that a 10% decrease in wind speed leads to around a 27% reduction in wind power output.[12]

Lower mean wind speeds are set to co-exist with the projected intensification of tropical cyclones. Tropical cyclones that exceed the limit of wind power plants could temporarily halt their operation and may cause physical damage to turbines. They also risk causing electricity grid failures by damaging transmission and distribution lines, poles and transformers. It is worth noting in this context that the active storm season that hit the United States in 2020 led to historical highs in the frequency and length of power outages.

Floods caused by storms and heavy rainfalls could well be another cause of disruption to energy supplies even though thermal power plants are generally equipped with flood protection structures. In Bangladesh, for example, more than five gas-fired power stations in Sylhet were shut down pre-emptively when flood water engulfed them in June 2022. In the United States, flooding along the Missouri River in June 2011 caused the Fort Calhoun nuclear power station to close for nearly three years after water leaked into the turbine building. Floods and heavy rainfall may also lead to disruptions in coal mining and coal-fired power plants. When a severe flood hit the Rhenish lignite mining area in Germany in 2021, the connected 2 GW Weisweiler power station was suspended for several days. Similarly, three-out-of-four units in coal power plants at Yallourn in Australia were shut for a few days in 2021 when the coal mine supplying them stopped operations as a result of flooding. Given that heavy rainfall and floods are likely to increase in many parts of the world, disruptions of this kind may become more frequent.

SPOTLIGHT

What is the financial impact on energy assets from climate risks?

The increase in frequency and severity of climate hazards such as floods or droughts will have an increasing impact on energy infrastructure assets and their financial viability. By causing damage to assets such as power plants and refineries and interrupting their normal business operations, climate risks can impair the value of assets and in turn negatively impact company balance sheets.

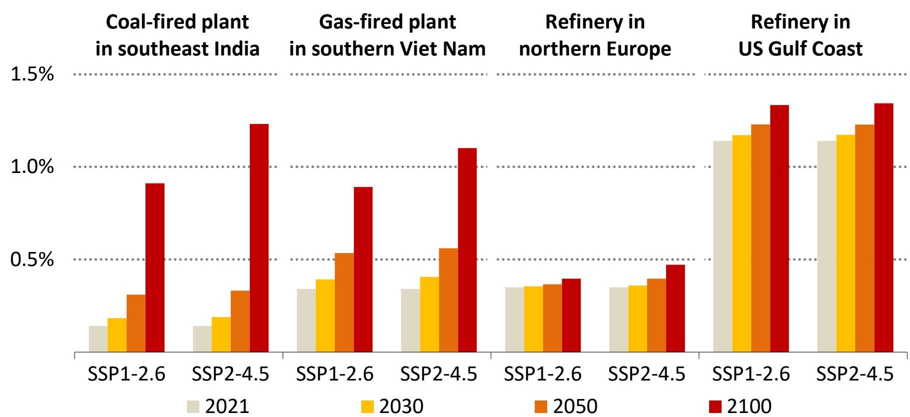
We conducted an illustrative analysis of flood risk at four energy infrastructure sites: a coal power plant in Southeast India; a gas-fired plant in southern Viet Nam, and refineries in northern Europe and the southern United States (Figure 4.21). A refinery in the southern United States currently suffers the highest annual average loss from flooding at 1.1% of its asset value, but this increases only marginally by 2100. A refinery in northern Europe is also projected to face relatively small increases in annual average losses. The two power plants in India and Viet Nam have lower annual average losses today than the two refineries, but those losses are projected to increase much more rapidly. Both plants

[12] When the wind speed is within the range between cut-in speed and rated speed.

could experience average annual losses that increase to 0.3-0.6% of asset value by 2050 and reach up to 1.2% by 2100. This reflects the significant projected increase in more severe and frequent floods at these locations.

The financial impact analysis also shows the benefits of investing in flood defences. The US refinery used in our analysis has flood defences installed: were it not for this, its annual average loss would be around four-times higher.

Figure 4.21 ⊳ Annual average loss of asset value from flooding at four indicative energy supply infrastructure sites based on two IPCC scenarios



The average annual financial impact of floods could amount to 0.3-1.2% of total asset value by 2050

Notes: Annual average loss is the mean expected loss per year with changes in severity and frequency (including the probability of hazard events of different scales occurring) taken into account. In any one year, a large-scale hazard event such as a flood that happens every 100 years could cause much higher loss than the annual average. For the purpose of this illustrative analysis, four assets in distinct locations that have at least some flood risks based on historical data were selected. Projected flood data is based on the IPCC scenarios: SSP1-2.6 and SSP2-4.5 representing different temperature outcomes (SSP1: 2.6-2 °C, SSP2: 4.5-3 °C).

Sources: IEA analysis based on data from Jupiter Intelligence (2022); IPCC (2021); European Commission JRC (2017).

Performing full-fledged and forward-looking climate risk assessments and calculating the potential financial impact caused by climate hazards is still a novel exercise for most governments and energy suppliers. However, assessments of this kind can support energy infrastructure planning, identify worthwhile adaptation investments, help protect the value of energy assets and safeguard their normal operation. Governments should consider incentivising the uptake and improvement of climate risk assessments by including them in planning and corporate disclosure regulations as well as in climate risk stress tests. Regulators, central banks and market authorities in jurisdictions such as Brazil, Canada, European Union, Singapore, United Kingdom and United States have either already implemented mandatory climate risk assessments or announced their support for them.

A growing catalogue of extreme weather events could also have direct impacts on energy demand in key end-use sectors. Rising global temperatures are likely to increase energy demand for cooling in regions such as southern Europe, south and southeast Asia and the Middle East, and air conditioner ownership is set to expand rapidly as a result. This may put extra strain on electricity grids at times of peak demand. Cooling demand in buildings already accounts for as much as 30% of peak electricity loads in some major markets. High temperatures tend to increase it, and the power grid operator in Texas (United States) had to take emergency measures to avoid blackouts during a heatwave in 2022. Periods of intense cold also tend to increase electricity demand. In 2022, a cold snap in Australia led to increased electricity demand that strained the grid system and triggered the first ever curtailment of gas exports and actions to cap energy prices.

Governments need to act to ensure that electricity systems have the ability to accommodate and recover from adverse impacts caused by extreme weather events. Making reliable climate and weather data publicly available could help energy suppliers better understand potential climate risks and impacts, and a combination of regulations and financial support could facilitate private investment in resilience measures. There is also scope to incentivise switching to more resilient technologies such as dry cooling systems for thermal power plants, new designs with enhanced ventilation to enable wind turbines to operate at temperatures of up to 45 °C and state-of-art solar PV cooling technologies. Physical system hardening has a part to play too, for example by improving floodwalls and dikes around power plants and relocating substations to higher ground and increasing the spillway capacity at hydropower facilities. Deploying wind power plants with stronger towers, customised rotor sizes and reinforced foundations in areas prone to tropical cyclones can also help. Improvement of electricity networks with underground lines, upgraded towers and highly meshed systems can also reduce potential physical damages from extreme weather events. Our analysis suggests that the benefits of these measures would generally outweigh the costs over the longer term. Nonetheless, it needs to be noted that reducing emissions is one of the most powerful measures to limit the exposure of energy infrastructure to various climate risks.

4.10 Provide strategic direction and address market failures, but do not dismantle markets

Governments have to take the lead in ensuring secure energy transitions, but they can be significantly assisted by well-functioning markets and market mechanisms that reflect the costs of pollution, by bringing in private capital and allocating it efficiently.

How should governments view the role of markets in delivering reliable and secure energy transitions? For some, the urgency of tackling climate change points towards a strongly interventionist role for policy and regulation in determining where the energy sector needs to go; the severity of today's energy security crisis arguably supports that view. Intervention is undoubtedly required to deliver emissions reductions and security of supply. Yet the much needed transformation of the energy system is unlikely to be efficient if it is managed on a top-down basis alone, especially given the scale of the investment required. One way or another, governments need to harness the vast resources of markets and incentivise private actors to play their part. To do this effectively they need to put in place stable, predictable long-term market frameworks designed to support the achievement of their goals.

One early task for governments is to eliminate distortions and barriers that actively hinder energy transitions such as lengthy permitting procedures, unnecessary trade barriers, inefficient fossil fuel subsidies, and outdated market arrangements that favour incumbent producers and technologies. Fossil fuel subsidies remain pervasive, despite longstanding efforts to phase them out, including a commitment in the Glasgow Climate Pact to accelerate efforts for their removal (Box 4.4).

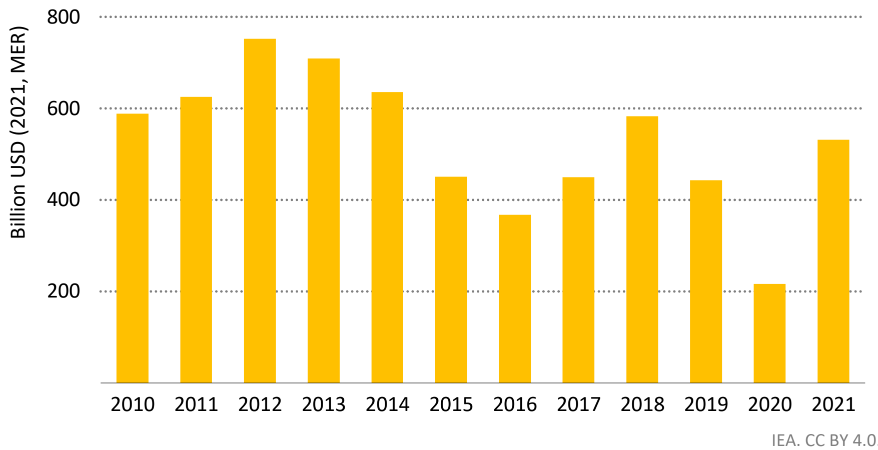
Box 4.4 ▷ Fossil fuel subsidies are back on the rise

Fossil fuel subsidies are a roadblock to a more sustainable future, but the difficulty that governments face in removing them is underscored at times of high and volatile fuel prices. Consumers demand protection from a rising cost of living, and there is a social imperative to protect the most vulnerable in society. In the short term, governments have few instruments at their disposal to respond so they tend to intervene to fix prices or temporarily suspend levies or other taxes. In addition to these short-term measures, some governments habitually keep the prices for certain categories of fuels at low levels. When these interventions hold end-user prices below a reference price that reflects the market value of the energy source in question, then we consider these to be a fossil fuel consumption subsidy. The IEA has tracked these subsidies for many years and, after a noticeable dip in 2020, they were on the rise again in 2021 (Figure 4.22). The global energy crisis will certainly prompt another sharp increase in the estimate for 2022.

One of the most visible costs of fossil fuel consumption subsidies is the fiscal burden that it imposes on countries. This has been particularly severe among fuel importing countries in 2022. For example, in Malaysia, the government estimates that the budget for fuel subsidies will reach MYR 30 billion (around USD 7 billion) in 2022, which is equivalent to 12% of national fiscal revenue; MYR 5 billion (about USD 1 billion) was spent in June alone. In Indonesia, state subsidy spending in 2021 surpassed the budget allocation by 40%, and is set to do the same again in 2022. In fuel exporting countries, the subsidy is the opportunity cost of foregone revenue, rather than an explicit budget item. The less visible costs are felt in the way that subsidies encourage excess consumption of fossil fuels, and the distorted incentives that they introduce for investment.

Pricing reform is essential, but politically difficult; low cost fuels are often part of the implicit social contract in many developing economies, especially those with large hydrocarbon resources. Subsidy removal, on its own, is a blunt tool, so efforts in this area need to be part of a broader strategy that includes efficiency policies to improve the supply of more energy-efficient goods and services as well as measures to protect vulnerable groups. There are a number of examples of successful reform for countries to draw upon. For example, the United Arab Emirates started to gradually phase out gasoline and diesel subsidies in 2015, when global oil prices were relatively low, thus smoothing the impact on citizens affected by the reform. By 2022, gasoline and diesel prices in the country were near the global average.

Figure 4.22 ▷ Fossil fuel consumption subsidies in selected countries



High fossil fuel prices and additional measures to protect consumers during the energy crisis are set to lead to a further sharp increase in fossil fuel subsidies in 2022

Notes: MER = market exchange rate. Fossil fuel consumption subsidies in the following countries are included in this analysis: Algeria, Angola, Argentina, Azerbaijan, Bahrain, Bangladesh, Bolivia, Brunei, China, Colombia, Ecuador, Egypt, El Salvador, Gabon, Ghana, India, Indonesia, Iran, Iraq, Kazakhstan, Korea, Kuwait, Libya, Malaysia, Mexico, Nigeria, Pakistan, Qatar, Russia, Saudi Arabia, South Africa, Sri Lanka, Chinese Taipei, Thailand, Trinidad and Tobago, Turkmenistan, United Arab Emirates, Ukraine, Uzbekistan, Venezuela and Viet Nam.

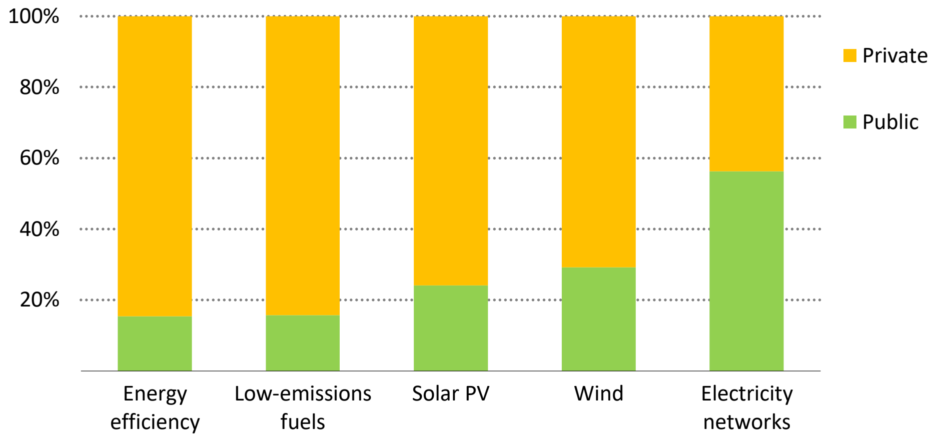
Improving market functioning requires attention to be paid to the changing nature of energy markets, especially in electricity where more and more variable renewables are being added to systems, complemented by more expensive but dispatchable sources of generation to ensure reliability. Most of the latter are currently natural gas-fired plants, and the current energy crisis has sparked a debate in many countries about the merits of a market design in which expensive gas-fired power has pushed wholesale prices to very high levels. As the energy regulatory authority in the United Kingdom recently concluded, current wholesale electricity markets "may not be configured to deliver net zero at lowest cost to consumers" (Ofgem, 2022).

Another important job for governments is to intervene to correct for market failures. The over consumption of fossil fuels that cause climate change is a textbook example. In effect, the absence of a price for carbon makes clean energy technologies less competitive, slowing the transition from fossil fuels, accentuating energy security vulnerabilities and ultimately adding to the damage done by climate change. Putting a price on carbon is one way to internalise these external costs; for the moment, however, less than one-quarter of global energy consumption is covered by a carbon price of some description. Carbon pricing has proved politically difficult to implement in many countries and sectors and, where it exists, in most cases it plays a supplementary role among a broader suite of regulatory measures and targets.

Technology innovation and early stage deployment is an area where markets tend to under invest because of high costs and risks. Deploying public funds or providing tax incentives helps to counteract these obstacles; in order to get to net zero emissions by 2050, innovation cycles for early stage clean energy technologies need to be more rapid than has typically been achieved historically. Bringing early stage clean energy technologies to market by 2030 requires going from first prototype to market around 20% faster on average than the quickest energy technology developments in the past, and around 40% faster than was the case for solar PV. Demonstration projects in sectors where economies of scale favour large installations, such as for sustainable fuels and industrial decarbonisation, are generally the hardest to fund without public support (IEA, 2022g).

The overall scale of investment required to get to a net zero emissions energy system is well beyond the capacity of governments to mobilise directly. Over the course of the current decade, investment in key elements of energy transitions needs to – at least triple – in order to get on track for net zero emissions by 2050. Private capital will have to provide the bulk of the investment, although public finance institutions will be essential in a number of markets to catalyse this spending and help improve the bankability of clean energy projects where the private sector does not yet see the right balance of risk and reward (Figure 4.23). Overall, we estimate that 70% of the investment required in energy transitions needs to come from private sources. This does not mean leaving everything to the market: over 95% of current investments in the electricity sector worldwide rely on regulated revenues or mechanisms to manage price risks. But competitive procurement, such as auctions, is vital to deliver efficient investment on this scale, and to keep costs down for consumers.

Figure 4.23 ⊳ Sources of finance by sector in the NZE Scenario, 2026-2030



Public finance, though its role varies by sector, cannot cover more than a fraction of total investment requirements, yet it needs to act as a catalyst for private capital

Proceeding with energy transitions in a secure way also requires work by governments to set frameworks and to co-ordinate actions. The energy sector in most countries consist of a mix of regulated monopolies, state-owned enterprises and market-driven private players, while transitions require involvement from various levels of government and buy-in from consumers. Markets will need to be guided by overall government strategy and to operate within regulatory frameworks informed by this strategy in order to ensure coherent and well-sequenced actions across multiple areas (see section 4.5).

Well-functioning international markets are also valuable to energy security because they allow trade flows to respond to price signals and scarcity. This was demonstrated in 2022 when higher natural gas prices in Europe were able to attract additional destination-flexible LNG cargoes, albeit at the expense of buyers elsewhere. There are also hopes that international carbon markets may play a positive role in advancing energy transitions, now that governments have reached an agreement on the rules governing international carbon markets (Article 6 of the Paris Agreement) at COP26. Around 85% of new or updated Nationally Determined Contributions (NDCs) have indicated that they plan to use or will possibly use these markets to reach and go beyond NDCs ambition, and voluntary markets – mostly used by corporate entities – have also been expanding rapidly. These markets are still developing, and will need more transparency to counter scepticism about their environmental integrity if they are to flourish, but could play a useful role in complementing large-scale direct mitigation.

Conclusion

The global energy sector is going through a fundamental transformation. While moving towards net zero emissions brings clear and sustained security benefits, the process of transition also entails risks. As energy systems become more interconnected, complex and diverse, new security considerations are emerging alongside traditional energy security risks. The traditional watchwords for energy security – notably the importance of diverse energy sources, supplies and routes – remain as relevant as ever, but they are joined by new considerations and challenges. Tackling new potential hazards may look daunting in light of the current crisis, but ignoring them would be infinitely worse.

It is worth remembering that, although the crisis in the 1970s brought a great deal of economic difficulty and hardship, it also acted as a trigger for energy diversification and rapid technological innovation. It should also be noted that a secure energy system can only be achieved with proper investment in security mechanisms that provide appropriate buffers in the system. Since the oil crisis in the 1970s, the world has long invested in traditional aspects of energy security, including the foundation of the IEA, which provided a backbone of today's energy security framework. The current energy crisis reaffirms the need to invest in the framework that anticipates new energy security risks in an era of decarbonisation.

Outlook for energy demand

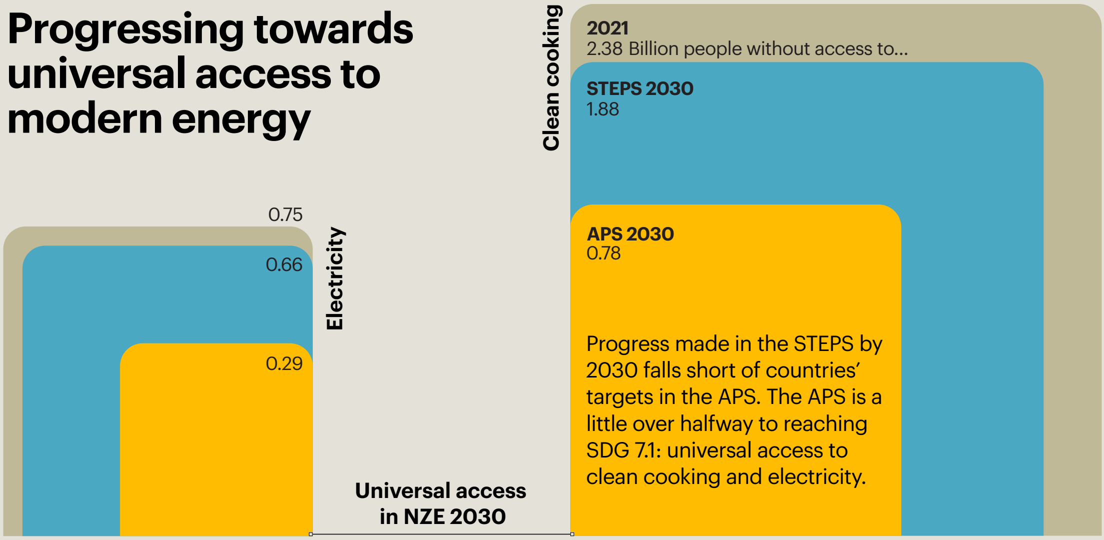
Old habits hard to kick?

SUMMARY

- A gloomy economic outlook leads to lower projections of energy demand growth in this *Outlook* than in last year's edition. High energy prices, heightened energy security concerns and strengthened climate policies are putting an end to a decade of rapid progression for natural gas; its annual demand growth slows to 0.4% from now to 2030 in the Stated Policies Scenario (STEPS), down from 2.3% from 2010 to 2019. Coal sees a temporary surge in demand in some regions from the power and industry sectors in response to increases in natural gas prices, but efforts to reduce emissions soon put coal into decline again, ending the decade with demand 9% lower than today. Renewables, notably solar PV and wind, gain the most ground of any energy source this decade, accounting for 43% of electricity generation worldwide in 2030, up from 28% today. Oil demand rises 0.8% per year to 2030, but peaks soon after at around 103 million barrels per day as electric vehicles (EVs) and efficiency gains undermine its prospects.
- The tone for accelerated clean energy development this decade in advanced economies is being set by new policy packages and government plans and targets, notably those set out in: Inflation Reduction Act (United States); RePowerEU plan and Fit for 55 package (European Union); Climate Change Bill (Australia); and GX Green Transformation (Japan). While not all national energy and emissions targets are reached in the STEPS, advanced economies still see declining demand for all fossil fuels by 2030 – a first in the STEPS. However, these measures take time to roll out. Short-term actions are needed to reduce dependency on fossil fuel imports this winter, especially in Europe, which includes an important role for consumers in terms of behaviour change. In emerging market and developing economies, demand for fossil fuel rises more slowly than in previous versions of the STEPS, notably for natural gas in Asia. The slowdown in fossil fuel demand growth is led by China, where slowing economic growth and policy efforts lead to a peak in emissions during this decade.
- In the Announced Pledges Scenario (APS), fossil fuel use declines further by 2030 than in the STEPS on the assumption that countries meet their national net zero emissions pledges, including those announced by India and Indonesia since the *World Energy Outlook 2021 (WEO-2021)*. All sectors accelerate progress on electrification and energy efficiency compared to the STEPS, with notable acceleration of EVs and electric heating in the transport and buildings sectors. Renewables meanwhile rise rapidly in the power sector and account for nearly 50% of electricity generation by 2030. These outcomes require end-users to spend more upfront in the APS on efficient and low-emissions equipment, but the cost of this equipment declines faster in the APS than in the STEPS due to economies of scale.

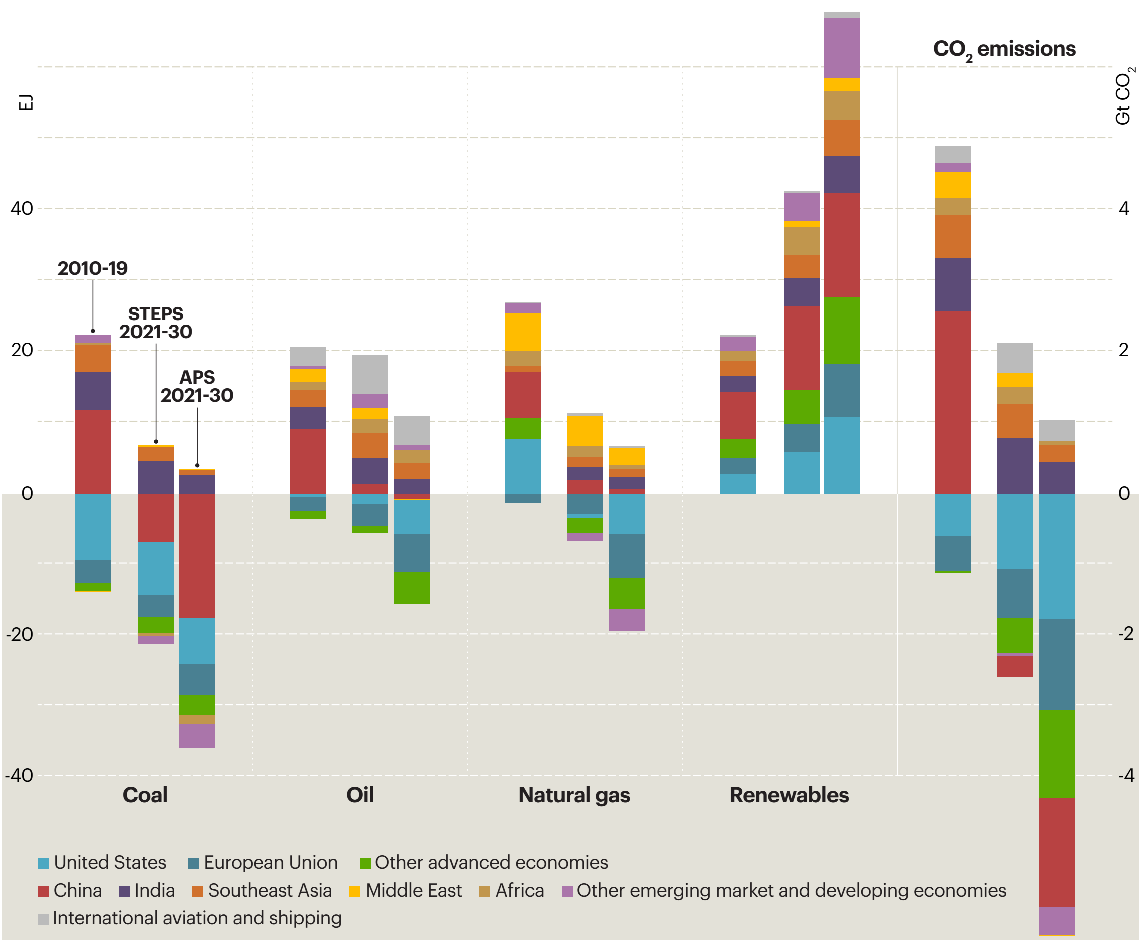
- Energy-related emissions in the STEPS continue to increase in the next two years before starting to decline in the mid-2020s. They fall to 36.2 gigatonnes of carbon dioxide (Gt CO_2) in 2030 – slightly below current levels. In the APS, they are down further to 31.5 Gt CO_2 by 2030 as governments take early and ambitious action with the aim of delivering significant reductions in emissions in this decade, together with improvements in air quality. The private sector plays an important role in the APS, with almost 800 companies pledged to reach net zero emissions, including through sector-wide initiatives for steel, cement, aviation and shipping. However, even the actions in the APS are well short of what is needed in the Net Zero Emissions by 2050 (NZE) Scenario.
- In the developing world, high prices and inflation are slowing progress towards universal access to modern energy. The number of people without electricity is likely to rise in 2022 for the first time in decades. Setbacks in sub-Saharan Africa threaten to erase nearly all the progress made there since 2013. Meanwhile surging prices for liquefied petroleum gas (LPG) may drive up to 100 million people that use it for cooking to revert to traditional fuels. These headwinds mean that the projected number of people without access in 2030 is higher in the STEPS this year than it was in the *WEO-2021*. The APS projects more progress, but achieving all relevant country-level access targets still only gets halfway to universal access for both electricity and clean cooking by 2030. Full achievement of universal access by 2030 will require more ambitious targets, effective implementation measures and higher levels of investment.
- Around 5 billion people live today in areas with substantial needs for space cooling. However, only one-third of households have an air conditioner, mostly in advanced economies. By 2050, climate change and population growth increase the number of people with substantial cooling needs to 7 billion. Electricity demand for space cooling approaches 5 200 terawatt-hours (TWh) in the STEPS as the number of air conditioners rises from the current 1.5 billion to 4.4 billion by 2050, with 90% of the increase in emerging market and developing economies. Growth in demand is cut by more than 50% in the APS as a result of determined efforts to improve the efficiency of air conditioners and with the use of passive cooling measures in buildings.
- Peak oil demand moves forward from the mid-2030s in the STEPS to the mid-2020s in the APS, largely as a result of the faster adoption of EVs. In the APS, EVs account for over 35% of global car sales by 2030, and for more than 50% of sales in China, the European Union and the United States. As a result, the electric car market in 2030 is six-times its size in 2021. This reflects targets to phase out internal combustion engine (ICE) vehicles in 36 countries as well as plans by major manufacturers to pivot to EV production.

Progressing towards universal access to modern energy



Decoupling emissions from growing demand

Renewables are the fastest growing energy source in many regions, and CO_2 emissions fall to 36.2 Gt in the STEPS – slightly below current levels, and to 31.5 Gt in the APS, a 14% reduction compared to current levels.



Introduction

The current energy crisis is reshaping previously well-established demand trends. Industries exposed to global prices are facing real threats of rationing and are curbing their production. Consumers are adjusting their patterns of energy use in response to high prices and, in some cases, emergency demand reduction campaigns. Policy responses vary, but in many instances they include determined efforts to accelerate clean energy investment. This means an even stronger push for renewables in the power sector and faster electrification of industrial processes, vehicles and heating.[1] As many of the solutions to the current crisis coincide with those needed to meet global climate goals, the crisis may end up being seen in retrospect as marking a critical turning point in the drive for both energy security and emissions reductions.

This chapter explores how these developments come together to reshape energy demand trends. In the first part, projections in the Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS) are examined by fuel, by region and by sector, with a particular focus on the period to 2030, and are compared to those from the Net Zero Emissions by 2050 (NZE) Scenario. The chapter also analyses how CO_2 emissions, air pollution and investment are being affected by new developments, and looks at what further action is needed to meet national net zero emissions pledges. In the second part of the chapter, three key themes are explored: how the current crisis is affecting the drive to achieve universal access to electricity and clean cooking; how energy efficiency policies can temper electricity demand for cooling; and how the rapid uptake of EVs is leading to an earlier peak in oil demand.

Scenarios

5.1 Overview

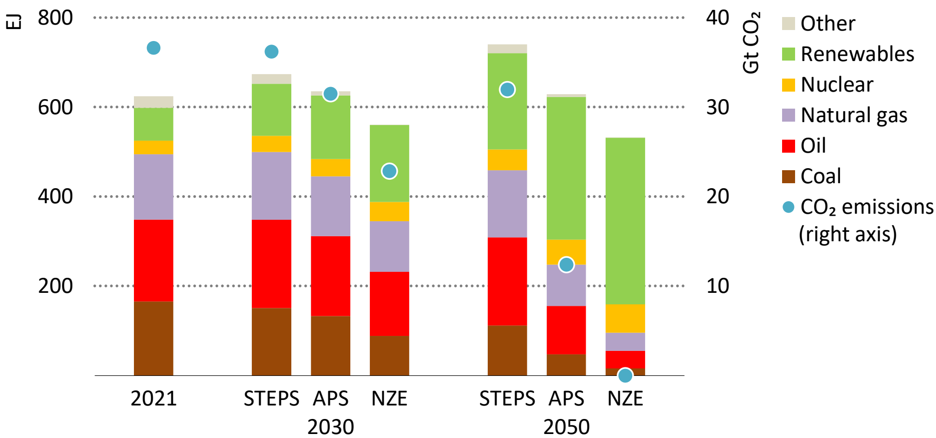
High energy prices, a sobering economic outlook and policy responses to energy security concerns lead to lower projected energy demand growth to 2030 in this STEPS and APS than in the *WEO-2021*. Consumers are forgoing purchases in the face of market uncertainty and high prices, and industry is scaling back production. The duration of the energy crisis remains highly uncertain, but there is likely to be a correlation between its duration and the damage it does to long-term economic prospects.

Economic growth to 2030 is slower than previously projected, which means lower levels of activity in all sectors and in turn lower energy demand growth. Despite a strong economic rebound from the Covid-19 pandemic in 2021, the current crisis has reduced projections of global GDP growth to 3.3% per year through to 2030 (see Chapter 2). Energy demand rises more slowly in both the STEPS and APS as a result, and the energy sources used to meet this demand change substantially from previous projections. In the STEPS, the world grapples with today's energy price shocks, with some regions reverting to previous trends while others with stronger decarbonisation policies see a faster shift to renewables and end-use

[1] The *Future of Heat Pumps*, a forthcoming *World Energy Outlook* Special Report will be published in late 2022.

electrification. Primary energy demand is set to increase in the STEPS by around 1% a year to 2030, which is largely met through increased use of renewables (Figure 5.1). The APS sees the same trends, but governments, companies and citizens take additional measures to ensure that the response to these trends is consistent with long-term climate ambitions, which have been strengthened by new commitments since the *WEO-2021* (see section 5.3). In the APS, energy demand is set to increase by 0.2% a year to 2030.

Figure 5.1 ▷ Total energy supply by fuel and CO_2 emissions by scenario



Renewable energy increases more than any other energy source in each scenario; CO_2 emissions hold at current levels in the STEPS to 2030, but drop14% in the APS

Notes: EJ = exajoule; Gt CO_2 = gigatonnes of carbon dioxide; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Natural gas sees the largest slowdown of any fuel in the STEPS compared to the *WEO-2021*, with annual growth falling to around 0.4% from 2021 to 2030, ending the decade with demand at around 4 400 billion cubic metres (bcm) per year. Concerns about enduring high prices have lasting effects across all sectors. New gas power plant construction **slows**, with countries opting for other sources to maintain system adequacy and flexibility while accelerating renewables in parallel. Energy demand in industry also slows in the face of a stronger push for the electrification of new industrial capacity. Policy interest in compressed natural gas (CNG) vehicles wanes, and global efforts to reduce natural gas use accelerate the electrification of heating in buildings. In the APS, natural gas use begins to decline this decade and demand falls to less than 3 900 bcm in 2030, an 8% reduction from current levels. Emerging market and developing economies still see growth, but this is more than outweighed by advanced economies using 460 bcm less natural gas in 2030 than today, with the decreases primarily in the power and buildings sectors. In the NZE Scenario, natural gas declines to under 3 300 bcm by 2030 as policies restrict the sale of fossil fuel boilers in buildings after 2025 and as the use of renewables in power generation accelerates.

Coal demand rebounded strongly in 2021 to over 5 600 million tonnes of coal equivalent (Mtce) as economies recovered from the pandemic and as some countries – notably India and China – turned to domestically produced fuel sources in the interests of affordability and energy security. This surge is not a long-term one in any of our scenarios. In the STEPS, coal demand remains near its historic peak for the first-half of the decade, but returns to structural decline in the second-half of this decade. Increased demand in industry to 2030 is concentrated in emerging market and developing economies, where coal already accounts for 35% of energy use in industry. In the APS, coal demand declines more rapidly, falling by 175 Mtce each year from 2025 to 2030 to 4 540 Mtce in 2030, compared with 5 150 Mtce in the STEPS. Coal use falls in power generation as the use of renewables increases. It also declines in industry, where there is an acceleration of green steel production, a general shift away from coal in cement kilns and a sharp reduction in the use of coal for the provision of low-temperature heat in light industries. In the NZE Scenario, coal demand falls to around 3 000 Mtce in 2030 and all coal subcritical power plants are phased out by that date.

Oil demand is set to increase by 0.8% per year this decade in the STEPS, but the uptake of EVs causes oil demand to peak at around 103 million barrels per day (mb/d) in the mid-2030s as declining demand in advanced economies outweighs continuing demand growth in emerging market and developing economies. In the APS, oil demand reaches a peak in the mid-2020s as sales of passenger EVs rise reflecting national and corporate targets, with current oil prices and policy support increasing consumer appetite for all-electric or plug-in hybrid vehicles. EVs account for 20% of global car sales by 2025, up from 9% today (see section 5.8). In the NZE Scenario, oil demand declines to 75 mb/d in 2030 as the road transport sector undergoes rapid electrification, and electric cars account for 60% of global car sales by 2030.

Renewables continue their rapid ascent in the STEPS, expanding faster than any other source of energy. Accelerated electrification creates more headroom for renewables and they increasingly out-compete other sources of generation in most regions. The share of renewables in electricity generation rises from 28% in 2021 to 43% in 2030, with wind and solar PV alone accounting for nearly 90% of the increase in electricity generation to 2030. In the APS, renewables deliver nearly 50% of power generation globally by 2030 as the G7 countries make progress towards achieving their commitment to decarbonise power by 2035. The increase of renewables worldwide outpaces electricity demand growth to 2030 in the APS, decreasing the share of fossil fuel generation. Wind and solar PV continue to dominate the growth in renewable electricity, complemented mainly by hydropower, bioenergy and geothermal. The use of biofuels also increases to 5.5 million barrels of oil equivalent (mboe/d) in 2030 from 2.2 mboe/d today, aided by wider adoption of blending requirements. In the NZE Scenario, wind and solar PV expand even more rapidly; by 2030 annual capacity additions exceed 1 050 gigawatts (GW).

Nuclear power generation increases by 2030 in both the STEPS and APS, with China accounting for the largest growth. (See Chapter 6, section 6.3 and IEA, 2022a). The use of low-emissions **hydrogen and hydrogen based-fuels** also increase by 2030, thanks to early commercial-scale projects in industry initiated by emerging public-private partnerships (Box 5.1). In the NZE Scenario, the use of low-emissions hydrogen and hydrogen-based fuels is three-times higher in 2030 than in the APS.

In aggregate, these trends are projected to increase energy-related **CO_2 emissions** in the STEPS in the coming years, although emissions are still set to peak by 2025. Emissions then fall to 36 Gt CO_2 by 2030, 0.4 Gt CO_2 lower than today (Table 5.1). In the APS, annual CO_2 emissions peak before 2025 and then fall to 32 Gt CO_2 by 2030. Progress is made on access to electricity and clean cooking in the APS as the pledges made by various countries are met in full, but still falls short of achieving universal access by 2030 (see section 5.6).

Table 5.1 ▷ Key energy indicators by scenario, 2010-2050

			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Access (million people)								
Population without access to electricity	1 392	754	663	727	292	112	0	0
Population without access to clean cooking	2 916	2 386	1 880	1 601	783	535	0	0
Premature deaths from (million people):								
Ambient air pollution	n.a.	4.2	4.8	7.1	4.6	6.5	3.3	2.9
Household air pollution	n.a.	3.6	2.9	3.0	1.6	1.9	1.0	1.2
Energy-related CO_2 emissions (Gt)	**32.9**	**36.6**	**36.2**	**32.0**	**31.5**	**12.4**	**22.8**	**0**
CO_2 captured via CCUS	0	0.04	0.1	0.4	0.5	4.3	1.2	6.2
Primary energy supply (EJ)	**542**	**624**	**673**	**740**	**636**	**629**	**561**	**532**
Share of unabated fossil fuels	81%	79%	74%	61%	69%	34%	59%	10%
Energy intensity of GDP (GJ per USD 1 000, PPP)	5.1	4.3	3.4	2.2	3.2	1.9	2.9	1.6
Electricity generation (1 000 TWh)	**22**	**28**	**35**	**50**	**36**	**61**	**38**	**73**
CO_2 intensity of generation (g CO_2/kWh)	524	459	325	158	280	41	165	-5
Share of low-emissions generation	32%	38%	53%	74%	59%	91%	74%	100%
Total final consumption (EJ)	**383**	**439**	**485**	**544**	**451**	**433**	**398**	**337**
Share of unabated fossil fuels	69%	66%	64%	57%	61%	36%	56%	15%
Share of electricity in TFC	17%	20%	22%	28%	24%	39%	28%	52%

Notes: Gt = gigatonnes; CCUS = carbon capture, utilisation and storage; EJ = exajoule; GJ = gigajoule; PPP = purchasing power parity; TWh = terawatt-hour; kWh = kilowatt-hour; TFC = total final consumption. STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Box 5.1 ▷ Reporting volumes of low-emissions hydrogen

Nearly all hydrogen produced today comes from fossil fuels converted within industrial facilities such as refineries and chemical plants. Much of this is onsite production, which means the energy balances for these sectors report only the purchased fuel input, such as natural gas, and not how much hydrogen is produced or used. The increasing interest in new methods of producing and consuming hydrogen means that alternative reporting processes are needed to enable a full understanding of the roles that hydrogen plays in the global energy economy in various scenarios.

This *Outlook* only reports volumes of low-emissions hydrogen (Table 5.2). This type of hydrogen is produced from electricity generated by renewables or nuclear, from bioenergy, or from fossil fuels with minimal methane emissions and used with carbon capture, utilisation and storage (CCUS) or produced via pyrolysis. It can be used as a fuel or chemical feedstock, or transformed into other energy carriers, including electricity, oil products, biofuels and low-emissions hydrogen-based fuels (ammonia, methanol, synthetic kerosene and synthetic methane). Low-emissions ammonia is treated as a liquid fuel.

Low-emissions hydrogen reported in final energy consumption includes those volumes produced in one facility and transported to another, typically under a merchant contract. Total low-emissions hydrogen production is calculated by adding the volumes of low-emissions hydrogen in final energy consumption to volumes produced onsite and the volumes used to produce other energy carriers. Reported trade volumes include both low-emissions hydrogen and low-emissions hydrogen-based fuels.

Table 5.2 ▷ Supply and demand of low-emissions hydrogen and fuels

	STEPS		APS		NZE	
Mt hydrogen equivalent (energy basis)	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total low-emissions hydrogen production	6	24	30	225	90	452
Water electrolysis	4	17	21	167	58	329
Fossil fuels with CCUS	2	8	9	57	31	122
Bioenergy	0	0	0	1	0	2
Transformation	3	10	14	95	50	186
To power generation	0	1	4	19	27	60
To hydrogen-based fuels	0	3	6	69	18	118
To oil refining	2	5	3	6	2	4
To biofuels	1	1	1	1	3	3
Demand by end-use sector	3	15	16	131	40	266
Total final consumption	1	10	12	80	31	174
Onsite production	2	4	4	51	9	92
Low-emissions hydrogen-based fuels	0	3	3	55	15	96
Total final consumption	0	1	3	39	7	68
Power generation	0	2	0	16	8	28
Trade	1	5	4	44	18	73

Notes: Mt = million tonnes. 1 Mt hydrogen = 120 petajoules. Transformation to hydrogen-based fuels incurs energy losses that are the difference between hydrogen inputs to hydrogen-based fuels and the demand for these fuels.

5.2 Energy demand

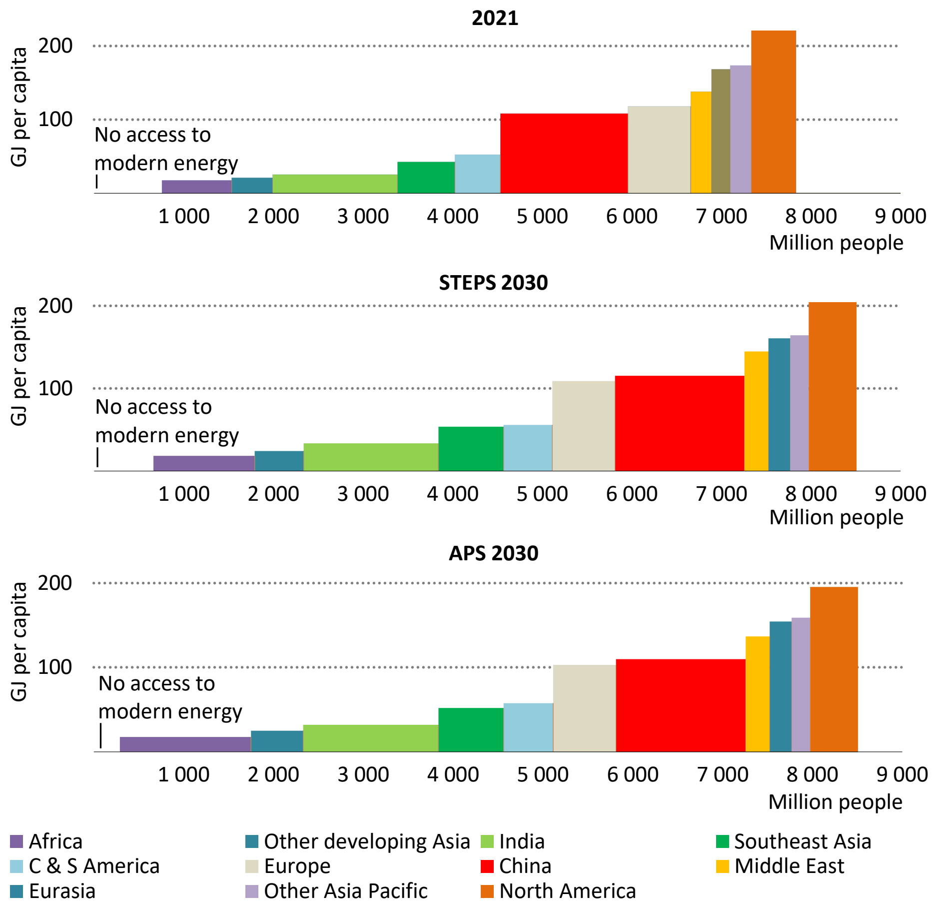
Regional trends

Energy demand in advanced economies declines over the rest of this decade by around 0.5% per year in the STEPS. In the APS, renewables and electrification increase faster, and fossil fuel demand is 17% lower in 2030 than in the STEPS. Energy demand is projected to continue to increase in emerging market and developing economies by over 1.4% per year in the STEPS through to 2030: China and India alone accounting for nearly half of this growth. Renewables, on average, meet over half of the overall increase in energy demand. Demand also increases in the APS, although at the lower rate of 0.7% per year. These divergent trends in advanced economies and in emerging market and developing economies lead to per capita energy demand in China rising above the level in Europe in both the STEPS and the APS by 2030, but the changes are not large enough to bring any other major alterations in existing regional patterns of energy use (Figure 5.2).

In the **United States**, the Inflation Reduction Act and the Bipartisan Infrastructure Act together are set to provide nearly USD 560 billion in public support for clean energy, with the Inflation Reduction Act alone contributing roughly USD 370 billion, mobilising much more in private investment. This helps to spur progress. In the STEPS, coal demand falls by three-quarters to 2030, largely driven out by increasing shares of solar PV and wind (Figure 5.3). Natural gas demand increases for a few years, but peaks before 2030, and ends the decade just under the level it reached in 2021. Oil demand falls by 1 mb/d from nearly 18 mb/d today to nearly 17 mb/d in 2030, driven largely by rising EV sales (EVs account for 30% of car sales in 2030) and fuel economy improvements. In the APS, a more rapid uptake of EVs – accounting for 50% of car sales in 2030 – brings about a reduction in oil demand of over 1 mb/d by the end of the decade.

In the **European Union**, climate policies, high fossil fuel prices and efforts to reduce import dependency on Russia combine to reduce fossil fuel demand, despite a temporary resurgence of coal in the current crisis (Spotlight). Government spending in favour of clean energy transitions enacted in the framework of national Covid-19 recovery plans and energy crisis packages contribute around USD 389 billion to clean energy by 2030, helping spur this reduction. In the STEPS, demand for coal declines by around half before 2030, and demand for natural gas and for oil by almost a fifth. Wind and solar PV expand rapidly, and account for almost 30% and 15% of electricity generation respectively by 2030, up from 13% and 5% in 2021. Nuclear power output in the STEPS is consistent with the latest announcements on closures and extensions. Reductions in natural gas use in buildings and industry are also responsible for the decline in fossil fuel demand, together with reductions in oil use that reflect the rise in EV sales. In the APS, targets in the Fit for 55 plan are largely met – and in some cases exceeded – fulfilling the EU's NDC to reduce GHG emissions by 55% by 2030 relative to 1990. In the APS, the uptake of renewables accelerates, and the combined share of wind and solar PV in power generation in the European Union rises to 50% in 2030. EV sales also rise at a faster rate than in the STEPS.

Figure 5.2 ▷ Total modern energy supply per capita by region in the STEPS and APS, 2021 and 2030

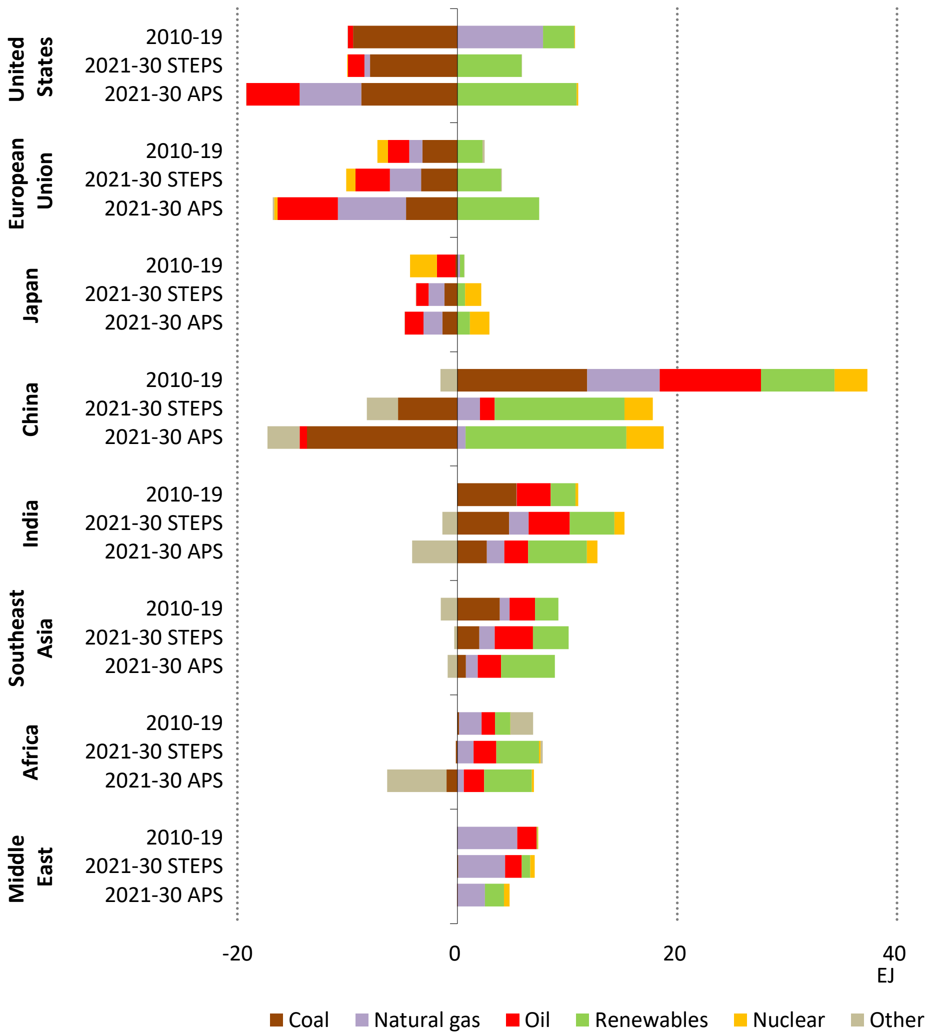


Energy supply per capita declines in advanced economies to 2030 while increasing elsewhere as incomes rise, but the shifts are modest and existing regional patterns remain

Notes: GJ = gigajoule; C & S = Central and South America. Modern primary energy demand excludes traditional use of solid biomass. The country/regional blocks show only people with access to modern energy.

Japan is working to reduce its energy security risks while pushing forward with its climate agenda through measures to decrease exposure to imported fossil fuels, increase its share of nuclear and renewables, and improve energy efficiency. In the STEPS, these policies lead to an annual decline in total energy supply of 1% in line with the targets laid out in the Strategic Energy Plan approved in October 2021. In the APS, further electrification of industry and boosted energy efficiency improvements based on the new Energy Efficient Technological Strategies and strengthening of the Top Runner programme reduce demand further, as do new materials standards for building construction and further electrification of the transport sector, in line with national decarbonisation pledges. Decarbonisation of the power sector in the APS reflects the recent Green Transformation Plan that aims to step up the restart of its nuclear reactors and to introduce further measures to support manufacturers of nuclear technology.

Figure 5.3 ▷ Change in total energy supply by region, fuel and scenario, 2010-2019 and 2021-2030



IEA. CC BY 4.0.

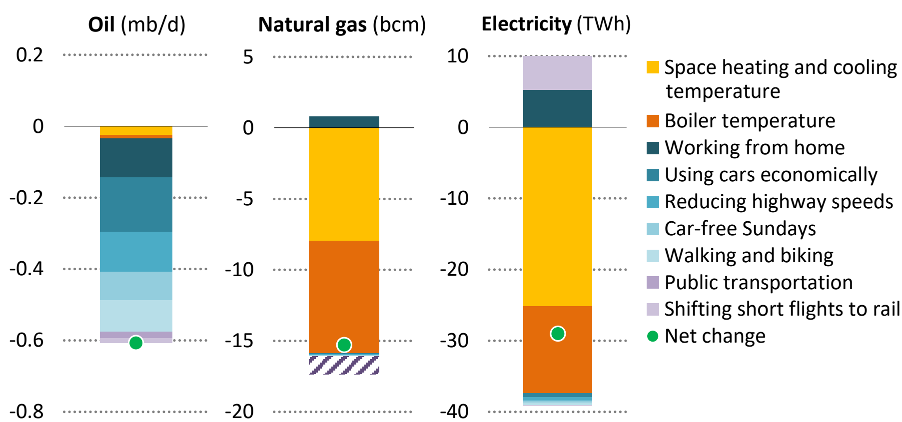
Advanced economies shift significantly from fossil fuels to renewables this decade, while demand for all sources rises in most emerging market and developing economies

S P O T L I G H T

I save, you save, we save

Energy savings at the level of the individual or household can make a sizeable difference to reductions in energy demand and related emissions, provided that policies are put in place to enable and support individuals to change behaviour. In the wake of Russia's invasion of Ukraine, the IEA released *A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas* and *A 10-Point Plan to Cut Oil Use* in March and April 2022 (IEA, 2022b, IEA, 2022c). Drawing on these, the IEA also released *Playing My Part* in April 2022, which identifies actions that national and local governments can take to support consumers to reduce demand and unlock more energy savings (IEA, 2022d). If all the *Playing My Part* recommendations were to be implemented in full, it would save 220 million barrels of oil a year and around 17 bcm of natural gas, cutting households energy bills on average by more than EUR 450 per year (Figure 5.4).[2]

Figure 5.4 ▷ Oil, natural gas and electricity demand reductions from EU citizen actions based on the *Playing My Part* recommendations



Behavioural changes could immediately save 0.6 mb/d of oil, 17 bcm of gas and 30 TWh of electricity a year

Notes: mb/d = million barrels per day; bcm = billion cubic metres; TWh = terawatt-hour. The hashed area for natural gas shows the amount of gas that could be displaced from the reduction of electricity consumption. Energy impacts of working from home and shifting short flights to rail are net negative and represent energy savings. In the *Playing My Part* report, 0.6 mb/d of oil savings and 17 bcm of natural gas savings were calculated including indirect fuel savings from lower electricity consumption, which is shown separately in this figure.

[2] Analysis based on an average across all EU households which will vary between individual households. Energy bill savings correspond to the savings that can be achieved for representative households, i.e. for households that can apply these measures, for example, working from home cannot be done for all jobs, thus savings related to this measure only apply to households for which it is possible.

Citizens can play a major part in realising these reductions. A majority of the recommendations in *Playing My Part* are concerned with behavioural change. Seeking behavioural change as part of crisis response is not a novelty and has successfully been done in the past, notably during the 1970s oil crises and as part of the response in Japan to the Fukushima disaster. Ten countries in the European Union have already implemented some form of policy to support the behaviour changes laid out in *Playing My Part*. For example, Germany and Austria have reduced public transport fares, Belgium is promoting car-sharing, and the Netherlands and Italy are encouraging households to turn down their thermostats and at the same time requiring temperatures to be moderated in public buildings. Continued policy support for measures of this kind through to 2030 and beyond would help to bring the world closer to the NZE Scenario trajectory.

Around 15% of the savings in oil demand are emergency response measures to cushion the impact of the current crisis, such as car-free Sundays. These emergency measures would temporarily inconvenience citizens and in some cases pose real challenges to their everyday lives, but they have the potential to contribute 0.1 mb/d of oil savings in the European Union. However, most behavioural measures proposed would reduce the day-to-day energy used by citizens without materially reducing energy service. These so-called sustainable behavioural changes could become ingrained and contribute lasting energy reductions beyond the present crisis.

The importance of behavioural change was highlighted in the IPCC Sixth Assessment Report (AR 6) in many of the scenarios which limit global warming to below 1.5 °C (IPCC, 2022). Many of the behavioural changes proposed in this analysis play a lasting role in the NZE Scenario (see Chapter 3).

Energy demand growth in **China** begins to slow this decade in the STEPS. It peaks just before 2030, as do emissions, in line with its Nationally Determined Contribution (NDC) and national targets. Coal remains China's largest energy source, but its dominance in the power sector is increasingly squeezed by renewables, which are responsible for nearly 45% of electricity generation in 2030 in the STEPS. Meanwhile, the coal-based chemical industry in China reaches a plateau. Oil demand peaks in the second-half of this decade, reaching around 16.5 mb/d (the same level of demand as in the United States in 2030) and then begins to decline. This decline reflects expanding electrification of transport, with EVs accounting for more than 50% of car sales by 2030. These outcomes are consistent with the 14th Five-Year Plan (2021-25). In the APS, the peak in emissions occurs slightly earlier and at a slightly lower level as demand for renewables rises faster, particularly in the power sector. This faster growth puts renewables on track to play their part in the achievement of carbon neutrality in China before 2060.

Energy demand in **India** continues to rise at over 3% per year in the STEPS from 2021 to 2030, spurred by GDP growth of more than 7% per year in the same period. Coal meets a third of this growth with demand rising above 770 Mtce by 2030, and continuing thereafter before peaking in the early 2030s. Oil demand meets a further quarter of the energy demand growth and rises to nearly 7 mb/d by 2030. Government programmes, such as the Gati Shakti National Master Plan and the Self-Reliant India scheme, lead to increases in renewables and sales of EVs in the STEPS. Helped by these programmes, renewables meet 30% of demand growth to 2030, notably through a rapid increase in solar PV deployment. By 2030, renewables account for 35% of generation, and solar alone accounts for 15%. In the APS, both electrification and renewables increase faster in line with the progress needed for India to its reach net zero emissions target by 2070.

Southeast Asia also sees rapid growth in energy demand. In the STEPS, demand rises over 3% per year from 2021 to 2030, surpassing the level of growth over the last decade. Oil is the biggest component of this increase in demand with consumption rising to 6.7 mb/d by 2030. Renewables, natural gas and coal demand all rise quickly too. Coal continues to dominate the electricity sector, though its share of generation declines from 42% today to 39% by 2030 in the STEPS. In the APS, renewables become the dominant source accounting for close to 40% while coal declines to a third by 2030. EV sales rise sharply, thanks in part to progress towards Thailand's commitment to end the sale of new internal combustion engine (ICE) cars by 2035, Singapore's commitment to do the same by 2040, and Indonesia's target of 2 million electric car fleet by 2030.

Africa sees a modest improvement in the number of people without access to electricity in the STEPS by 2030, however, current energy price surges threaten near-term progress. By 2030, the number of people without access to clean cooking reaches almost 1 billion from 965 million in 2021. Per capita energy use remains low and this hinders economic growth. However, increases in low cost renewable power resources add substantially and account for more than 35% of Africa's power supply by 2030. Most of the increase in renewables is from hydropower and solar PV, but some also derives from wind and geothermal resources. Growth in demand for oil in transport and for LPG in cooking pushes demand to over 5 mb/d by 2030. As well, natural gas experiences an uptick in demand, supported by the discovery of new reserves: it is used in particular in the expanding steel, cement, desalination and fertiliser industries. The effects of climate pledges by African countries and of reaching universal access are explored in detail in *Africa Energy Outlook 2022* (IEA, 2022e).

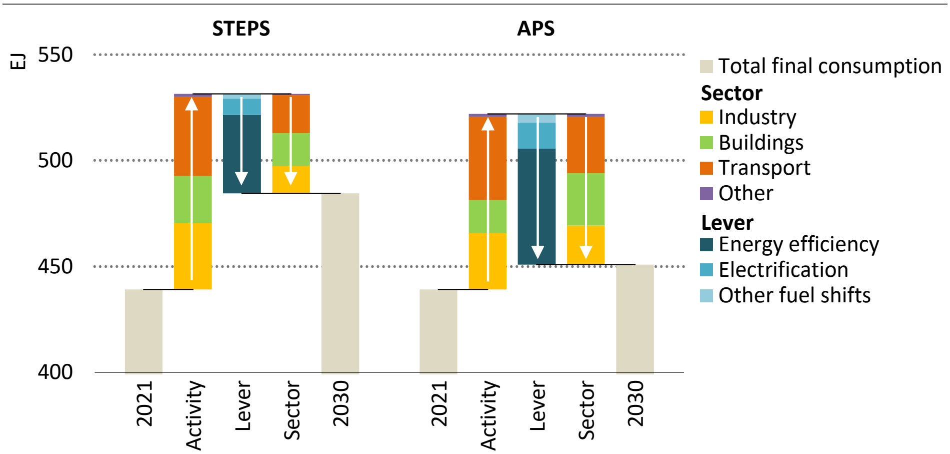
The **Middle East** sees increasing demand for natural gas, which meets over 60% of the overall demand growth to 2030 in the STEPS, but renewables emerge as a notable contributor in the power sector, thanks to some of the lowest cost solar in the world and to increasing interest in economic diversification.

Sectoral trends

Primary energy intensity improves by 2.4% a year over the period to 2030. The share of electricity in total final consumption in the STEPS rises from 20% in 2021 to 22% by 2030, and electrification drives improvements in energy efficiency, notably via the faster adoption of EVs and heat pumps that are more efficient than their fossil fuel counterparts. New industrial facilities become more efficient through the electrification of low-temperature heat applications, the use of best-in-class electric motors in light industry and an increase in the number of electric arc furnaces in the steel industry. Insulation in buildings improves, and new appliances meet higher energy efficiency standards. These changes are reinforced by unprecedented levels of financial support for energy efficiency in government recovery packages, notably for building retrofits in advanced economies. End-use efficiency improvements and electrification are together able to curb the effects of activity growth, resulting in total final consumption by 2030 in the STEPS being 10% higher than current levels, well below the 20% increase in activity growth over the period (Figure 5.5).

In the APS, the more rapid gains from end-use efficiency and electrification result in total final consumption being lower by 2030 than in the STEPS. The share of electricity in total final consumption increases to 24% in 2030 in the APS, with faster electrification in all sectors. Innovation also makes a bigger difference in the APS, with new targets and increased commitments reducing the risks of investing in demonstration projects for near zero emissions technologies. This plays a large part in driving down costs and increasing the deployment of clean energy technologies in hard-to-abate sectors.

Figure 5.5 ▷ Changes in global final energy consumption by lever and sector in the STEPS and APS, 2021-2030

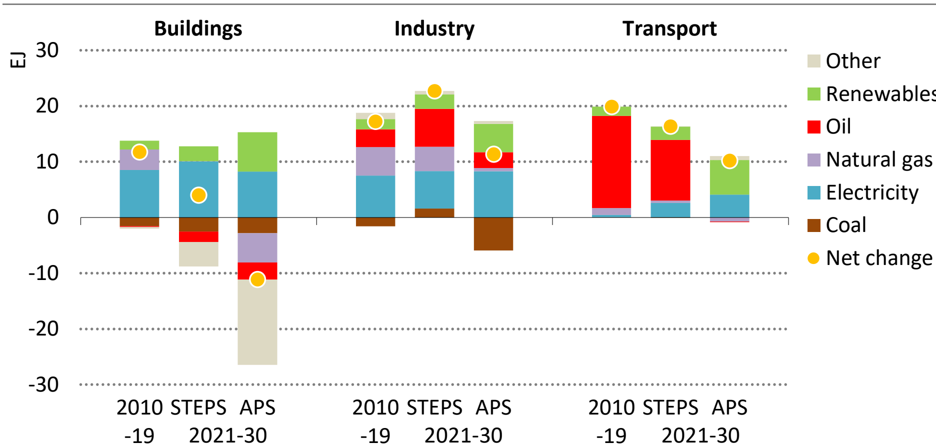


Efficiency improvements and electrification moderate the impact of increasing demand for services on final energy consumption in the STEPS, and almost eliminate it in the APS

Energy use in **buildings** continues to rise in the STEPS, ending the decade 3% higher than in 2021, driven by an overall expansion of floor area and growth in the ownership of appliances in emerging market and developing economies. Electricity dominates demand growth, increasing by 10 exajoules (EJ) to 2030 (Figure 5.6). Most of the increasing demand for electricity is for appliances and air conditioners, but demand for electric heating and cooking increases by 2.7 EJ, displacing fossil fuel use in some regions. Improvements in building codes and stronger support for building retrofits under the US Inflation Reduction Act and the EU Energy Performance Buildings Directive, appliance efficiency standards and fuel switching incentives in force or announced by governments are sufficient to improve the energy intensity of the building stock by about 20% per square metre by 2030 in the STEPS. This corresponds to energy efficiency savings in the global buildings sector of around 14 EJ by 2030, and offsets more than 60% of activity growth.

In the APS, energy demand in the buildings sector declines by 8% from current levels by 2030, and is about 10% lower than in the STEPS by 2030. The divergence from the STEPS is driven mostly by global advances in access to clean cooking; as people switch to cooking with more efficient fuels and stoves, the traditional use of biomass drops by 15 EJ to 2030. It is also driven by efforts to cut natural gas demand in Europe by improving the efficiency of building envelopes, switching to heat pumps and placing more reliance on buildings management systems (BMS). Emerging market and developing economies make notable strides to improve efficiency in buildings and increase electrification. The net result is that efficiency and electrification in buildings offset almost 1.5-times the energy demand growth stimulated by activity growth by 2030 in the APS.

Figure 5.6 ▹ Change in total final consumption by sector, fuel and scenario, 2010-2019 and 2021-2030



Electricity grows the most in the STEPS as buildings, industry and increasingly transport are electrified. In the APS deeper electrification and renewables uptake transforms the mix.

Note: EJ = exajoule.

In **transport,** energy demand in the STEPS is projected to be 15% higher by 2030 than 2021, most of which is met by oil. Accelerating uptake of EVs tempers this boost in oil demand, as do more hybrid vehicles and energy efficiency gains in ICE road vehicles, ships and planes. Between 2021 and 2030, efficiency in road vehicles saves around 3.5 mb/d, while electrification of road transport (including hybridisation) saves around 4 mb/d. Together these effects improve the energy intensity of the global road fleet by around 15% by 2030 in the STEPS. Oil demand for road transport is already on the decline in advanced economies, but is projected to continue to rise in emerging market and developing economies, except in China. In emerging market and developing economies (excluding China), ICE vehicles maintain a dominant share of sales in the STEPS, especially where the second-hand vehicle market plays a prominent role. Although aviation and shipping see shifts in demand, their total energy consumption continues to rise, with few cost-effective low-emissions alternatives beyond improving efficiency available out to 2030.

In the APS, EV sales expand fast in all regions; in 2030 over 35% of cars sold are electric. Overall oil demand and demand for oil in transport both peak in the mid-2020s and the latter returns to its 2021 level by 2030, around 51 mb/d (see section 5.8).

Energy demand in **industry** grows by 1.4% per year to 2030 in the STEPS. This is the only end-use sector where both advanced and emerging market and developing economies experience demand growth. Energy efficiency reduces demand by around 15 EJ from 2021 to 2030; the installation of more efficient equipment in industrial facilities helps reduce demand, as does phasing out inefficient production capacity in heavy industry and shifting to new, more efficient lines. In aggregate, energy intensity in industry improves by around 15% to 2030. The fuel mix does not change much over the course of the decade. Electricity gains some ground, especially in light industries in advanced economies, but fossil fuels continue to dominate, especially for high-temperature heat applications and for chemical feedstock.

In the APS, industrial demand increases much more slowly, by around 0.7% per year to 2030. Electrification proceeds more briskly than in the STEPS, with electricity increasingly being used to provide low-temperature heat in light industries. The APS also sees faster deployment of large-scale near zero emissions plants in energy-intensive industries. Demand for low-emissions hydrogen – both produced onsite and offsite – rises to 11 million tonnes (Mt) in 2030 for use in the production of ammonia, steel and methanol.

5.3 Emissions

In 2021, energy-related CO_2 emissions reached 36.6 Gt CO_2, with the largest annual increase in history (IEA, 2022f). This reflects strong economic rebound from the Covid-19 pandemic, amplified by adverse weather, but it also indicates that global energy systems have yet to make significant structural changes to decouple energy use from emissions. This rise in emissions to new record level is at odds with what is needed to meet countries' NDCs by 2030 and their pledges to reach net zero emissions. [3]

[3] The Paris Agreement requests each country to outline and communicate their post-2020 climate actions, known as Nationally Determined Contributions. NDCs embody efforts by the country to reduce their greenhouse gas emissions and adapt to the impacts of climate change.

Emissions reductions targets

By September 2022, 194 countries had submitted their first NDC, and 162 had formally updated their NDC in line with the Paris Agreement (2015), which requests countries to update their NDCs or submit new ones every five years (Table 5.3). Many countries, among them twelve G20 countries and the European Union, have submitted updated NDCs with more ambitious emissions reduction targets than in their first NDCs (Figure 5.7).

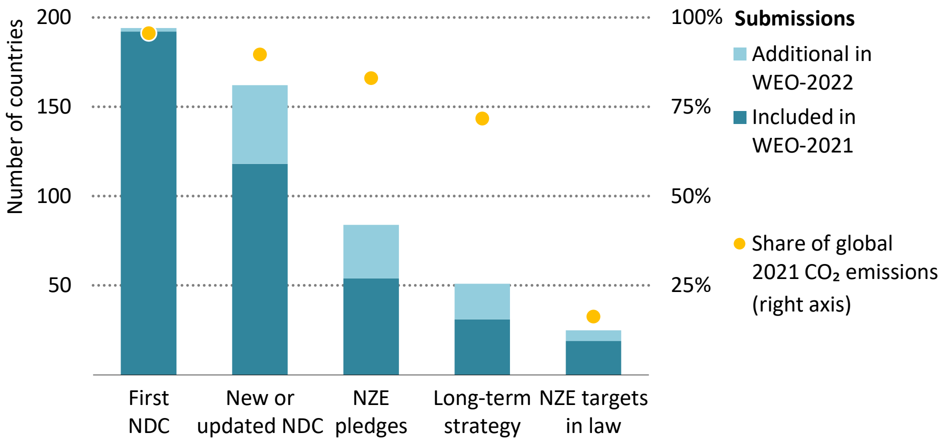
Table 5.3 ⊳ Selected updated NDCs under the Paris Agreement

Country	2030 reduction target	Base year	Target type
Economy-wide greenhouse gas emissions			
Australia	43%	2005	Base year
Canada	40-45%	2005	Base year
European Union	At least 55%	1990	Base year
Japan	46%	2013	Base year
India	45%	2005	Emissions intensity
Kenya	32%*	2030	Business-as-usual
Korea	40%	2018	Base year
Morocco	45.5%*	2030	Business-as-usual
Nigeria	47%*	2030	Business-as-usual
Peru	40%*	2030	Business-as-usual
United Arab Emirates	31%	2030	Business-as-usual
United Kingdom	68%	1990	Base year
United States	50-52%	2005	Base year
Economy-wide CO_2 only			
China	Peak before 2030	2005	Emissions intensity

* Conditional on collective ambition or international financial and technical support.

In the STEPS, only some regions meet their stated ambitions; those where NDCs are reflected in law or where credible policies have been put in place to meet or exceed their targets. The APS assumes that all NDCs and net zero emissions pledges are delivered in full and on time. For 2030, the APS projects that CO_2 emissions to be more than 2 gigatonnes (Gt) lower than the same scenario in the *WEO*-2021. This reflects more ambitious targets stated in the updated NDCs submitted since the publication of the last *Outlook*. However, this reduction would have to be about five-times larger – around 10 Gt – to be consistent with the NZE Scenario which is based on keeping global temperature increase to below 1.5 °C by 2100. The Intergovernmental Panel on Climate Change (IPCC) has reinforced the scientific understanding of the impacts of a warming world, and the need to keep global temperature rise below 1.5 °C by the end of this century (IPCC, 2022; IPCC, 2021; IPCC, 2018). In the NZE Scenario, this is achieved by reducing energy-related emissions by 1.3 gigatonnes of carbon-dioxide equivalent (Gt CO_2-eq) on average every year until 2050.

Figure 5.7 ▷ Countries with NDCs, long-term strategies and net zero emissions pledges, and their shares of global CO_2 emissions



New or updated NDCs and additional net zero emissions pledges in many countries underpin more pronounced decarbonisation in this year's APS

Notes: NDC = Nationally Determined Contributions; NZE = net zero emissions.

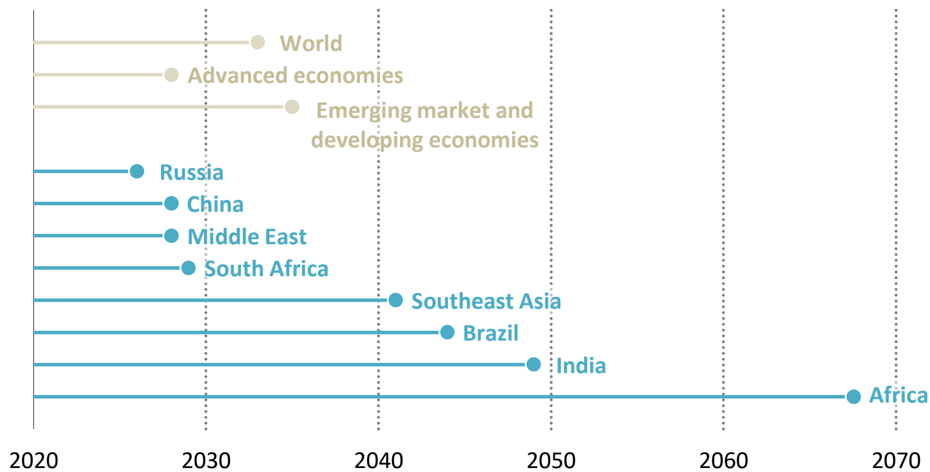
An increasing number of countries are setting long-term net zero emissions targets. By September 2022, 84 countries and the European Union had pledged to meet net zero emissions targets, together accounting for around 85% of current global GDP, about the same percentage of global energy-related CO_2 emissions, and more than half of energy-related methane emissions. Among the new announcements submitted, India's net zero emissions pledge and Indonesia's net zero emissions target with its 2021 Long-Term Low Emissions Strategy are the most significant, and account for a high proportion of the reduced level of emissions in 2030 in this *Outlook* compared with the APS in the *WEO*-2021. Some of the announced targets rely on CO_2 removal technologies such as removal from the atmosphere through CCUS, or direct air capture (DAC), or through nature-based solutions which involve the absorption of atmospheric CO_2 emissions in vegetation, soil and rocks.[4]

If the world is to keep the global temperature rise below 1.5 °C by the end of this century, it must keep to very exacting limits on cumulative emissions, as in the NZE Scenario. These cumulative CO_2 emissions are currently being exhausted in a highly unequal manner by people in various age groups, locations and income segments, and climate justice and equity issues are becoming central themes in the discussions leading up to the COP27 in Egypt in November 2022. In advanced economies, average annual energy-related per capita

[4] A net zero pledge for all GHG emissions does not necessarily mean that CO_2 emissions from the energy sector need to reach net zero. A country's net zero plans may envisage some remaining energy-related emissions are offset by the absorption of emissions from the agriculture, forestry and other land use (AFOLU) sink.

emissions are 8 tonnes of carbon-dioxide equivalent (t CO_2-eq), while in sub-Saharan Africa they are less than 1 t CO_2-eq.[5] If all countries were to produce the same level of carbon emissions per capita as advanced economies, the cumulative CO_2 emissions until 2050 in the NZE Scenario would be exhausted by 2028 (Figure 5.8). If the world aims to stay within 1.5 °C limit, the average person born in the 2020s will be able to emit only one-tenth of the lifetime emissions produced by their parents (IEA, 2022g).

Figure 5.8 ▷ Year when the cumulative CO_2 emissions until 2050 in the NZE Scenario would be exhausted if the global population had the same per capita emissions as...



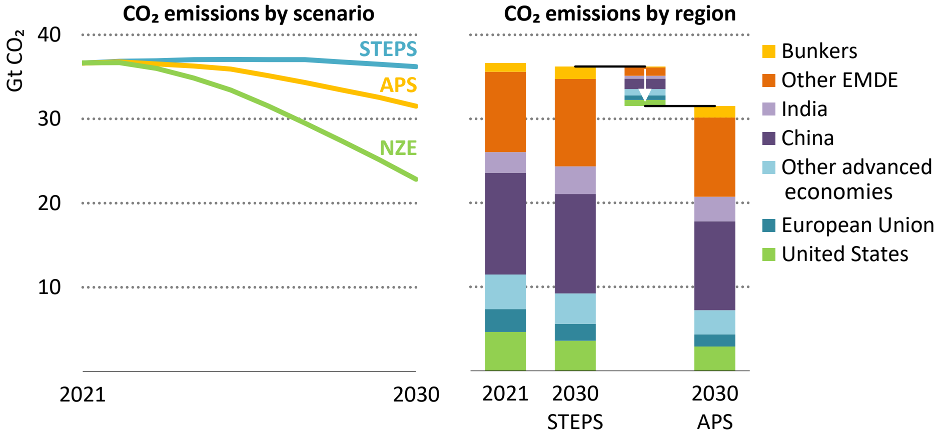
At the current level of emissions per capita, the global cumulative CO_2 emissions until 2050 in the NZE Scenario would be exhausted by 2033

Emissions outlook

Current policies fall far short of what is needed during the critical period for climate action between now and 2030 to meet the collective emissions reduction commitments in the NDCs. In the STEPS, energy-related emissions peak in the mid-2020s and then decline: by 2030, they fall slightly below the level they were at in 2021 (36.2 Gt CO_2). In the APS, the commitments in the NDCs bring about a faster reduction in emissions: global emissions peak before 2025 and fall to 31.5 Gt CO_2 in 2030, which is around 15% lower than in the STEPS. More than half of the additional CO_2 emissions reductions in the APS compared with the STEPS occur in China, the United States and the European Union (Figure 5.9).

[5] Per capita emissions are assessed on a territorial rather than a consumption basis.

Figure 5.9 ⊳ CO_2 emissions by scenario and by region, 2021 and 2030



While global emissions stay broadly flat in the STEPS to 2030, they fall by almost 5 Gt in the APS, with more than half of the difference from China, United States and European Union

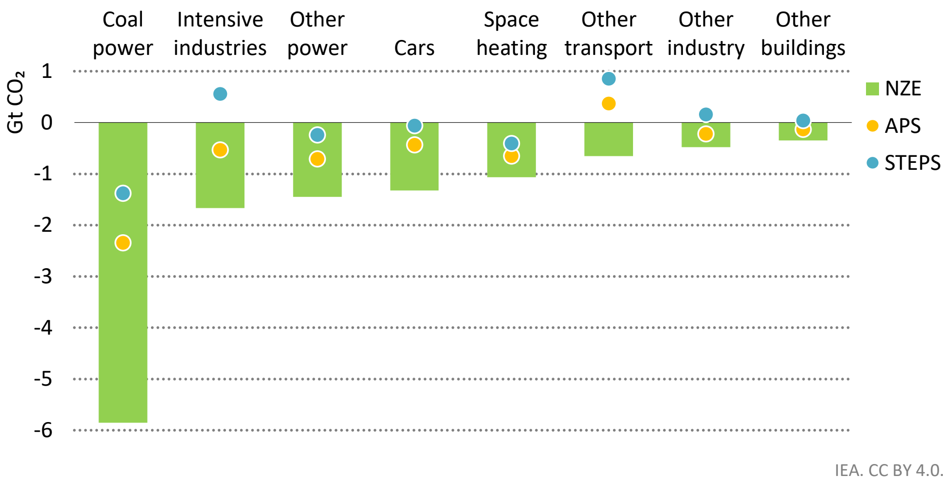
Notes: Gt CO_2 = gigatonnes of carbon dioxide; EMDE = emerging market and developing economies.

The gap in CO_2 emissions reductions between the APS and the NZE Scenario in 2030 is almost twice as large as the amount between the STEPS and the APS, highlighting the size of the remaining global ambition gap. In 2030, CO_2 emissions in the APS are almost 5 Gt CO_2 lower than in the STEPS, but around 9 Gt CO_2 higher than in the NZE Scenario. Without the new or updated NDCs and net zero emissions pledges announced in 2022, the gap between energy-related CO_2 emissions in 2030 in the APS and the NZE Scenario would be 2 Gt bigger. In all scenarios, the largest contribution to reducing emissions is replacing coal-fired power generation with renewable energy sources (Figure 5.10).[6] Almost half of the difference in emissions reductions between the STEPS and the APS in 2030 is delivered by faster deployment of renewables in the APS. Most of the rest is from more rapid energy efficiency improvements and electrification of end-uses in the APS. In industry, bigger emissions reductions in the APS reflect more stringent efficiency standards than in the STEPS and wider deployment of large-scale near zero emissions plants in energy-intensive industries. In road transport, accelerated roll out of EVs and supporting infrastructure deliver the emissions reductions.

In hard-to-abate sectors, the risks associated with being a first mover deter some firms from adopting innovative low-emissions technologies during this decade. New sectoral net zero initiatives aim to address this barrier. As of September 2022, firms participating in such initiatives and top-20 companies with individual pledges cover around one-third of emissions from shipping and aviation as well as steel and cement production (Box 5.2).

[6] The IEA will release Coal in Net Zero Transitions: Strategies for rapid, secure and people-centred change in November 2022.

Figure 5.10 ▻ CO_2 emissions reductions by sector and scenario, 2021-2030



Across scenarios, around half of total emissions reductions to 2030 are from renewables replacing coal power; industry delivers reductions from fuel switching and efficiency

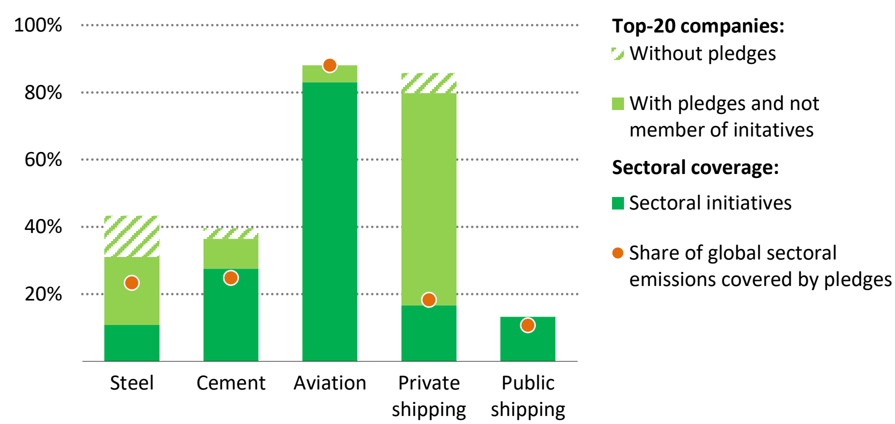
Note: Gt CO_2 = gigatonnes of carbon dioxide.

Box 5.2 ▻ Sectoral initiatives for net zero emissions pledges in hard-to-abate sectors gain momentum

As of July 2022, almost 800 companies worldwide had made net zero emissions pledges (Net Zero Tracker, 2022). Increasingly, companies in hard-to-abate sectors are joining sectoral initiatives, notably in the steel, cement, aviation and shipping industries. To date, roughly one-third of current emissions from these sub-sectors are covered by major initiatives and pledges of top-20 companies. The majority of the top-20 companies in each sub-sector are either part of such initiatives or have individual net zero emissions commitments (Figure 5.11). The International Air Transport Authority (IATA) Net Zero Carbon Emissions from the Global Air Transport Industry by 2050 strategy covers around 80% of worldwide aviation activity and emissions. So far, other industries have much lower levels of coverage, with initiatives and top-20 company pledges in the steel, cement and shipping sub-sectors each covering around 25% of their global emissions. More than half of the companies participating in sectoral initiatives for emissions reductions have their headquarters in advanced economies.

These initiatives often bring together public and private actors with the aim of reducing the perceived risks of being an early adopter of innovative low-emissions technologies. They have the potential to accelerate adoption and secure off-take agreements for low-emissions offerings within this decade, but they depend upon consistent standards and transparent reporting to ensure that all participating companies are making progress consistent with sectoral ambitions: uneven progress between firms can undermine the effectiveness of such collective agreements. It is also important that companies prioritise reducing their own emissions in decarbonisation strategies, and that where they rely on the use of carbon credits to compensate for their residual emissions, they use only high quality carbon credits that result in permanent, additional and verified emission reductions or removals. Transparent data about company current and projected Scope 1, 2 and 3 emissions, as well as planned use of carbon credits to achieve targets, should help to improve accountability and to fast track progress.

Figure 5.11 ▷ Coverage of initiatives and additional corporate net zero emissions pledges in selected sub-sectors



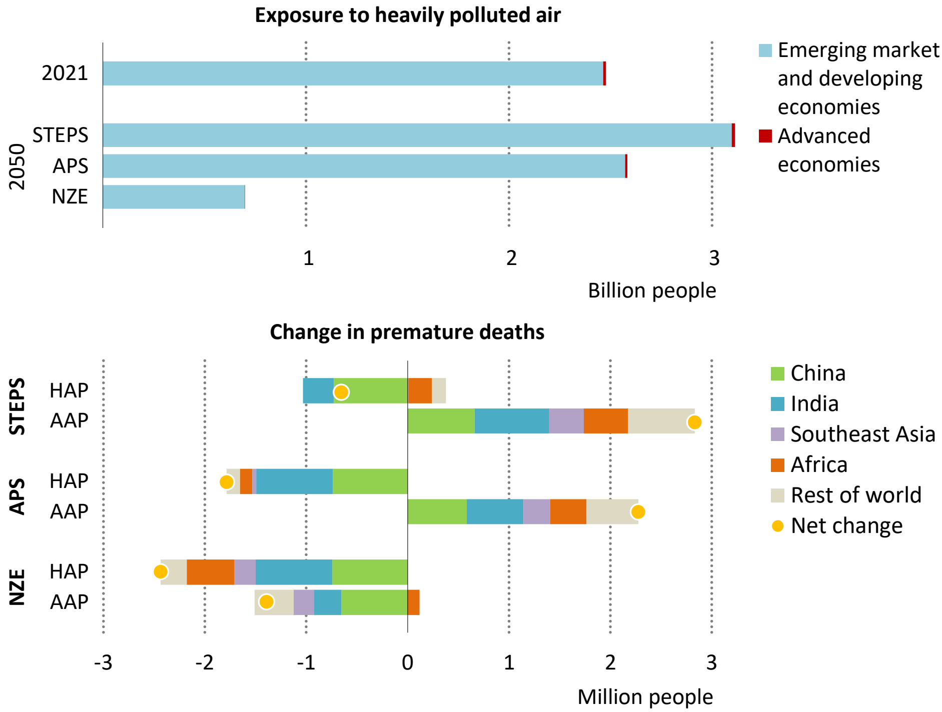
Sectoral initiatives and pledges made by top-20 companies in selected hard-to-abate sub-sectors cover about one-third of their collective CO_2 emissions

Notes: Initiatives analysed include: Net Zero Steel Initiative (steel); Concrete Action for Climate (cement); Net Zero Carbon Emissions from the Global Air Transport Industry by 2050 (aviation); First Movers Coalition on Shipping (private shipping); and the Declaration on Zero Emissions Shipping by 2050 (public shipping). All sectoral initiatives are considered in the APS except for the IATA aviation initiative for which government support for international aviation to reach net zero emissions by 2050 was announced in October 2022.

5.4 Air pollution

Polluted air has caused at least 19 000 excess deaths per day in recent years. In 2021, indoor air pollution caused around 3.6 million premature deaths, while outdoor air pollution was responsible for 4.2 million. Air pollution also comes with significant economic costs. Some are direct costs, such as those due to the provision of healthcare, and some are indirect, such as those incurred as a result of labour productivity losses or crop damage. It is estimated that the global health cost of mortality and morbidity caused by exposure to fine particulate matter air pollution alone is equivalent to around 6% of global GDP and to more than 10% in certain countries, most notably in India and China (World Bank, 2022).

Figure 5.12 ▷ **Population exposed to heavily polluted air and change in premature deaths from air pollution by region and scenario, 2021 and 2050**



The number of people exposed to heavily polluted air in 2050 in the STEPS and APS is higher than today, but in the NZE Scenario it is reduced by almost 2 billion people

Notes: Heavily polluted air = $PM_{2.5}$ concentrations ≥ 35 microgrammes per cubic metre. AAP = ambient air pollution; HAP = household air pollution.

In the STEPS, a combination of minimum standards for tailpipe emissions from road transport, reduced use of coal for electricity generation and reduced use of fuelwood for heating and cooking, together result in a modest fall in global emissions of major air pollutants [7] between 2021 and 2050. However, population growth and urbanisation, particularly in parts of the world where emissions reductions are less pronounced, or even absent, mean that 640 million more people are exposed to high concentrations of fine particulate matter ($PM_{2.5}$) pollution in 2050 than in 2021 (Figure 5.12).[8] As a result, there are

[7] Fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_X) and sulphur dioxide (SO_2) are the main energy-related air pollutants associated with premature morbidity and mortality.

[8] In this section, high concentration corresponds to a $PM_{2.5}$ density greater than 35 microgrammes per cubic metre, in accordance with the World Health Organisation Interim Target 1 (WHO, 2021).

almost 3 million more premature deaths due to ambient air pollution worldwide in 2050 than there were in 2021, despite an overall decrease in air pollutants (Rafaj, Kiesewetter and Krey, 2021). Three-fifths of these excess premature deaths occur in China, India and Southeast Asia. Owing to a shift towards cleaner cooking fuels, premature deaths from household air pollution fall by around 650 000 per year over the same period. This reflects a reduction in India and China, although there are increases in premature deaths from dirty household air in Africa and elsewhere in 2050 compared to today due to population growth and insufficient progress on access to clean cooking in the STEPS.

In the APS, the number of people exposed to high concentrations of $PM_{2.5}$ rises marginally between 2021 and 2050, but is almost 20% below the level in the STEPS by 2050. Just over 2 million more premature deaths per year are caused by ambient air pollution in 2050 than today, which is 560 000 fewer than in the STEPS. Fossil fuel use in emerging market and developing economies does not dramatically decline in this scenario until after 2030, leaving many exposed to high levels of pollution in the meantime. Together with the failure to achieve universal access to clean cooking by 2030, this accounts for the majority of the difference between excess deaths in the APS and in the NZE Scenario.

In the NZE Scenario, exposure to high concentrations of $PM_{2.5}$ declines dramatically from today's level: by 2050 almost 2 billion fewer people breathe heavily polluted air. This results in around 1.4 million fewer premature deaths from ambient air pollution in 2050 compared to 2021, some 3.7 million fewer than in the APS Scenario in that year. Universal access to clean cooking solutions cuts exposure to dirty household air, resulting in around 2.3 million fewer premature deaths from household air pollution in 2050 than today, an improvement of around 650 000 compared to the APS Scenario.

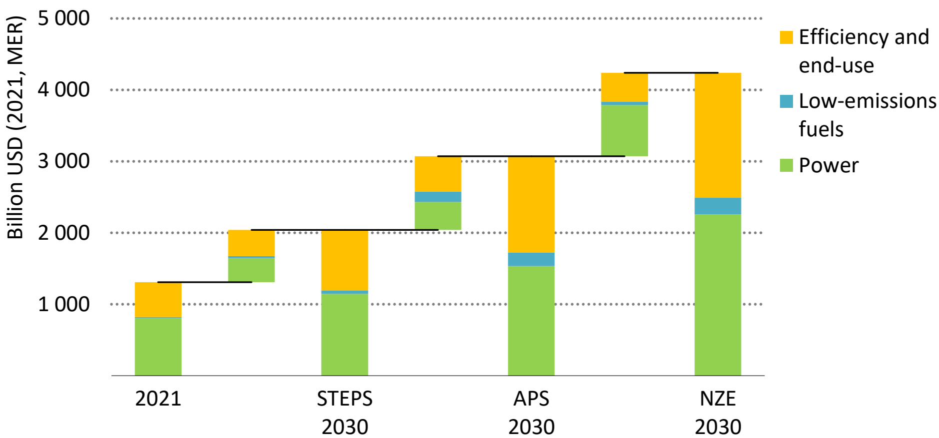
5.5 Investment

Clean energy investment was around USD 1.3 trillion per year in 2021. This increases by more than 50% from current levels by 2030 in the STEPS, more than doubles in the APS, and triples in the NZE Scenario (Figure 5.13). Investment in fossil fuels falls in both the APS and NZE Scenario, but increases in the STEPS (see Chapters 6-9 for fuel specific investments).

End-use investment is a major component of clean energy investment. It includes the cost of energy efficiency upgrades and fuel switching in buildings, appliances, industry and vehicles. Energy efficiency and end-use investment were about USD 500 billion in 2021. This is set to increase in 2022, partly as a result of post-pandemic government stimulus packages that are providing support for retrofits, heat pumps and EVs. In particular, sales of EVs have risen with spectacular speed.

In the STEPS, end-use investments represent half of the USD 700 billion increase in annual clean investment over today's levels, and are primarily driven by continued growth in EV sales and investments in the buildings sector. End-uses are not the primary driver of investment increases in the APS and NZE, but moving from the STEPS to the NZE Scenario requires an additional USD 900 billion per year by 2030, which is more than double the growth in annual end-use investment needed between today and 2030 in the STEPS. EVs and heat pumps are much more widely adopted in the APS and NZE than in the STEPS by 2030, but the investment costs are much reduced by the falling costs of these technologies.

Figure 5.13 ▷ Annual clean energy investment by sector and scenario, 2021 and 2030



Investment in end-uses would need to almost quadruple by 2030 to reach the levels required in the NZE Scenario; EV sales are already projected to quadruple in the STEPS

Note: EVs = electric vehicles; MER = market exchange rate.

Rising interest rates and inflation could sour the near-term outlook for end-use investment, notably in the buildings and transport sectors, which are strongly tied to disposable income and the ability of consumers to access affordable financing. Recovery packages have committed around USD 440 billion to the end-use segments over the 2020-50 period, and that may help to support investment levels. This support, however, is concentrated in advanced economies, and much of it is front-loaded. As stimulus funding fades in the future, it will be necessary to reinforce enabling conditions and support for new investment. This will depend on the global economic outlook, the speed of technology cost reductions and the pace of adoption of new, more efficient technologies. Some banks are starting to design dedicated financing packages for energy efficiency and end-use investment, which could help boost private sector financing.

In the NZE Scenario, renewables become the foundation of an electricity system that is four-times larger in 2050 than it is today. By 2030 in the NZE Scenario, capital spending on clean power doubles compared to the STEPS and is three-times higher than in 2021, with investments across a wide range of options for low-emissions electricity generation, including wind, solar, nuclear, hydrogen, CCUS, storage and networks.

Key themes

5.6 Energy access

The current energy crisis is causing fuel prices, food prices and inflation to surge, pushing up the number of people living in extreme poverty, especially in sub-Saharan Africa. This is set to slow progress towards universal access to electricity and clean cooking, compounding two prior years of setbacks due to the Covid-19 pandemic. It is also exacerbating an affordability crisis that may push many into forgoing the use of modern energy. This section:

- Provides 2022 estimates for electricity and clean cooking access based on a country-by-country assessment.
- Quantifies how the effects of the Covid-19 pandemic and the energy crisis change the trajectory for global progress towards the goal of universal access to clean cooking and electricity by 2030 (Sustainable Development Goal [SDG] 7.1) in the STEPS.
- Assesses for the first time how country-level access targets, if implemented on time and in full, measure up against the SDG 7.1 target of universal access realised in the NZE Scenario.

5

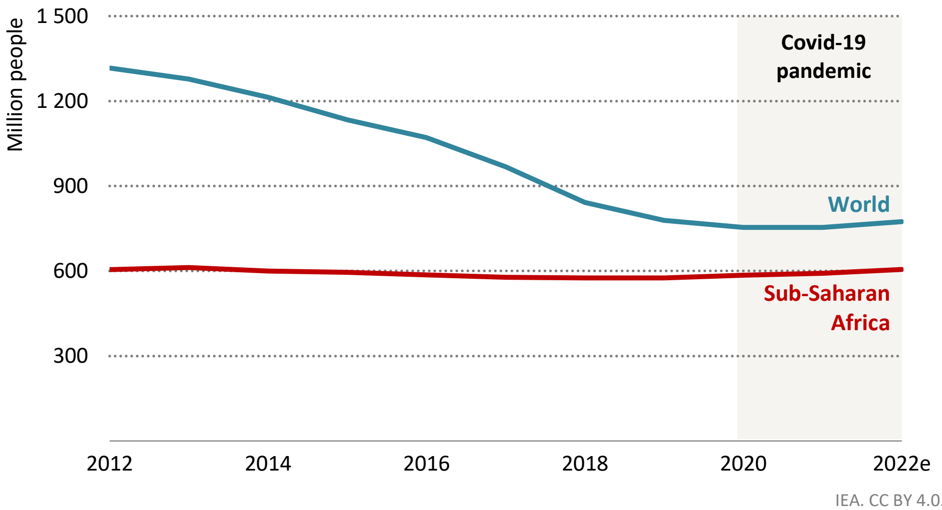
Electricity access

For the first time in decades, the number of people around the world without access to electricity is set to rise in 2022. It is likely to reach 774 million, which would mean an increase of 20 million people from 2021, and coming after the pandemic-related slowdown in both 2020 and 2021 would take the number of those without access to electricity to levels last seen in 2019 (Figure 5.14). The rise in the number of those without access occurs largely in sub-Saharan Africa, where the number of people without access is nearly back to the highest level seen in 2013, and where almost 80% of those without access live.

Consumers are now facing rising inflation levels that make getting and maintaining access to electricity less affordable (see Chapter 4). At the same time, investment in expansion of distribution systems and new connections is slowing down as a result of the mounting burden of debt that most utilities are facing related to the pandemic. During the pandemic, utility electrification programmes continued in some parts of developing Asia, notably in Myanmar (where 5% of the population has been connected annually). However, even front-runner countries on electricity access, such as Ghana and Ethiopia, are set to see a difficult year for access gains against a background of rising inflation rates (30% inflation in Ghana and 35% in Ethiopia by the end of the second-quarter of 2022[9]) (Ethiopian Statistics Service, 2022; Ghana Statistical Service, 2022).

[9] These are year-on-year inflation rates.

Figure 5.14 ▻ **Number of people without access to electricity in sub-Saharan Africa and the world, 2012-2022**



On the heels of the Covid-19 pandemic, the 2022 energy crisis is leading to a reversal of global progress on electricity access for the first time in more than a decade

Note: 2022e = estimated values for 2022.

Grid connections proved resilient in 2020 and 2021, but the rate of new connections is set to slow for 2022. Projects in the pipeline from before the pandemic have largely been completed, but new procurement has slowed. The budgets of many utilities were refocussed during the pandemic, reducing funds available for energy access projects. Utilities in Africa were already in a perilous financial situation heading into the pandemic. Operational losses climbed substantially during the pandemic, and many utilities are still being asked to extend lifeline tariffs while facing higher operational costs (Balabanyan, 2021). Cost-reflective tariff reforms were also paused in many regions to avoid potentially exacerbating the affordability crisis for the poorest households, further setting back institutional efforts to make utilities more attractive to investors.

The current inflationary environment is also affecting the already rising costs of off-grid access components, especially solar PV modules, batteries and other electronic components such as inverters. The costs of solar and hybrid **mini-grids** are estimated to have increased on average by at least 20% in 2022 compared to pre-pandemic levels.[10] Combined with the strong depreciation of local currencies in developing countries, this is making new projects less appealing for investors, especially in rural areas. It is also causing problems with respect to contracts for new projects that have already been signed in cases where the contracts lack the flexibility to permit adjustments in light of current economic conditions.

[10] Based on personal communication with Africa Minigrid Developer Association (AMDA) officials, July 2022.

Solar home system (SHS) costs are also on the rise, with average market prices for a new SHS increasing by 28-36% since 2020 (Lighting Global/ESMAP, GOGLA, 2022). This is leading to households opting for smaller or lower quality systems. Sales of large SHS were 25% below their 2019 peak in 2020 and 33% below it in 2021 (GOGLA, 2022).[11]

In the STEPS, the number of people without access to electricity is projected to reach 660 million by 2030, up by around 10 million from the STEPS projection in the *WEO-2021*. About 85% of those without access in 2030 will be in sub-Saharan Africa, up by around six percentage points from 2021.

Table 5.4 ▷ Countries with targets for access to electricity and clean cooking

	Africa	Developing Asia	Central and South America
Access to electricity			
Universal access by 2030	Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Kenya, Mauritania, Mozambique, Nigeria, Rwanda, Senegal, Sudan, Togo	Bangladesh, Myanmar, Pakistan	Bolivia, Guatemala, Honduras, Panama
Other targets	Burkina Faso, Burundi, Central African Republic, Chad, Republic of the Congo, Djibouti, DRC, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Namibia, Niger, Sierra Leone, Somalia, Tanzania, Uganda, Zambia, Zimbabwe	Papua New Guinea	Haiti
Access to clean cooking			
Universal access by 2030	Angola, Kenya, Malawi, Mali, Mozambique, Rwanda, Sierra Leone, Sudan	Bangladesh, China, Fiji, India, Indonesia, Nepal, Myanmar, Mongolia, Viet Nam	Peru
Other targets	Burkina Faso, Cameroon, Côte d'Ivoire, DRC, Ethiopia, Ghana, Liberia, Mauritania, Nigeria, Niger, Senegal, Tanzania, Uganda, Zimbabwe	Bhutan, Pakistan, Thailand	Honduras, Guatemala, Nicaragua

Notes: DRC = Democratic Republic of the Congo. Universal access by 2030 includes countries that have targets to reach 100% access rates by 2030 or before. Other targets include countries with other less ambitious targets. Includes only targets for countries with access rates lower than 95%.

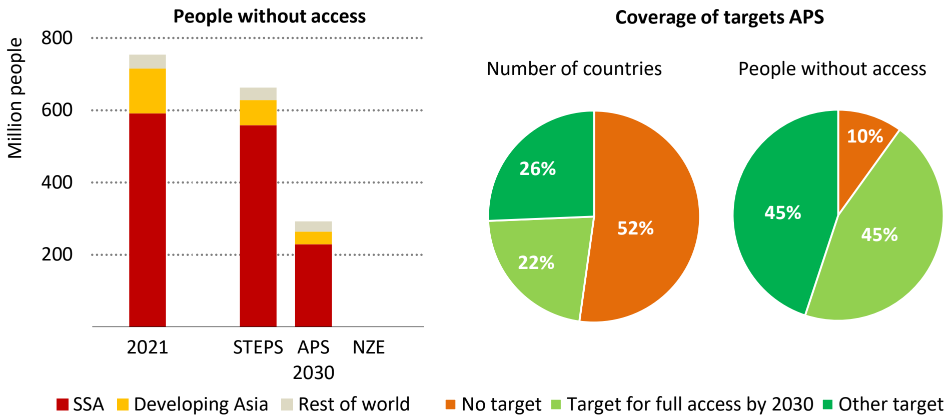
Source: IEA analysis based on official country and third-party publications.

In the APS, it is assumed that all targets, including those focussed on access to electricity, are met on time and in full. Out of the 113 countries without universal access, 54 have targets for access to electricity, of which 25 have targets to reach universal access prior to or by 2030 (Table 5.4 and Figure 5.15). Meeting all these targets reduces the number of people without access to electricity to 290 million in 2030. However, only 20% of the countries with targets, e.g. Côte d'Ivoire, Kenya, Senegal, Rwanda, Myanmar, have comprehensive national electrification strategies in place, have reasonably-staffed national agencies responsible for

[11] Solar home systems larger than 20 Watts, which if coupled with high efficiency appliances can power multiple lights, a television and a fan.

electrification, strong and timely tracking procedures, and the inclusion of off-grid solutions and affordability measures, e.g. social or lifeline tariffs. (The IEA has programmes for African access institutions with the objective to help build capacity for setting and delivering access targets [Box 5.3]).

Figure 5.15 ▷ Number of people without access to electricity in 2021 and 2030 by scenario, and coverage with targets in the APS



Achieving national targets for electricity access reduces the number of people without access by 60% by 2030, while stated policies reduce this number by just 12%

Notes: SSA = sub-Saharan Africa (excludes South Africa). The *target for full access by 2030* category includes countries with 100% access to electricity targets by 2030. The *other target* category includes countries with targets less ambitious than full access by 2030. The share of countries with and without targets and the number of people without access living in those countries is based on their status as of 2021.

Box 5.3 ▷ IEA activities focussed on Africa

The IEA has worked for two decades to advance the development of energy data and analysis in Africa. The IEA collects energy and access data for all African countries and has developed authoritative outlooks for various regions across Africa. The IEA counts three African countries as Association members – Morocco, Egypt and South Africa –and has an in-depth partnership with Senegal. A continent-wide outlook was published recently – *Africa Energy Outlook 2022* – in collaboration with the African Union Commission and the United Nations Economic Commission for Africa (IEA, 2022e). In addition, the IEA provides capacity building programmes on energy statistics and energy system planning.

- The IEA **energy statistics and modelling training**, in partnership with the European Union Directorate General for International Partnerships, focusses on improving energy data and supporting whole system energy modelling processes within African ministries. This training has been delivered to ten countries and will be extended to more in the future.

- The IEA **data-driven electrification in Africa programme**, in partnership with the United States Agency for International Development and Power Africa, addresses electricity access data gaps to enhance strategic access planning. This programme provides data collection guidelines, as well as support for implementing those guidelines in six countries and for integrating the use of geospatial tools for electrification planning in three pilot countries**.**
- The IEA **Clean Energy Transition reports**, with support from the Ministry of Foreign Trade and Development Cooperation of the Netherlands, develops region-specific clean energy transition roadmaps. These roadmaps include North Africa (IEA, 2020a), the Sahel (IEA, 2021) and Greater Horn of Africa (IEA, 2022h).
- The IEA **Clean Energy Transition Programme** supports an energy efficiency policy capacity building programme with African regulators and analytical support for low-emissions hydrogen in Africa, supported by participating member countries including Belgium and Japan.

Reaching universal access to electricity by 2030 – the target met in the NZE Scenario – would require almost 110 million people to gain access every year from 2022, and over 30 countries in sub-Saharan Africa to connect more than 5% of their population every year. This is a tall order, but progress on this scale has been achieved in other countries in the past.

In the NZE Scenario, 45% of people gaining electricity access for the first time do so with grid connections, 30% with mini-grids and 25% with stand-alone systems. Almost 90% of new connections are based on renewables. These projections are based on a country-by-country geospatial least-cost analysis, which considered technical barriers, commercial viability, historic installation rates, and speed to market to develop a feasible route for achieving universal access to electricity in the next eight years.

Clean cooking

In 2021, 2.4 billion people globally lacked access to clean cooking, 40% of them in sub-Saharan Africa and 55% in developing Asia. We estimate that the number of people still cooking with traditional biomass, coal and kerosene in 2022 is continuing to increase, as it has since 2020 due to the pandemic. The setbacks this year are primarily driven by surging fuel prices, particularly for LPG.

International LPG prices are twice as high in 2022 as they were on average in 2019. Together with soaring prices for food and other basic goods, the high cost of LPG may push up to 100 million people back to the use of traditional fuels for cooking absent effective interventions. Most of the people at this risk are in developing Asia where LPG use is high, and where programmes which provided LPG canisters to the poor have begun to cut subsidies. In Africa, this adds to substantial mark-ups on delivered LPG prices, owing to under-developed fuel delivery infrastructure and a lack of transparent, competitive fuel markets.

The financial burden of providing subsidised LPG is ballooning, pushing a number of countries to remove or reduce financial support, including Kenya and India. There may be scope in some cases to move from broad-based, fuel specific subsidies for LPG to more targeted support so as to reduce subsidy burdens without sacrificing affordability for those without clean cooking access. In India, for example, LPG subsidies were removed in June 2020, but were then reintroduced in May 2022 for a targeted number of households under the Ujjwala scheme. Other countries, e.g. Indonesia, Kenya and Nepal, are continuing with programmes to promote electric cooking in order to reduce import dependency on LPG and the costs of providing LPG subsidies.

Around 1.9 billion people remain without access to clean cooking in 2030 in the STEPS.[12] Half of those are in sub-Saharan Africa, up from 40% in 2021. In the APS, it is assumed that all clean cooking targets are met on time and in full. Around 128 countries lack universal access to clean cooking, but only 39 countries have clean cooking targets, of which only 19 aim to achieve universal access by 2030 in line with the SDG 7.1 (Table 5.4). If all the targets are achieved, as assumed in the APS, 780 million people would remain without access by 2030, about 60% fewer than in the STEPS (Figure 5.16). China and Indonesia are close to being on track to achieve their targets, whereas many other countries with targets are currently falling well short of them, underlining that there is a need to improve implementation as well as to raise the current level of ambition.

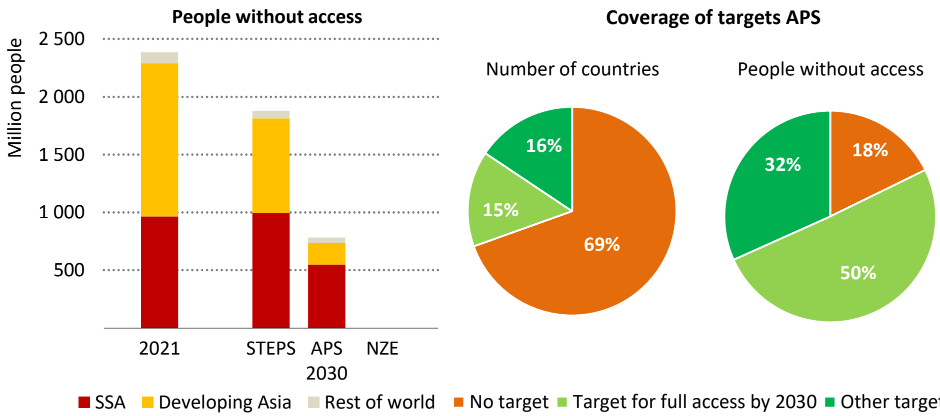
In the NZE Scenario, around 290 million people gain access to clean cooking each year, and universal access is achieved by 2030. Of those, 40% gain access with LPG, 35% with improved cook stoves[13] (especially in rural areas), 15% with electricity and the remaining 10% with biogas or ethanol. Electric cooking is becoming a more attractive option as the costs of electric appliances decline, and as the current price crisis leads to efforts to reduce dependence on imported fuels. Electric cooking may not immediately meet all household cooking needs, but it plays an important role in reducing demand for other fuels through clean fuel stacking.[14]

[12] This number is significantly lower than previous editions of the *World Energy Outlook*, due to a downward revision in the historic number of people cooking with traditional biomass in China. This revision by the World Health Organisation is based on recent surveys, which suggest that around 200 million fewer people in China were cooking with the traditional use of biomass or charcoal in 2021, changing the access rate from around 65% in 2021 to almost 80% (WHO, 2022). This is largely driven by national programmes to eliminate polluting sources of cooking to improve air quality in urban centres. Many of those transitioning from traditional fuels are reported to use electric cooking, but it is likely a combination of electric and LPG or natural gas wok cooking. These revisions impact access rates for all years between 2000 and 2020. Based on the new data, China reaches universal access by 2030 in the STEPS while in previous estimates this was projected by the late 2040s.

[13] Improved cook stoves include intermediate and advanced improved biomass cook stoves (ISO tier > 1). It excludes basic improved stoves (ISO tier 0-1).

[14] Clean fuel stacking refers to households using multiple cooking solutions, e.g. LPG stove and a microwave and kettle.

Figure 5.16 ⊳ Number of people without access to clean cooking in 2021 and 2030 by scenario, and coverage with targets in the APS



Universal clean cooking access struggles to find a place on the political agenda, though stated policies cut the number without access to clean cooking by 500 million by 2030

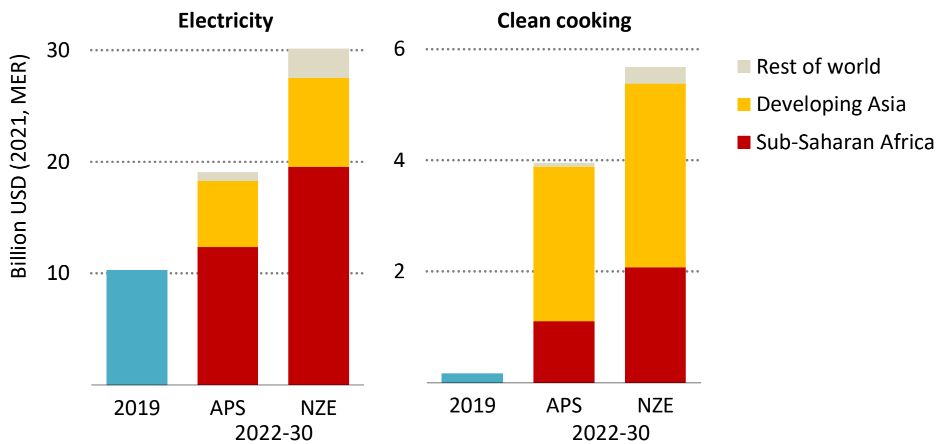
Notes: SSA = sub-Saharan Africa (excludes South Africa). The *target for full access* category by 2030 includes countries with 100% access to clean cooking targets by 2030. The *other target* category includes countries with targets less ambitious than full access by 2030. The share of countries with and without targets and the number of people without access living in those countries is based on their status as of 2021.

Investment

Investment needed to achieve universal access to electricity and clean cooking in the NZE Scenario amounts to around USD 36 billion per year, equivalent to 10% of what is spent in a year by the upstream oil and gas sector (Figure 5.17). This compares with investment of USD 23 billion per year in the APS in order to deliver stated targets. However, investment to improve electricity access in 2019 was only around USD 10 billion, which is about 45% of the annual investment required in the APS, and less than 30% of what is needed in the NZE Scenario. Investment levels for clean cooking are also well below what is needed to meet the target of universal access by 2030. The bulk of current investment is concentrated in developing Asia, and investment in Africa represents only around 6% of what is necessary to achieve universal clean cooking access by 2030.

International support is essential to catalyse higher investment, especially in today's difficult financial conditions. Concessional finance has a key role to play in helping to de-risk commercial participation. This includes supporting legal frameworks to open climate finance flows from organisations such as the Green Climate Fund, which has done much to advance clean cooking programmes in some countries in Africa. Regional institutions and local governments also have a key role to play in allocating capital to access projects and in creating a healthier investment environment by developing local access agencies and programmes, improving regulatory and legal frameworks, reducing administrative burdens and delays, decreasing taxes on access components, and implementing cost-reflective reforms. An emerging area of interest is the provision of upfront support for the purchase of efficient appliances, particularly for productive uses such as irrigation pumps (RMI, 2018).

Figure 5.17 ▷ Annual investments for access to electricity and clean cooking by scenario relative to tracked 2019 investments



Current investment in access to electricity is less than 30% of what is needed to achieve universal access by 2030, while investment in clean cooking lags even further behind

Notes: MER = market exchange rate. Sub-Saharan Africa excludes South Africa.

Sources: IEA analysis; SEforALL and CPI (2021).

5.7 Efficient cooling for a warming world

The seven years up to and including 2021 rank as the world's seven hottest years on record; global average mean temperatures in 2021 were around 1.1 °C above pre-industrial levels (NASA Goddard Institute for Space Studies, 2022). This trend is set to continue for 2022. August 2022 was one of the warmest August months ever, with heatwaves over central and eastern China and western regions of North America, while Europe experienced its hottest summer on record, with temperatures that were 1.34 °C above the historical 1991-2020 average (Copernicus Climate Change Service, 2022).

As temperatures have risen, those with access to air conditioners have been using them more frequently. Many others have purchased cooling equipment. However, billions of people living in hot areas do not have access to such equipment. Space cooling is already one of the fastest growing sources of electricity demand, and rapidly increasing air conditioner ownership and use is likely to cause it to rise even faster. Against this background, the efficiency of cooling appliances and buildings envelopes will have major impacts on electricity demand, emissions from electricity generation and household electricity bills.

Household space cooling needs and access today

Today around 7.5 billion people worldwide live in areas with some space cooling needs, of which 5 billion live in climates with substantial cooling needs.[15] Space cooling needs tend to vary substantially between advanced economies and emerging market and developing economies. In advanced economies, which tend to be relatively northerly, energy use for space heating is about eight-times higher than demand for space cooling. This ratio is reducing rapidly as climate change and urbanisation push temperatures higher, but advanced economies nonetheless experienced an average of only 700 cooling degree days (CDDs)[16] per year between 2016 and 2021. This contrasts with 2 300 CDDs per year in Africa. On average, emerging market and developing economies experience around 2 150 CDDs per year.

The majority of the population with space cooling needs remain without access to adequate means to cool their homes. Around 35% of households have at least one air conditioner (up from 20% in 2000). Around 55% of households have access to a fan, providing at least some form of respite. Despite higher cooling needs in emerging market and developing economies, these regions have significantly lower access to cooling than advanced economies, with only 30% of households having an air conditioner, and as few as 11% of households in India and 7% in Africa. This compares to 50% in advanced economies. On average there are 1.3 air conditioners per household in advanced economies, and ownership is close to 100% in the United States, with an average of 2.4 units per household.

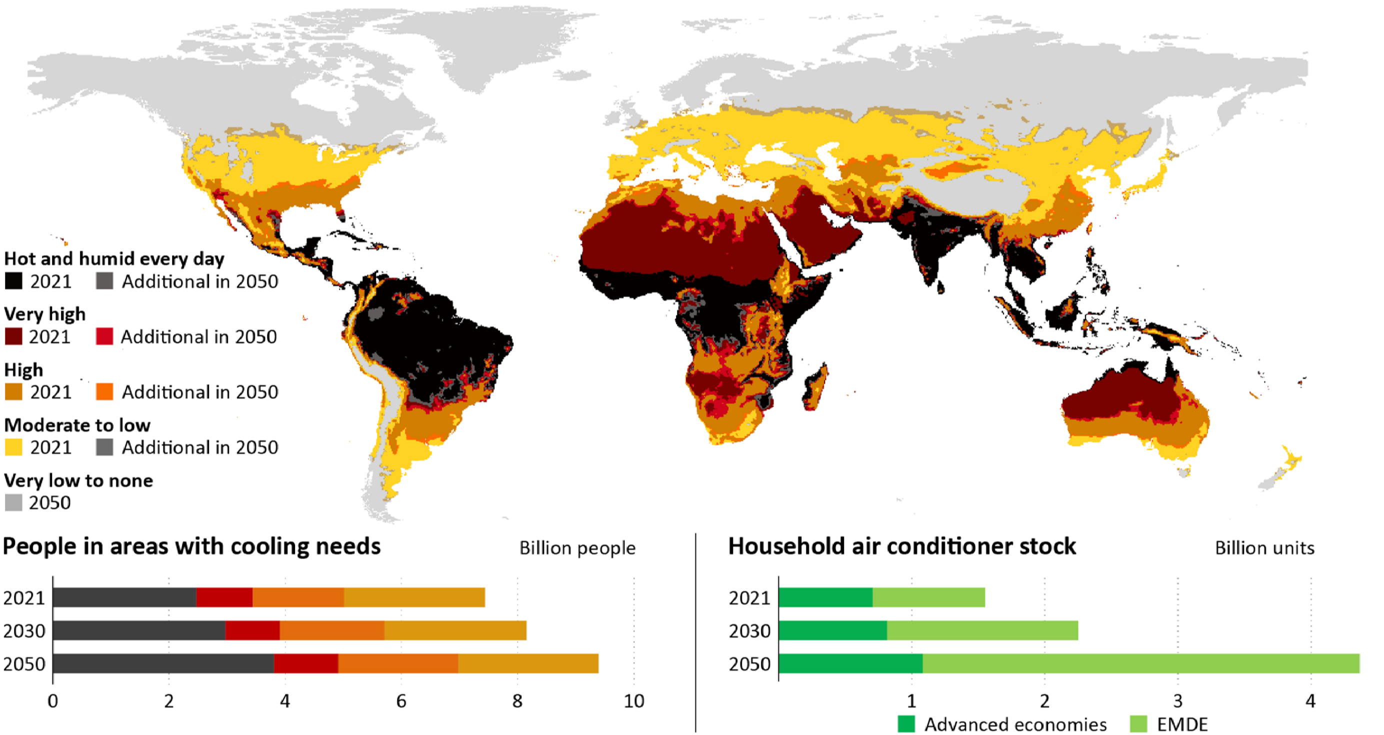
Demand for cooling services set for growth

Heatwaves and wider cooling needs are expected to increase in frequency and intensity as average temperatures rise and populations grow and become increasingly urbanised. The number of people living in areas of the world with at least some cooling need is projected to increase to 9.4 billion by 2050 (more than 95% of the global population), which is almost 2 billion more than today (Figure 5.18). As our climate changes, many more countries will experience days in which temperatures pose a public health risk by 2050. Access to space cooling services of one kind or another will become increasingly essential for public health, comfort and productivity, and by the same token lack of access to cooling services will increasingly be seen as a hallmark of energy poverty.

[15] Substantial cooling needs refer to areas that are hot and humid every day, or areas with high or very high cooling needs, as shown in Figure 5.18.

[16] Cooling degree days are a measure of cooling needs. This recognised standard metric allows comparison of cooling needs between regions. A CDD measures how warm a given location is by comparing actual temperatures with a standard base temperature. For this analysis, CDDs are calculated with a base temperature of 18 °C and integrate the impact of humidity.

Figure 5.18 ▷ **Space cooling needs and household air conditioner stock in the STEPS, 2021-2050**

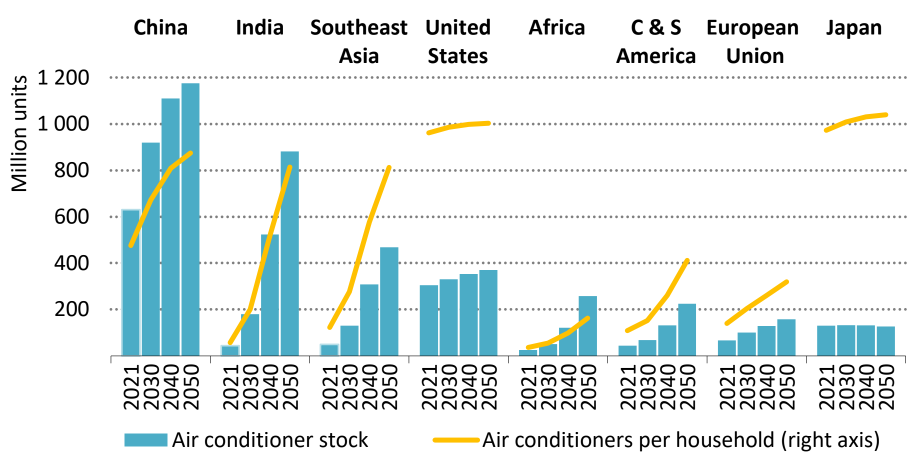


The number of people living in areas with cooling needs expands by 25% to 2050, a key driver in rising energy needs for cooling

Notes: EMDE = emerging market and developing economies. For more information on cooling needs classification see IEA (2020b).

In the STEPS, the global stock of household air conditioners increases from 1.5 billion units today to 2.2 billion in 2030 and 4.4 billion in 2050. Rising incomes and cooling needs in emerging market and developing economies account for almost 90% of the increase in the air conditioner stock to 2050. Average rates of air conditioner ownership in India increase from 11% today to 85% in 2050; in Africa they increase from 7% today to 20% by 2050 (Figure 5.19). Two-thirds of households in China today have an air conditioner, and almost all households will have one by 2050, broadly in line with current levels in the United States. Higher levels of electricity access in the APS and universal access to electricity by 2030 in the NZE Scenario push the global stock slightly higher than in the STEPS in 2030, but by 2050 this is offset by slightly lower cooling needs in the APS and especially the NZE Scenario as a result of global temperatures being a little lower than in the STEPS.

Figure 5.19 ▷ Household air conditioner ownership in selected regions in the STEPS, 2021-2050



Almost 90% of the growth of household air conditioners to 2050 is in emerging market and developing economies, adding 2.4 billion units as incomes and temperatures rise

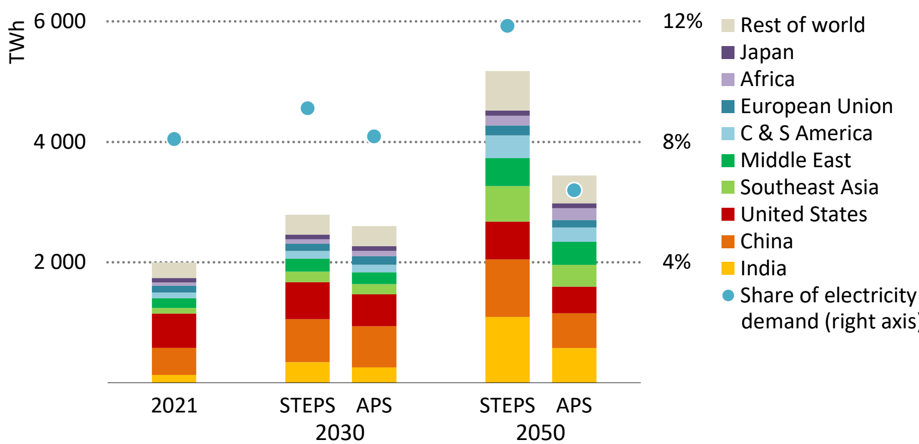
Note: C & S America = Central and South America.

Outlook for building cooling-related electricity demand

Space cooling today is responsible for slightly more than 5% of final energy consumption from residential and commercial buildings, or 15% of their electricity consumption. Energy demand for space cooling has expanded rapidly over the last 20 years, more than doubling to reach 2 000 terawatt-hours (TWh) in 2021. Growth would have been higher without the progressive implementation of minimum energy performance standards (MEPS) for cooling equipment. Today such standards are in place in 86 countries.

Space cooling demand continues to increase on a similar trajectory in the STEPS, with global demand rising to about 2 800 TWh in 2030, a 40% increase from 2021 (Figure 5.20). Cooling demand approaches 5 200 TWh in 2050, double total electricity demand in the European Union today. Nearly 90% of the total increase in space cooling electricity demand to 2050 occurs in emerging market and developing markets, where MEPS are weaker than in advanced economies.

Figure 5.20 ▷ Space cooling demand by region in the STEPS and APS, 2021-2050



Electricity demand for cooling rises by 3 200 TWh to 2050 in the STEPS; growth is cut by more than 50% in the APS thanks to air conditioner and building envelope efficiency gains

Note: TWh = terawatt-hour; C & S America = Central and South America.

Space cooling electricity demand in the APS is kept in check by further efficiency improvements, notably an increase in the scope and stringency of MEPS and building energy codes in countries with net zero emissions targets. Nonetheless, electricity demand for cooling still increases to 2 600 TWh in 2030 and over 3 400 TWh by 2050. The impact of energy efficiency improvements on cooling electricity demand in the APS is most significant in the Asia Pacific region, where over 500 million additional residential air conditioners are projected to be in use in 2030 compared with today. Half of the difference in electricity demand for cooling between the APS and the STEPS reflects differing assumptions about what happens in just two countries – India and China.

In the NZE Scenario, space cooling energy demand is kept down to 2 500 TWh in 2050, less than half the level in the STEPS. Energy efficiency and behavioural changes mean that cooling electricity demand is only 25% higher than today, despite an additional 2.5 billion air conditioners being in operation (see Chapter 3).

Energy efficiency is the key to cooling comfort that is compatible with net zero emissions ambitions

The energy efficiency of space cooling has major implications not only for electricity demand and CO_2 emissions from electricity generation but also for household energy bills and electricity system operations. Households spent a total of USD 90 billion on electricity for space cooling in 2021; this rises to USD 130 billion by 2030 and USD 300 billion by 2050 in the STEPS. In the APS, energy efficiency offsets the impact of higher electricity prices in the short term and reduces costs in the longer term: household spending on cooling in 2050 is USD 120 billion lower than in the STEPS, with two-thirds of the savings coming in emerging market and developing economies. Improving the energy efficiency of cooling also reduces energy requirements at times of peak demand for many electricity systems, which helps to keep down the need for investment in electricity system flexibility, additional peaking capacity and distribution networks.

In the STEPS, the efficiency of the air conditioner stock by 2030 is almost 10% higher than today, and MEPS in most major markets together with mandatory efficiency labelling boost sales of high efficiency air conditioners. However, rising average temperatures and increasing wealth mean that units are used more often, resulting in higher average electricity consumption per unit in 2030 than today, and energy efficiency improvements are insufficient to offset this completely. The outlook is different in the APS, where the use of air conditioners rises as it does in the STEPS, but more rapid energy efficiency improvements mean that the average electricity consumption of an air conditioner drops by 5% to 2030.

Today, best-in-class air conditioners are more than twice as efficient as the average equipment sold (IEA, 2022i). In several markets the efficiency of the average equipment sold is three-times less than the best available technologies in the same market (IEA, 2022j). Progressive increases in MEPS and mandatory energy efficiency labelling of appliances would increase the energy efficiency of units without major increases in product costs for consumers. MEPS and mandatory labelling might also help to discourage the sale of portable packaged air conditioners, which are often purchased during heatwaves and are typically much less efficient than split air conditioning systems. Efforts could also be made to convey the message that alternative solutions to refrigerant-cycle air conditioners may be best suited to provide cooling comfort in certain contexts.[17] In households, this could include dehumidifiers, and desiccant and evaporative cooling. In densely populated areas, district cooling could meet needs more efficiently than individual cooling systems.

Improvements in building envelopes and passive cooling measures could also substantially reduce cooling demand, as well as making buildings more comfortable and resilient in the face of heatwaves and electricity outages. Passive cooling measures include shading, low

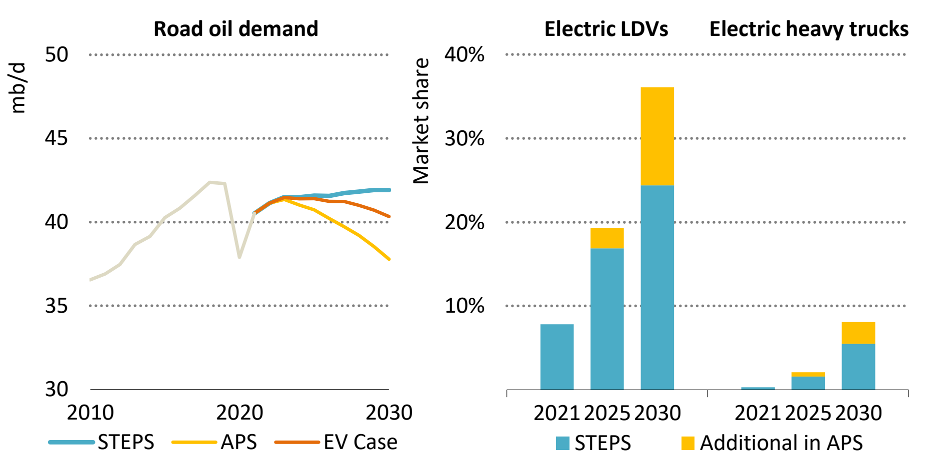
[17] Refrigerants are an essential component to the functioning of most air conditioners. While refrigerants operate in a closed loop, leaks may occur during the operation and maintenance of equipment. Due to their high global warming potential (GWP), 138 countries have ratified the Kigali Amendment to the Montreal Protocol, which aims to phase out the use of hydrofluorocarbons and to rely on alternatives as safe and stable as their predecessors but with lower GWPs.

emissivity glass (low-E) windows, natural ventilation and reflective roofing materials. Passive cooling and improvements to the energy performance of buildings could reduce the use of air conditioners, and in some more temperate regions they could make them unnecessary. The APS assumes that passive measures are encouraged by country-specific zero carbon-ready building energy codes in countries with building energy efficiency targets in their NDC or with broader net zero emissions targets.

5.8 Bringing forward the peak in oil use for road transport

Global oil demand grows at less than 1% per year this decade before peaking in the mid-2030s at around 103 mb/d in the STEPS. In the APS, global oil demand peaks in the mid-2020s and returns to current levels by the end of this decade. Road transport is responsible for over 40% of oil demand today. Vehicle electrification is key to reducing oil demand in the road transport sector. In a special EV case, based on the STEPS trajectory augmented with the assumed EV penetration levels in the APS, the oil peak for the road sector is brought forward almost one decade sooner than in the STEPS and the oil demand would be over 1.5 mb/d lower in 2030 relative to the STEPS (see EV case in Figure 5.21)

Figure 5.21 ▷ Global road transport oil demand by scenario, 2010-2030, and EV sales by scenario, 2021-2030



Oil demand in road transport increases slightly to 2030 in the STEPS despite the growth of EVs, with faster growth for electric LDVs and heavy trucks it would peak a decade earlier

Notes: EV = electric vehicle; LDVs = light-duty vehicles which include passenger cars and light trucks. Heavy trucks include medium- and heavy-freight vehicles. Electric refers to battery electric vehicles as well as plug-in hybrid vehicles. The EV case shows the STEPS trajectory with the penetration of EVs at similar levels of the APS.

Over 10 million electric cars are set to be sold in 2022. China remains the global leader, with one-out-of-four new cars sold being an EV in 2022. The United States is also on track for rapid electrification of its car fleet: among other measures, the provisions of the recent Inflation Reduction Act and the target set in California to phase out ICE car sales by 2035 will boost electric car registrations and manufacturing capacity. The European Union has also taken steps to promote EVs and electrification of the car fleet is set to proceed briskly there too.

The STEPS only takes account of policies for the road transport sector which are backed by existing legislation, whereas the APS assumes that all targets and pledges are met on time and in full. Currently, 36 countries and several US states have announced commitments to halt the sales of ICE cars by a specified date, some also target light trucks. Major automobile manufacturers have announced targets for production of EVs as a proportion of their total production output, notably in Europe (Table 5.5).

5

Table 5.5 ▷ Selected policies and targets to phase out sales of ICE LDVs by country/state and automaker

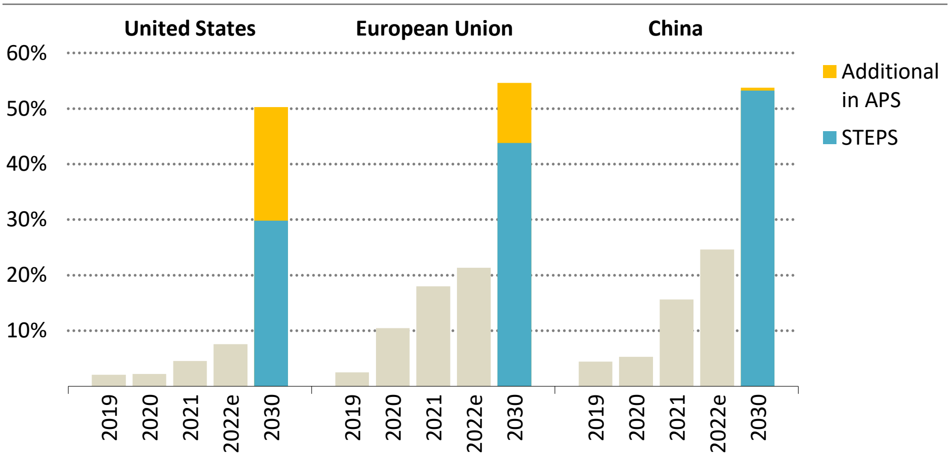
Year	Country/state	Type of vehicle
2025	Norway	LDVs
2030	Austria, Slovenia, Washington (United States)	LDVs
	Denmark, Iceland, Ireland, Netherlands, Singapore	Passenger cars
2035	European Union, Cape Verde, Canada, Chile, United Kingdom, California, Massachusetts and New York (United States)	LDVs
2050	Costa Rica, New Zealand*, Connecticut, Maryland, New Jersey, Oregon, Rhode Island, Vermont (United States)*	Passenger cars
Year	**Automaker**	**Announcement (passenger cars)**
2025	Jaguar	100% EV sales
2027	Alfa Romeo	100% EV sales
2028	Opel	100% EV sales in Europe
2030	Bentley, Cadillac, Fiat, Mini, Rolls-Royce, Volvo	100% EV sales
	Ford, Stellantis	100% EV sales in Europe
	Honda	100% EV sales in China
2033	Audi	100% EV sales
2035	General Motors, Lexus	100% EV sales
	Hyundai, Volkswagen	100% EV sales in Europe
	Toyota	100% EV sales in West Europe

*Country/states included based on their membership in the International Zero Emissions Vehicle Alliance.

Notes: LDVs = light-duty vehicles which include passenger cars and light trucks. This table covers those countries and states with legislation, a target or stated ambition in place to phase out the sales of ICE LDVs. Only automakers which have announced a complete phase out of ICE vehicles are included. West Europe includes European Union, European Free Trade Association countries and the United Kingdom.

These targets are reflected in the APS, and as a result, sales of EVs rise faster in the APS than in the STEPS. By 2030, EVs account for over 35% of total car sales in the APS, and for 8% of total heavy truck sales. More than 40 million electric cars are being sold every year by 2030, six-times more than in 2021. In the United States, the European Union and China, one-of-every-two new cars sold is electric (Figure 5.22). The shift to produce EVs means that eventually fewer ICE vehicles are sold on to developing economies, and that increases EV sales in those countries. China, the European Union and the United States are currently responsible for nearly 90% of electric car sales worldwide. This falls to just over 60% by 2030 as global electric car sales multiply in the APS.

Figure 5.22 ▷ Market share of electric cars in key markets by scenario to 2030



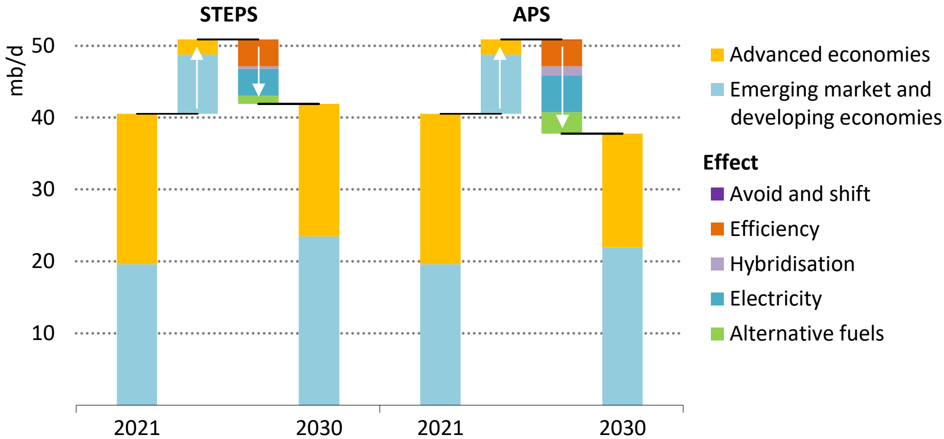
Half of all the cars sold in the world's largest car markets are electric by 2030 in the APS, building on recent momentum

Note: 2022e = estimated values for 2022.

Source: IEA analysis based on data from EV Volumes (2022).

Efficiency improvements have offset nearly 3.5 mb/d of growth in oil demand since 2015, and fuel switching – mostly to biofuels – avoided a further 1 mb/d. Over the next decade, however, most of the avoided oil demand comes from the electrification of the vehicle fleet. In the STEPS, energy efficiency, hybridisation and electrification all play significant roles in tempering oil demand growth in the road transport sector to 2030 with electrification (including hybridisation) helping to reduce oil demand by around 4 mb/d. In the APS, electrification proceeds at a faster pace as national targets and targets announced by manufacturers are met, and savings reach over 5 mb/d by 2030 (Figure 5.23). Medium- and heavy-duty trucks contribute twice as much to savings through electrification in the APS as they do in the STEPS by 2040.

Figure 5.23 ▷ Change in road transport oil consumption by region and effect in the STEPS and APS, 2021-2030



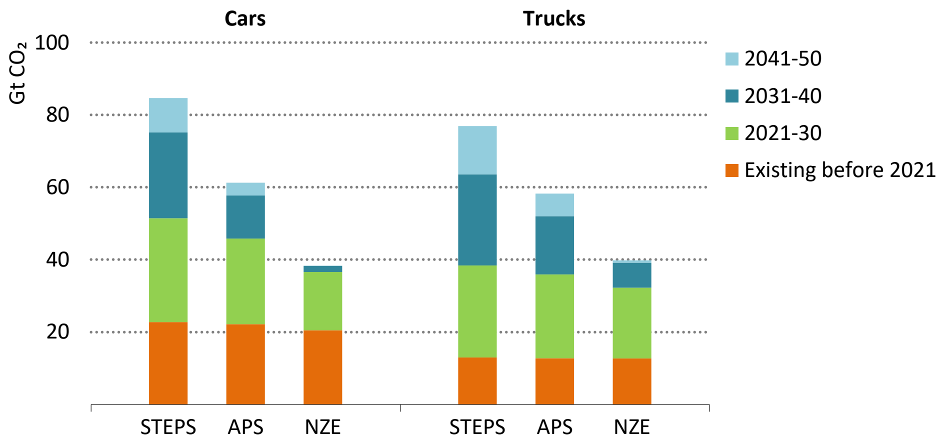
Electrification, efficiency improvements, hybridisation and shifting to alternative fuels curb oil demand growth by 8 mb/d in the STEPS and by over 10 mb/d in the APS

Notes: mb/d = million barrels per day; EMDE = emerging market and developing economies. Alternative fuels include natural gas, hydrogen, hydrogen-based fuels and biofuels.

Despite rapid expansion in EV sales, a slow turnover of stock limits reductions in oil demand in road transport. ICE cars remain in use long after their sales cease in the regions where governments and car manufacturers have announced phase-out dates. Despite being responsible for two-thirds of total new car sales by 2040 in the APS, EVs do not account for two-thirds of passenger cars on the road until a decade later. The brake on oil demand reduction due to slow stock turnover reinforces the case for moving as fast as possible to encourage the uptake of EVs. While very few of the cars manufactured today will still be on the road in 2050, this small car fleet nevertheless will contribute 9% of cumulative emissions from the road transport sector between now and 2050. Cars sold in the next decade contribute 24 Gt CO_2 of cumulative emissions to 2050 in the STEPS, but only 12 Gt CO_2 in the APS (Figure 5.24). In the roadmap to net zero emissions, one of the key milestones is ending new ICE car sales by no later than 2035 worldwide. This would reduce the cumulative emissions to 2050 from cars sold in the next decade to 1.7 Gt CO_2.

The ready availability of public charging infrastructure is crucial to overcome range anxiety on the part of EV owners and potential owners, and to pave the way for the electrification of long-distance trucking. From now to 2030, investment of around USD 150 billion is devoted to public charging infrastructure in the STEPS, and almost USD 190 billion in the APS. In the United States, together the Inflation Reduction Act and the Infrastructure and Jobs Act have earmarked nearly USD 11 billion for the establishment of a network of EV chargers. In Europe, a number of governments are taking action, while automotive companies have created joint ventures, e.g. Daimler, Traton and Volvo, to install high power charging points near highways and logistics hubs.

Figure 5.24 ▷ Cumulative emissions from cars and trucks by age band and scenario, 2021-2050



IEA. CC BY 4.0.

Timely restrictions on new ICE vehicles are key: cars and trucks yet to be purchased risk locking in 120 Gt of CO_2 to 2050 in the STEPS, more than triple the lock in from today's fleets

Notes: Gt CO_2 = gigatonnes of carbon dioxide. Trucks = light commercial vehicles, medium-freight trucks and heavy-freight trucks; ICE = internal combustion engine.

Further efforts to scale up EV production are also needed to achieve the ambitious targets that many countries have set. The current delays in delivery times for electric cars reflect not only the popularity of EVs but also the supply challenges that have emerged. Much of this is best left to the industry to work out, but governments could have a part to play here too, for example to help create more resilient battery supply chains to minimise future energy security risks. Additional investments in research and development could help to bring down battery costs and incentivise battery recycling, fuel cell development and advanced biofuel production. Progress in these areas would also help the shipping and aviation industries to make progress on decarbonisation, as well as the vehicle industry.

Outlook for electricity

Bright as the sun?

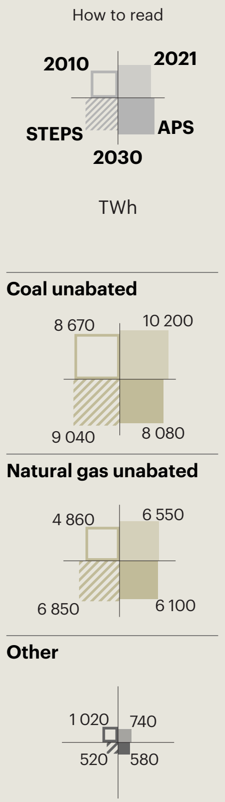
S U M M A R Y

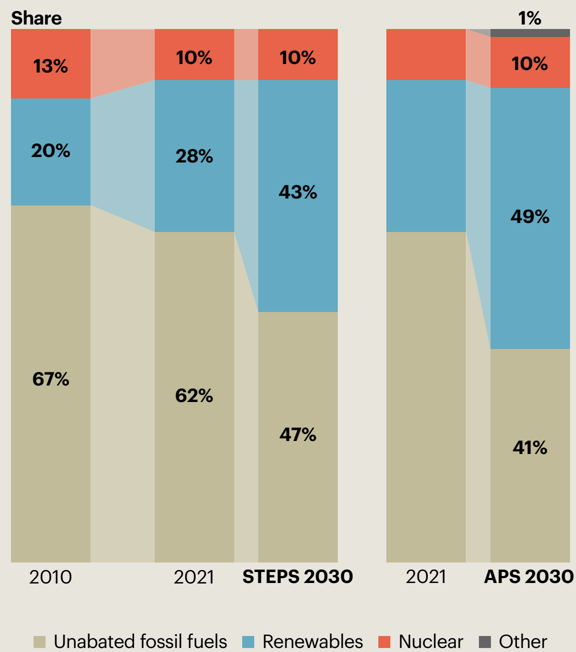
- Global electricity demand rises by 5 900 terawatt-hours (TWh) in the Stated Policies Scenario (STEPS) and over 7 000 TWh in the Announced Pledges Scenario (APS) by 2030, equivalent to adding the current level of demand in the United States and the European Union. In advanced economies, transport is the largest contributor to increased electricity demand as the market share of electric cars rises from about 8% in 2021 to 32% in the STEPS and almost 50% in the APS by 2030. In emerging market and developing economies, population growth and rising demand for cooling contribute to increasing electricity demand. In China, air conditioner ownership expands by around 40% from current levels in the STEPS and APS by 2030. Electricity provides a rising share of total final energy consumption in all economies. Global electricity demand in 2050 is over 75% higher in the STEPS than it is today, 120% higher in the APS and 150% higher in the Net Zero Emissions by 2050 (NZE) Scenario.
- Recently, coal use in the electricity sector has seen an uptick in many countries in response to strong demand, high natural gas prices and energy security concerns, but this is expected to be temporary. Even in the STEPS, unabated coal falls from 36% of generation in 2021 to 26% in 2030 and 12% in 2050, reflecting renewables growth, led by solar PV and wind. In the APS, pledges including net zero emissions targets in 83 countries and the European Union, are met on time and in full. This accelerates clean energy transitions. Renewables in electricity generation rise from 28% in 2021 to about 50% by 2030 and 80% by 2050. Unabated coal falls to just 3% in 2050. Solar PV capacity additions expand from 151 gigawatts (GW) in 2021 to 370 GW in 2030 and almost 600 GW in 2050, while wind capacity additions double to 210 GW in 2030 and rise to 275 GW in 2050. Recent events, market conditions and policies are shifting views on natural gas and limiting its role, while underlining the potential for nuclear power to cut emissions and strengthen electricity security.
- Electricity systems faced a number of challenges to affordability and security over the last year. We estimate that market conditions and the energy crisis are raising the global average cost of electricity supply by almost 30% in 2022. The European Union is facing particular pressures following a tripling of wholesale electricity prices in the first-half of 2022 relative to the previous year. This is mainly a consequence of record high natural gas prices, but it also reflects higher coal, oil and CO_2 prices, exacerbated by reduced availability of nuclear and hydropower. Actions to reduce energy use, projected reductions in fuel prices, planned nuclear restarts and possible market design reforms all offer potential future relief. Climate-related risks, including heatwaves, droughts, extreme cold and extreme weather events, have strained electricity grids and caused outages around the world. The evolving electricity mix is likely to improve some aspects of climate resilience but exacerbate others.

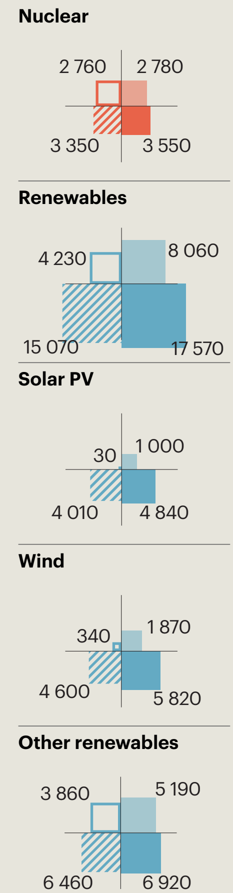
- The electricity sector emitted 13 gigatonnes of carbon dioxide (Gt CO_2) in 2021, accounting for over one-third of global energy-related CO_2 emissions. Electricity sector CO_2 emissions peak in the near future in all our scenarios, with steep reductions of 40% in the STEPS and over 80% in the APS by 2050. In the NZE Scenario, net emissions from electricity reach zero by 2040. In advanced economies, electricity sector emissions have been declining since 2007, with a temporary rise in 2021 due to the recovery from Covid-19, and fall by 5% per year in the STEPS and 14% in the APS. In emerging market and developing economies, emissions peak soon and then decline by over 1% annually in the STEPS to 2050 and 6% in the APS. Higher electricity sector investment enables these reductions, rising from an annual average of USD 860 billion in 2017-2021 to about USD 1.2 trillion in 2022-2050 in the STEPS, USD 1.6 trillion in the APS and USD 2.1 trillion in the NZE Scenario.
- System flexibility is the cornerstone of electricity security. Changing demand patterns and rising solar PV and wind shares double flexibility needs in the APS by 2030 and increase them almost fourfold by 2050. Flexibility needs also rise rapidly in the STEPS, where they more than triple by 2050. Today, power system flexibility is mainly provided by unabated coal, natural gas and hydro, but tomorrow's systems will rely increasingly on batteries, demand response, bioenergy and other dispatchable renewables, fossil fuels with carbon capture, hydrogen and ammonia.
- Electricity networks are the backbone of electricity systems, and need to expand and modernise to support energy transitions. Total grid lengths increase by about 90% from 2021 to 2050 in the STEPS, and another 30% in the APS. Annual investment rises in the STEPS from around USD 300 billion in recent years to USD 550 billion by 2030 and averages USD 580 billion per year to 2050. In the APS, investment rises further to USD 630 billion in 2030 and USD 830 billion in 2050. However, complex projects can take a decade or more to deliver, which is twice as long in most cases as developing solar PV, wind or electric vehicle charging infrastructure. Long-term planning is vital and must account for, among other things, demand growth, increasing amounts of variable renewables, as well as opportunities for digitalisation.
- Critical mineral demand linked to the electricity sector is set to rise from 7 Mt per year in 2021 to reach 11 Mt in 2030 and 13 Mt in 2050 in the STEPS as a result of increasing deployment of renewables, battery storage and networks. It grows much faster in the APS and NZE Scenario, reaching 20 Mt per year by 2050. Copper for grids, silicon for solar PV, rare earth elements for wind turbine motors and lithium for battery storage will be pivotal; critical minerals are a key component of the energy and electricity security landscape. Additional R&D is needed to reduce mineral intensity and enable mineral substitution in key applications, along with recycling, reuse of electric vehicle batteries and end-user energy efficiency measures.

How is the electricity mix changing?

Low-emissions sources of electricity, led by renewables, are poised to overtake fossil fuels by 2030 in the STEPS and APS, ending decades of growth for coal.

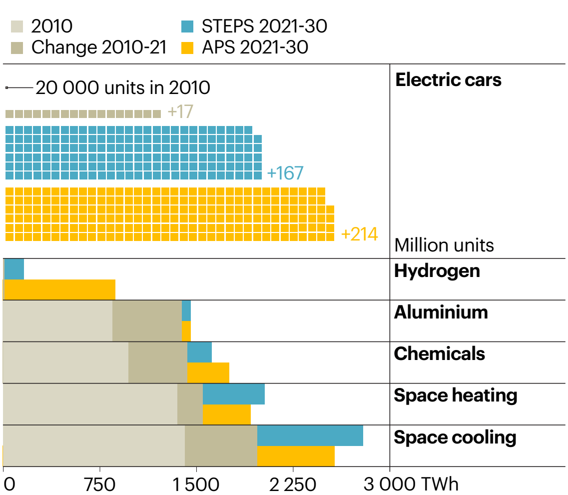






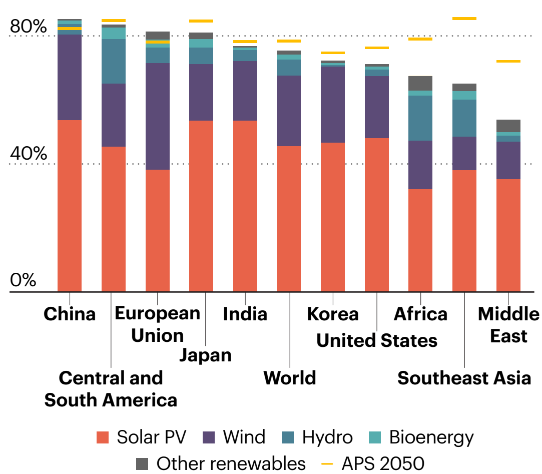
What drives electricity demand growth?

Global electricity demand rises by 25-30% to 2030 in the STEPS and APS due to more electric motors, EVs, heat pumps and hydrogen.



What new power capacity will be built?

Renewables are set to dominate global capacity additions, accounting for 75-80% of all new capacity to 2050 in the STEPS and APS, led by solar PV and wind.



Introduction

Electricity accounts for about 20% of the world's total final consumption of energy, but its share of energy services is higher due to its efficiency. It is central to many aspects of daily life and becomes more so as electricity spreads to new end-uses, such as electric vehicles (EVs) and heat pumps. The electricity sector accounted for 59% of all the coal used globally in 2021, together with 34% of natural gas, 4% of oil, 52% of all renewables and nearly 100% of nuclear power. It also accounted for over one-third of all energy-related CO_2 emissions in 2021.

This chapter mainly draws on two scenarios, the Stated Policies Scenario (STEPS) and the Announced Pledges Scenario (APS). As described in Chapter 2, the STEPS maps out a trajectory that reflects current policies, while the APS assumes that all long-term emissions and energy access pledges and targets are met on time and in full. This chapter also draws on the updated Net Zero Emissions by 2050 (NZE) Scenario, which describes a cost-effective pathway for the world to achieve net zero emissions by mid-century in the energy sector that also limits cumulative emissions in line with a 50% chance of limiting the global average temperature increase to 1.5 °C by 2100.

This outlook for electricity is produced through simulations in the Global Energy and Climate Model (GEC-M), which assesses energy demand sectors at the end-use level in 26 regions. It takes account of over 100 electricity generation technologies, plus energy storage and network infrastructure, and makes use of an hourly model of electricity demand and supply by end-use and technology for major markets.

Section 6.1 provides an overview of the outlook for supply and demand in the global electricity sector.

Section 6.2 takes a deeper look at electricity demand by region, sector and end-use across the scenarios. It also examines the importance of energy efficiency in clean energy transitions.

Section 6.3 highlights key trends in electricity supply, including the speed of the shift from unabated fossil fuels to renewables, nuclear and other low-emissions options. It also provides a regional view of major supply trends.

Sections 6.4 deals with CO_2 emissions from electricity generation.

Section 6.5 considers the investment needs of the electricity sector in each scenario.

Sections 6.6 to 6.8 explores three key themes for the electricity outlook:

- Power system flexibility needs and how to meet them, with a focus on battery storage.
- Grid expansion and the challenge of timely development to support transitions.
- Rising demand for critical minerals in electricity and options to moderate demand.

Scenarios

6.1 Overview

Global electricity demand increases significantly in all the three scenarios by 2050. It rises from 24 700 terawatt-hours (TWh) in 2021 by about 80% in the STEPS, by 120% in the APS and by 150% in the NZE Scenario (Table 6.1). Electricity demand growth to 2030 is 2.4% per year in the STEPS, which is below the annual average of 2.6% from 2010 to 2021, but is 2.8% in the APS and 3.5% in the NZE Scenario, reflecting faster electrification of end-uses. From 2030 to 2050, electricity demand growth slows in the STEPS, but in the APS and NZE Scenario robust growth continues until 2040 before slowing. The buildings sector is the largest consuming electricity sector today and remains so in the STEPS and APS through to 2050, with industry the second-largest. Other uses of electricity rise rapidly, especially in the APS and NZE Scenario, as more EVs (battery electric vehicles and plug-in hybrids) hit the road and as the use of clean hydrogen ramps up.

6

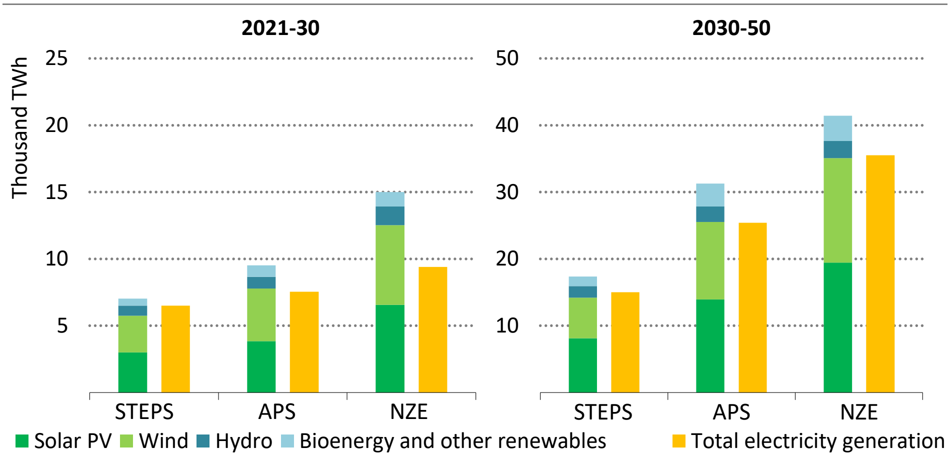
Table 6.1 ▷ Global electricity demand and supply by scenario (TWh)

			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Buildings	9 637	12 594	15 383	21 940	14 889	19 623	13 293	15 850
Industry	7 450	10 166	12 036	15 073	12 471	18 332	13 776	21 697
Transport	295	441	1 169	3 607	1 570	7 845	2 236	10 243
Hydrogen production	-	2	159	663	879	5 714	2 464	11 433
Global electricity demand	**18 548**	**24 700**	**30 621**	**43 672**	**31 752**	**53 810**	**33 733**	**62 159**
Unabated coal	8 670	10 201	9 044	5 892	8 076	1 580	4 666	0
Unabated natural gas	4 855	6 552	6 848	6 658	6 100	3 577	4 977	82
Unabated oil	969	682	432	312	363	175	180	3
Fossil fuels with CCUS	-	1	5	133	75	1 338	282	1 317
Nuclear	2 756	2 776	3 351	4 260	3 547	5 103	3 896	5 810
Hydropower	3 449	4 327	5 078	6 809	5 213	7 543	5 725	8 251
Wind	342	1 870	4 604	10 691	5 816	17 416	7 840	23 486
Solar PV	32	1 003	4 011	12 118	4 838	18 761	7 551	27 006
Other renewables	411	859	1 380	2 833	1 707	5 153	1 948	5 762
Hydrogen and ammonia	-	-	9	44	79	567	603	1 467
Global electricity supply	**21 539**	**28 334**	**34 834**	**49 845**	**35 878**	**61 268**	**37 723**	**73 232**
Renewables share	*20%*	*28%*	*43%*	*65%*	*49%*	*80%*	*61%*	*88%*

Notes: TWh = terawatt-hours; CCUS = carbon capture, utilisation and storage; PV = photovoltaics. STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Electricity demand is defined as total gross electricity generated less own use generation, plus imports, less exports and transmission and distribution losses. Other sources are included in electricity supply.

Global electricity supply is projected to shift away from unabated fossil fuels after recovering from current market disruptions. A number of countries marked a return to coal-fired power in 2022 as the economic recovery from Covid-19 pushed up electricity demand and as concerns rise about high natural gas prices and energy security. In the STEPS, the share of unabated coal in global electricity generation declines from 36% in 2021 to 26% in 2030 and 12% in 2050, while the share of unabated natural gas falls from 23% in 2021 to 20% in 2030 and 13% in 2050. Emissions pledges and goals drive faster reductions in the APS, where unabated coal falls to 23% of generation in 2030 and just 3% in 2050, and unabated natural gas drops to 17% in 2030 and just 6% by 2050 – the lowest share in 50 years. Oil makes up 2% of electricity supply today, and is mainly used in remote areas or near oil production sites: its use is set to decline further in all scenarios as generators turn to cheaper and low-emissions alternatives. Unabated coal, natural gas and oil decline even faster in the NZE Scenario, with electricity reaching net zero emissions globally by 2040.

Figure 6.1 ▷ Global growth in renewable electricity relative to total electricity generation growth by scenario, 2021-2050



Renewables outpace the increase of total generation in the STEPS, while they grow faster in the APS and displace more unabated fossil fuels

Note: TWh = terawatt-hours; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Renewable energy technologies currently provide close to 30% of electricity generation and are set for rapid growth in all scenarios, led by solar photovoltaics (PV) and wind. While renewables now represent the cheapest source of new electricity in most markets, the pace of their expansion depends on the retirement or reuse of existing sources of electricity generation as well as on new capacity, and therefore still rests largely in the hands of policy makers. In the STEPS, the growth of renewables generation exceeds the increase in total generation to 2030 and to 2050 (Figure 6.1), reducing the need for unabated fossil fuels.

In the APS, solar PV and wind alone outpace even higher demand growth to 2030 and 2050, unlocking deeper emissions reductions. In the NZE Scenario, renewables growth is 40% faster to 2030 and 20% faster to 2050 than in the APS, and this leads to electricity being rapidly decarbonised.

6.2 Electricity demand

Global electricity demand climbed to 24 700 TWh in 2021 – an increase of 6% from the previous year and the biggest annual increase since 2010 – reflecting a rebound in many economies following the pandemic. Nearly three-quarters of the global increase in electricity demand in 2021 was in emerging market and developing economies, with China alone accounting for about 700 TWh, or 50% of the global increase, an amount equivalent to total electricity demand in Africa today. Worldwide the current share of electricity in total final energy consumption is 20%. The largest electricity consumers are China, United States and Europe; together they account for over 60% of global electricity demand (Table 6.2).

Table 6.2 ▷ Electricity demand by region and scenario, 2010-2050 (TWh)

			STEPS		APS	
	2010	2021	2030	2050	2030	2050
North America	4 632	4 852	5 266	6 830	5 544	8 786
United States	3 880	4 004	4 281	5 482	4 529	7 187
Central and South America	932	1 097	1 308	2 168	1 447	2 940
Brazil	451	541	622	985	637	1 138
Europe	3 567	3 645	4 182	5 060	4 639	6 561
European Union	2 574	2 608	2 922	3 327	3 271	4 348
Africa	570	707	994	2 041	1 128	3 355
South Africa	214	194	229	365	248	494
Middle East	709	1 064	1 372	2 430	1 343	2 878
Eurasia	985	1 181	1 291	1 669	1 280	1 652
Asia Pacific	7 154	12 164	16 208	23 475	16 371	27 638
China	3 659	7 556	9 969	12 868	9 940	14 504
India	717	1 273	2 117	4 293	2 107	5 314
Japan	1 071	934	893	922	952	1 153
Southeast Asia	607	1 037	1 537	2 848	1 580	3 214
Global electricity demand	**18 548**	**24 700**	**30 621**	**43 672**	**31 752**	**53 810**

Note: TWh = terawatt-hours.

Electricity demand increases at 2.4% per year in the STEPS over the rest of this decade to reach more than 30 600 TWh by 2030. Demand grows faster in the APS, reaching around 31 750 TWh in 2030. Between 2030 and 2050, electricity demand growth in the STEPS slows to 1.8% per year to reach around 43 700 TWh by 2050. In the APS, annual demand growth is 2.7% after 2030 to reach nearly 54 000 TWh by 2050.

Today's unfolding global energy crisis has led to soaring electricity prices for consumers. For example, the average residential electricity price in the European Union was about 30% higher in the first-half of 2022 than during the same period in 2021 (IEA, 2022a; Energie-Control Austria, MEKH and VaasaETT, 2022). To tackle the crisis in the short-term and limit the impact of high wholesale electricity prices, some European governments have introduced measures such as price caps on retail electricity prices, subsidies for fossil fuel power generators, windfall taxes on profits and payments to shield end-users from rising electricity bills (Spotlight). Action to cushion the impact on end-users is understandable, nevertheless, there is a risk that muted electricity price signals may discourage the essential behaviour changes and efficiency improvements that reduce demand and, by doing so, help reduce prices. In a search for longer term solutions, the European Union is exploring whether the current electricity market design needs to be overhauled.

Despite the turbulence in today's electricity markets, the momentum for further electrification is strong across the world, with the deployment of electric cars and the installation of heat pumps set to increase, and with electricity being used to meet new end-uses. Electricity prices have risen dramatically, but so have prices for oil, natural gas and coal. Electricity generation moreover is set to reduce its dependence on fossil fuels in the years ahead, thus reducing emissions and enhancing its attractiveness. Reduced dependence on fossil fuels could also bring energy security benefits, provided that electricity grids are enhanced to help ensure resilience. In the STEPS, the share of electricity in total final consumption reaches 22% in 2030 and 28% in 2050. In the APS, these shares rise to 24% and nearly 40% respectively, and in the NZE Scenario they rise further to 28% and over 50% by 2050.

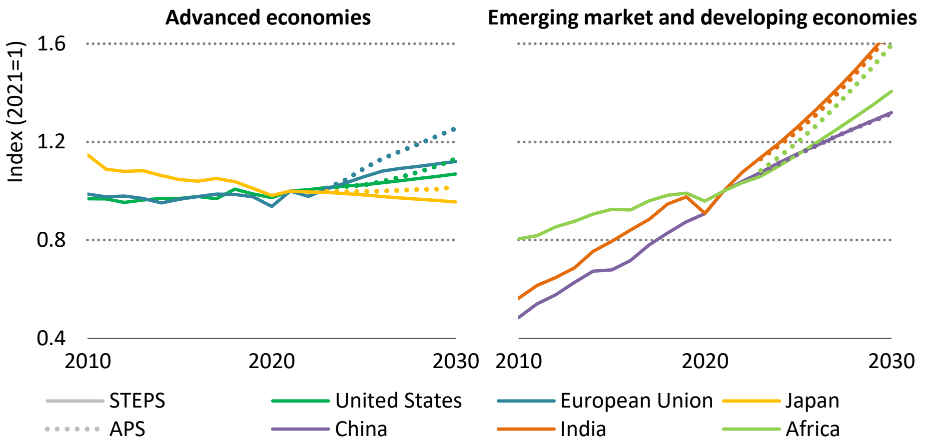
Electricity demand by region

A more granular look at regional trends reveals important differences in the evolution of electricity demand around the world. One of the most rapid increases in electricity consumption in recent years has been in China, where it doubled between 2010 and 2021 as a result of rapid economic and industrial growth (Figure 6.2). By far, China is now the world's largest consumer of electricity: it accounts for 30% of the global total, almost twice as much as the United States, the second-largest consumer with 16% of the global total. Advanced economies have seen a decline of over ten percentage points in their share of global electricity demand since 2010 as demand has surged in emerging market and developing economies. This trend continues in both the STEPS and APS as continuing rapid energy demand growth and electrification take place in China, India, Middle East and Africa, especially in the industry and buildings sectors.

In advanced economies, average electricity demand per capita declined by 0.2% per year since 2010, but is projected to increase by 0.8% per year by 2030 in the STEPS and twice as fast in the APS. Transport emerges as the largest contributor to electricity demand growth in both scenarios, mainly due to the rapidly increasing number of EVs. In the United States, the market share of electric cars increases from less than 5% in 2021 to 30% in the STEPS and

50% in the APS by 2030, with the increase stemming predominantly from the Inflation Reduction Act and state-level targets. The share of electricity in total final consumption in the United States increases from 21% in 2021 to 23% in the STEPS and to 24% in the APS by 2030. In the European Union, the accelerated deployment of heat pumps in buildings and industry and the expansion of the electric car fleet by around 35 million help to increase the share of electricity in total final consumption from 21% in 2021 to 25% in the STEPS and 29% in the APS by 2030. Efficiency gains from modern appliances and heating and cooling systems temper the growth in demand and the relatively high levels of electricity demand per capita.

Figure 6.2 ▷ Electricity demand in key regions by scenario, 2010-2030



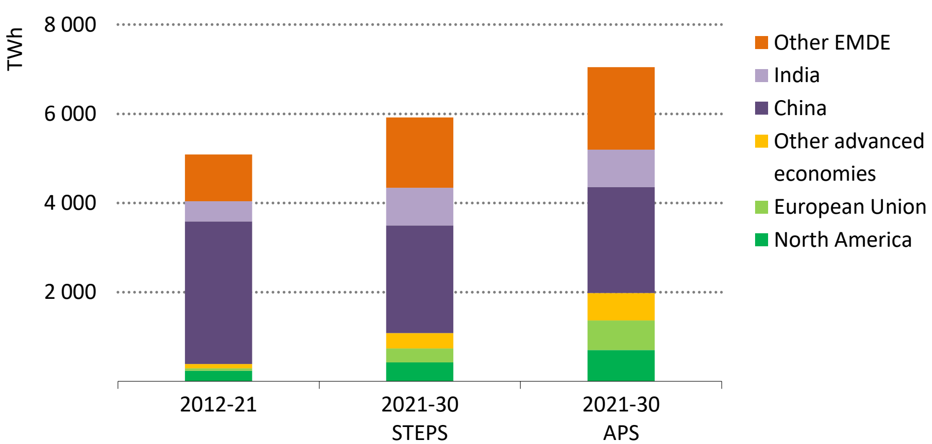
Electricity demand rebounds in most advanced economies after a decade of flat demand, while it continues to grow strongly in emerging market and developing economies

In emerging market and developing economies, average annual electricity demand per capita increased by 3.5% between 2010 and 2021. It continues to grow at an annual average rate of 2.2% in the STEPS and 2.3% in the APS through to 2030. Electricity demand in China increases in both scenarios by over 30% to 2030, and its share in global electricity demand rises in both scenarios in 2030 as its economy shifts towards services and high-tech industries. Economic growth and rising standards of living in India increase household appliance ownership and increase electricity demand by two-thirds by 2030 in both scenarios. A similar level of growth is projected in Indonesia: buildings account for the majority of this, driven in large part by an increase in the number of people with air conditioners as the country moves from an average of 0.1 units per household today to 0.4 per household by 2030. On the African continent, around 150 million people gain access to modern electricity services in the STEPS by 2030 and nearly 480 million in the APS; there is also a rise in ownership of appliances such as refrigerators and fans. These developments lead to increases in electricity demand of more than 40% in the STEPS and around 60% in the

APS by the end of this decade. The progress made in improving access to electricity in Africa by 2030 accounts for nearly 70% of the progress made worldwide in the STEPS: this rises to over 80% in the APS.

Global electricity demand increases by around 5 900 TWh between 2021 and 2030 in the STEPS, which means an annual rate of growth slightly lower than over the last decade. Demand growth is faster in the APS, which sees an increase in demand of over 7 000 TWh between 2021 and 2030, equivalent to nearly 70% of current electricity demand in advanced economies (Figure 6.3). Announced pledges lead in the APS to a more rapid deployment of EVs across all vehicle categories, and of heat pumps in buildings and for industrial processes. In the NZE Scenario, electrification goes even further than the APS as electricity demand surpasses 62 000 TWh by 2050, 40% higher than the STEPS levels. By 2030, the increase in the NZE relative to the STEPS is similar in both advanced economies and emerging market and developing economies.

Figure 6.3 ▷ Electricity demand growth by region and scenario, 2012-2030



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Global electricity demand growth picks up over the next decade, as a slowing in China is more than counterbalanced by strong increases in many other markets

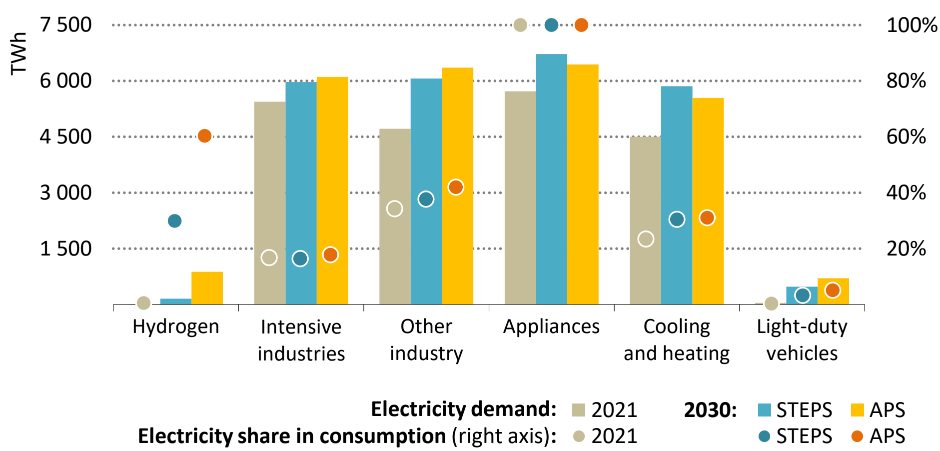
Note: EMDE = emerging market and developing economies.

The rapid penetration of electric motors in industrial processes and higher levels of ownership of appliances and air conditioners bring about a sharp rise in electricity demand in a number of emerging market and developing economies, notably in India and other emerging Asian economies. China's demand for electricity increases too, but at a slower rate. This changes the landscape of electricity demand over time. Between today and 2030, China's share of global electricity demand growth in emerging market and developing economies declines from the level of two-thirds seen over the last decade to about half in both the STEPS and the APS.

Electricity demand by sector

The biggest consumers of electricity today are the buildings and industry sectors, which together account for over 90% of global electricity consumption and have contributed over 90% (around 5 700 TWh) of global electricity demand growth since 2010. In buildings, electricity is consumed largely by appliances (45%) and by space cooling and heating (nearly 30%). By 2030, electricity demand for heating in buildings is smaller in the APS than in the STEPS as a higher level of efficiency improvements in the APS more than compensates the higher rate of electrification (Figure 6.4). In industry, electricity is mainly used for electric motors, but also for aluminium smelting and electric arc furnaces. Industry is the end-use sector that accounts for one-third of the total electricity demand increase in the STEPS and the APS by 2030: economic growth drives industrial output in emerging market and developing economies, and policies to reduce emissions spur the electrification of industrial equipment.

Figure 6.4 ▷ Global electricity demand and share of electricity in energy consumption in selected applications by scenario, 2021 and 2030



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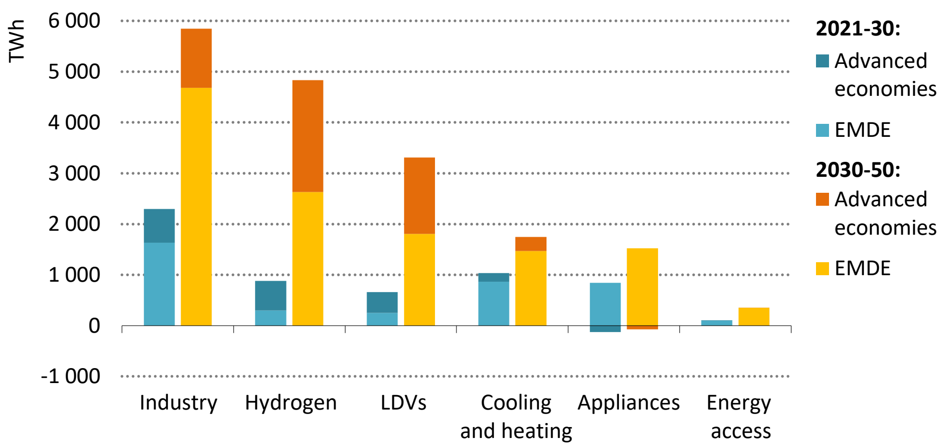
The electrification of many end-uses moves forward, though to varying degrees, raising electricity demand from established uses and new ones, like EVs and hydrogen production

Notes: Hydrogen corresponds to electricity needs for its production and the share of electricity in the total energy consumed during the process of hydrogen production. Appliances include refrigerators, washing and dishwashing machines, dryers, brown appliances (relatively light electronic appliances such as computers or televisions) and other electric appliances (excluding cooking, lighting, cooling, cleaning and desalination). Cooling and heating include space and water heating as well as space cooling in buildings. Intensive industries (Energy-intensive industries) include iron and steel, chemicals, non-metallic minerals, non-ferrous metals, and paper, pulp and printing industries. Other industry includes the remaining industrial sub-sectors, i.e. construction, mining and textiles.

Transport is the one of the leading contributors to electricity demand growth in the projections, especially in advanced economies. The number of EVs has increased rapidly in recent years; the current global EV fleet consumes nearly 100 TWh of electricity per year. Electric car sales reached 6.6 million in 2021 and are expected to surpass 10 million in 2022. In the STEPS, electric cars gain a market share of 25% by 2030; in the APS, this rises to over 35%. This rapid electrification of mobility is brought about by national and regional policies as well as ambitious targets from vehicle manufacturers (see Chapter 5). By far, rail was the largest consumer of electricity in transport over the last decade, but electricity demand in road transport surpasses rail by 2027 in the STEPS and a year earlier in the APS.

In the STEPS, the global electric car fleet expands eleven-fold in the coming decade, adding over 380 TWh to current global electricity demand (and boosting the scope for the use of EVs to balance grids and demand-side management alleviating potential integration challenges). Electrification is mainly focused on passenger vehicles (passenger cars, urban buses and two/three-wheelers), with progress on heavy trucks slowed by more complicated infrastructure needs such as deployment of high power chargers.

Figure 6.5 ▷ Electricity demand growth by application in the APS, 2021-2050



Industry, hydrogen production and light-duty vehicles contribute significantly to electricity demand growth in economies around the world

Notes: EMDE = emerging market and developing economies; LDVs = light-duty vehicles. Energy access represents the electricity demand that satisfies basic energy needs of people gaining energy access for the first time. Cooling and heating corresponds to electricity demand for space cooling and heating needs.

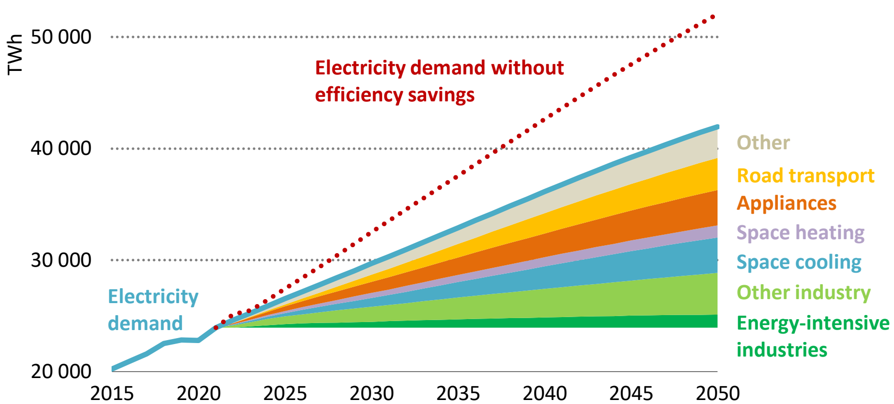
The rapidly rising demand for cooling in emerging market and developing economies makes it a large contributor to electricity demand growth, with climate change compounding the demand for cooling (see Chapter 5). In emerging market and developing economies, cooling needs rise, adding another 2 800 TWh to global electricity demand by 2050 in the STEPS. For example, the ownership of air conditioners is projected to increase by 40% from the current level in China by 2030. Energy efficiency policies are effective in tempering electricity demand (Box 6.1), therefore keeping this increase down to 1 400 TWh in the APS. Even more stringent efficiency standards for air conditioners, together with better insulation in homes, help to restrict additional electricity demand to only 765 TWh in the NZE Scenario, despite additional acceleration of electrification in this scenario.

Energy access constitutes a minor part of the increase in electricity demand, even though cumulatively over 580 million people gain access from today to 2030 and over 1 billion by 2050 in the APS. This reflects the low average electricity consumption of a person gaining access to electricity for the first time, and it shows that energy poverty reduction can be achieved with only a relatively small increase in global electricity demand (Figure 6.5).

Box 6.1 ▹ Energy efficiency tempers electricity demand growth and reduces raw material needs

A major shift towards EVs and heat pumps takes place across the world in the STEPS. Increasing cooling and heating needs, especially in emerging market and developing economies, also increase electricity consumption. Global total electricity consumption rises by nearly 18 000 TWh by 2050, which is roughly equivalent to current electricity demand in China and advanced economies combined. This implies a need to expand global electricity generation by three-quarters by 2050. Without energy efficiency gains, however, this level would be around 10 000 TWh higher (Figure 6.6).

Figure 6.6 ▹ Global total electricity consumption with and without energy efficiency gains in the STEPS, 2015-2050



Energy efficiency gains cut electricity consumption growth by around 10 000 TWh in the STEPS by 2050

Note: Efficiency gains are mainly due to stricter fuel economy standards in road transport; minimum energy performance standards and labels in the buildings sector; technological improvements and material recycling in industry.

In the STEPS, improved efficiency standards for appliances and motors, better insulation in buildings, optimised logistics and energy efficiency improvements in vehicles together lead to global electricity demand being about 10% lower than it otherwise would be in 2030 and around 20% lower two decades later. These gains highlight the huge part that energy efficiency has to play to moderate electricity demand, reduce requirements for additional power capacity and temper demand for the critical minerals needed in low-emissions power systems, grids, EVs and storage batteries (see section 6.8).

6.3 Electricity supply

The global share of fossil fuels in electricity generation declined from around 65% in 2018 to 62% in 2021 reflecting the rapid rise of solar PV and wind in power generation over the past decade. Current market conditions are also driving change. Global prices for oil and natural gas began rising rapidly in late 2020 as demand recovered with the easing of Covid-19 restrictions. This trend was hugely exacerbated in early 2022 by Russia's invasion of Ukraine. Concerns about the price of natural gas and energy security have led to a temporary return to coal-fired generation in some cases, but they have also sparked an ambition in some countries to make faster progress on reaching net zero emissions through enhanced support for combinations of renewables, nuclear power, carbon capture, hydrogen and ammonia, as well as earlier coal phase outs. This ambition builds on technology innovation and progress, including declining costs for solar PV, wind and batteries, together with advances in the development of small modular nuclear reactors and the use of hydrogen and ammonia in fossil fuelled power plants.

Recent policy developments

The policy landscape is a key determinant of the outlook for the electricity sector and it continues to evolve in the light of market conditions and world events. There have been a number of recent policy developments that will have an impact on the electricity supply outlook (Table 6.3).

During or after the COP26 in November 2021, several additional countries pledged to reach net zero emissions, e.g. Indonesia in 2060 or earlier and India by 2070. As of September 2022, 83 countries and the European Union had established net zero emissions targets. G7 members have also committed to ensuring that their power sectors are fully or predominantly decarbonised by 2035, and the measures they take to this end may help to clear a path for other countries (IEA, 2022b). The number of countries with renewable power policies rose from 145 in 2020 to 156 in 2021, continuing a multi-year trend. By the end of 2021, most countries worldwide had a renewable energy support policy in place, with most support continuing to focus on the power sector and less effort being made to accelerate renewables in the buildings, transport and industry sectors. The total number of countries with economy-wide targets for 100% renewables increased to 36 by the end of 2021, up from 32 the previous year (REN21, 2022).

Table 6.3 ▷ Recent policy changes and announcements regarding electricity supply

	Policy change	Authority
European Union	• Phase out coal-fired power plants in Czech Republic, Slovenia and Romania (emergency law).	Governments (January and June 2022)
United States	• Inflation Reduction Act provides funding for energy and climate programmes, including expanding and extending tax credits and incentives to promote clean energy technologies.	Federal government (in law August 2022)
	• Five states updated their renewable portfolio standard policies.	Various state governments
China	• New Plan for Renewable Energy Development: higher targets for renewables.	National Development and Reform Commission (June 2022)
Canada	• 2030 Emissions Reduction Plan outlines a sector-by-sector path to reach its emissions reduction target of 40% below 2005 levels by 2030 and net zero emissions by 2050.	Federal government (June 2022)
Korea	• Increase renewables in electricity generation to over 20% and nuclear power to over 30%, and decrease coal-fired power by 2030 under the New Energy Policy Direction.	State Council (July 2022)
Australia	• Climate Change Bill 2022 enshrines in law two national greenhouse gas emissions targets: 43% cut below 2005 levels by 2030 and achieve net zero emissions by 2050.	Federal government (in law July 2022)
Japan	• Restart nuclear power plants aligned with the 6th Strategic Energy Plan and the Green Transformation (GX) policy initiative.	Ministry of Economy, Trade and Industry (Aug 2022)

	Announced policy	Authority
G7 members	• Achieve predominantly decarbonised electricity sectors by 2035.	G7 Ministers of Climate, Energy and the Environment (May 2022)
European Union	• Fit for 55: Council agrees on binding 40% EU-level target for renewables in overall energy mix.	Council of the European Union (June 2022)
Germany	• Green energy law reforms set higher targets for wind and solar.	Government (July 2022)
Australia, Côte d'Ivoire, Israel, Nauru, United Arab Emirates, Viet Nam	• Net zero emissions targets by 2050.	Various national governments
Bahrain, Indonesia, Nigeria, Saudi Arabia	• Net zero emissions targets by 2060.	Various national governments
India	• Net zero emissions target by 2070.	Prime Minister (Nov 2021)
United Kingdom	• Energy Security Strategy sets new ambitions for offshore wind, nuclear and hydrogen.	Prime Minister (April 2022)
Japan	• Accelerated nuclear expansion, including SMRs, envisioned in the GX initiative.	(June 2022)

In addition to action on renewables, Germany and several other European countries are reverting to coal-fired power plants to cut their reliance on natural gas imported from Russia and to bolster energy security. This is a temporary measure: the current natural gas crisis looks likely in the medium term to lead to a determination to reduce reliance on imported fossil fuels in the name of energy security. Moreover, all G7 Members committed to "prioritising concrete and timely steps towards the goal of accelerating phase-out of domestic unabated coal power" (European Council, 2022).

A rising number of countries have announced plans to support new nuclear investment. For example, in February 2022, France announced plans to build six new large reactors starting in 2028 at a cost of about EUR 50 billion, with an option to build eight more by 2050. China plans to continue its current pace of construction of nuclear reactors in order to help meet its goal of carbon neutrality by 2060. Korea has recently reversed its nuclear phase-out policy and now supports lifetime extensions of existing facilities, the restarting of construction at two sites and an increase in the share of nuclear in electricity generation.

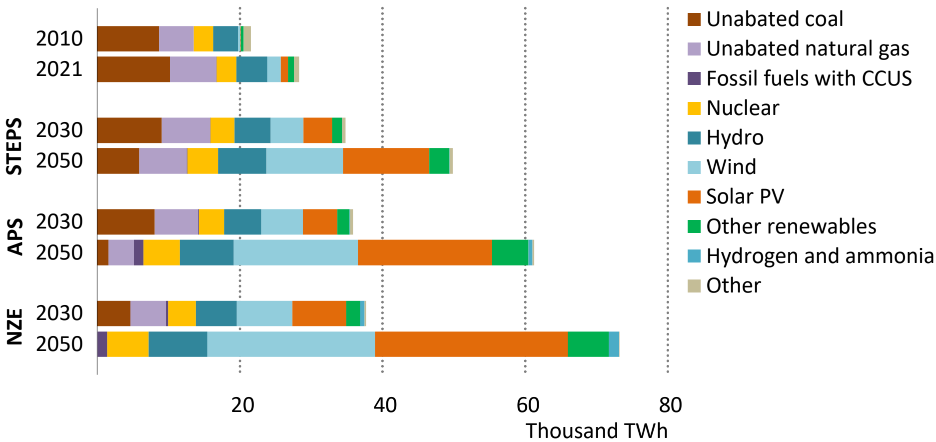
Other recent policy developments affect a range of low-emissions energy sources. In the United States, the Inflation Reduction Act provides additional funding and tax credits to incentivise multiple sources of clean energy, including energy storage, nuclear power, clean energy vehicles, hydrogen and carbon capture, utilisation and storage (CCUS), while the US Bipartisan Infrastructure Law will help fund new transmission lines to facilitate the expansion of renewables and clean energy. Canada recently announced a tax credit for capital invested in new CCUS projects. Plans to use hydrogen and ammonia in the power sector have advanced, with strengthened policies or targets in many countries, including in Europe, Japan, Korea and India (IEA, 2022c).

Electricity supply by source

Renewables are set to become the dominant source of electricity worldwide in the long term. Total electricity generation from renewables increased by more than 500 TWh from its 2020 level to reach a record high of over 8 000 TWh in 2021, driven mostly by rising solar PV and wind generation (Figure 6.7). As a result, the share of renewables in global electricity generation rose by 0.2 percentage points to reach nearly 29% for the first time. Renewables continue to scale up rapidly in the STEPS, with their share of generation rising to 43% by 2030 and 65% by 2050. The APS sees an even faster transition to renewables, with 35% higher growth than in the STEPS to 2030.

Renewables are projected to account for the majority of capacity additions in every region over the outlook period (Figure 6.8). By far, wind and solar PV are the largest contributors to this development, and total installed solar PV capacity in particular is projected to far outstrip that of any other source in both the STEPS and the APS from the 2030s onwards. In the STEPS, wind and solar PV together set new records every year to 2030 and then continue robust annual growth through to 2050. In all regions, they account for between 45% and 85% of all capacity additions over the period to 2050. Both solar PV and wind assume an even larger role in the APS: annual wind capacity additions increase from 95 GW in 2021 to 210 GW in 2030 and 270 GW in 2050, while solar PV capacity additions rise from 151 GW in 2021 to 370 GW in 2030 and nearly 600 GW in 2050. In the NZE Scenario, renewables increase even more rapidly, with their share of total generation increasing from 29% in 2021 to over 60% in 2030 and nearly 90% in 2050. The huge rise in the share of solar PV and wind in total generation in all scenarios fundamentally reshapes power systems and significantly increases the demand for power system flexibility (see section 6.6).

Figure 6.7 ▷ Global electricity generation by source and scenario, 2010-2050

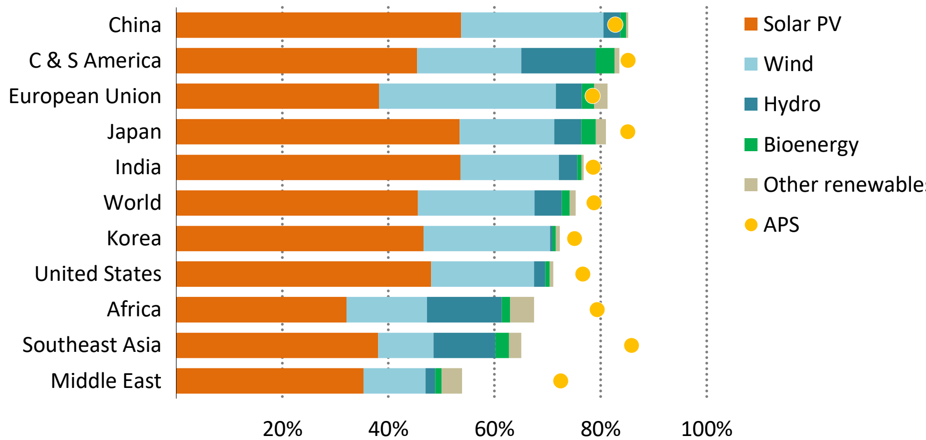


Electricity generation from unabated fossil fuels peak by 2030, as low-emissions sources ramp up and renewables dominate electricity supply in all scenarios by 2050

Note: Other renewables include bioenergy and renewable waste, geothermal, concentrating solar power and marine power.

Hydropower and other dispatchable renewables continue to play an important role in all the scenarios. In the STEPS, hydropower remains the largest source of renewable electricity until after 2030, when it is surpassed by both wind and solar PV. In the APS, hydropower and other dispatchable renewables such as bioenergy, geothermal and concentrating solar power (CSP) increase faster to help cut electricity sector emissions more quickly and integrate the fast rising share of variable wind and solar PV electricity generation. The role of hydropower to help provide power system balance and stability, however, may be affected by climate-related events, which have reduced its availability in many regions over the last year, straining power grids and raising questions about the resilience of electricity systems (Box 6.2).

Figure 6.8 ▷ Share of renewables in total power capacity additions by region in the STEPS, 2022-2050



Renewables account for the majority of capacity additions in all regions, with massive growth for solar PV and wind in all markets, followed by hydro in many

Note: C & S = Central and South America.

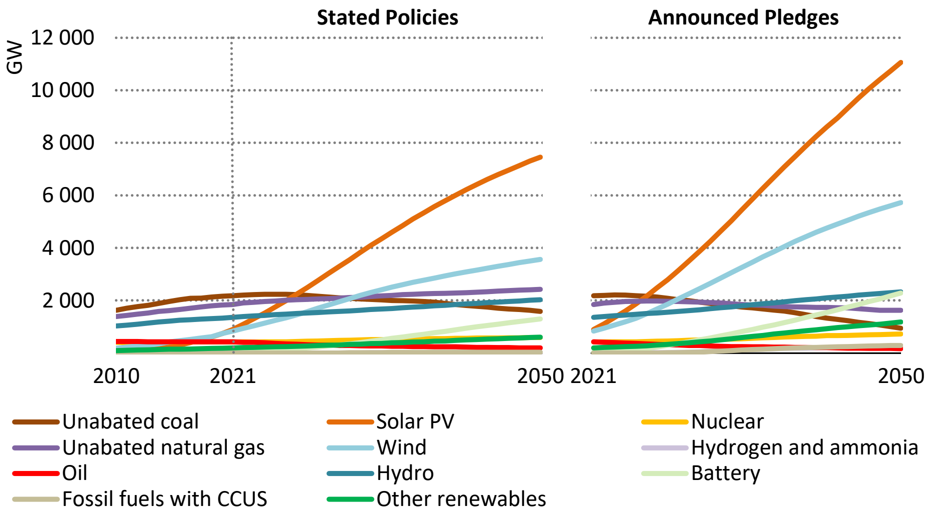
The continued role of **nuclear power** in the electricity sector relies on decisions to extend the lifetime of existing reactors and the success of programmes to build new ones. In the STEPS, nuclear maintains its share of about 10% in total electricity generation. This requires the completion of 120 GW of new nuclear capacity over the 2022-30 period, as well as the addition of another 300 GW worth of new reactors (the equivalent of almost three-quarters of the current global fleet) between 2030 and 2050 in over 30 countries. In the APS, around 18 GW of new nuclear capacity is added per year over the outlook period, over a quarter more than in the STEPS, but the higher level of electricity demand in this scenario means that the nuclear share of the electricity supply mix remains at close to 10%. In the NZE Scenario, a wave of lifetime extensions in advanced economies in the 2020s helps limit global emissions, and an average of 24 GW of capacity added each year between 2022 and 2050 more than doubles nuclear power capacity by 2050. The nuclear share of the electricity mix, however, falls to 8% in 2050 due to very strong growth in electricity demand in the NZE Scenario. More information on the potential and challenges for nuclear energy, including new, small modular reactors, is provided in the IEA special report *Nuclear Power and Secure Energy Transitions* (IEA, 2022d).

Other dispatchable low-emissions technologies include **fossil fuels with CCUS**, and **co-firing** with **ammonia** in coal plants and **hydrogen** in gas-fired power plants.[1] These technologies are currently at the pre-commercial stage of development and significant efforts would be

[1] Hydrogen in gas-fired power plants includes both co-firing and full conversions.

required for them to start being deployed at scale before 2030. In the STEPS, CCUS technologies gain a limited amount of traction over the outlook period, as the commitments to deep CO_2 emission reductions that provide the impetus for the deployment of CCUS have not yet been converted into concrete implementation plans in most countries. In the APS, by contrast, the first CCUS retrofits are completed before 2030, and over 200 GW of coal-fired capacity and over 80 GW of gas-fired plants equipped with CCUS are in operation by 2050 (Figure 6.9), together accounting for 2% of total global electricity generation. Most CCUS deployments take place in China; other significant applications are in Indonesia, Japan and the United States.

Figure 6.9 ▷ Global installed electricity capacity by source and scenario, 2010-2050



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Solar PV and wind installed capacity moves well beyond any other source by 2050, taking the lead from coal- and natural gas-fired power today

Similarly, the co-firing of ammonia or hydrogen remains very limited in the STEPS, and accounts for less than 0.1% of total electricity generation in 2050. The notable exception is Japan, where plans to co-fire ammonia in coal plants are under development and where co-fired ammonia and hydrogen are projected to reach a share of close to 5% of electricity generation in 2050. In the APS, co-firing makes strong inroads from 2030 onwards in other advanced economies too, and in particular in European Union, Korea and United States, with hydrogen seen as a tool to help achieve emissions reduction goals. In the NZE Scenario, nearly 190 GW is retrofitted to co-fire hydrogen or ammonia by 2030, rising to 580 GW by 2050. However, due to high cost, these fuels are primarily used as a source of flexibility to balance variable wind and solar PV output. Their overall contribution to the global electricity supply mix thus remains limited even in the APS (less than 1% in 2050) and NZE Scenario (close to 2% in 2050). The enormous size of the electricity sector nevertheless makes it one of the primary drivers of global hydrogen demand.

Unabated natural gas supplied 23% of global electricity in 2021. After a short-term decline, gas-fired generation rebounds in the STEPS, with increased demand in emerging market and developing economies more than offsetting reductions in advanced economies, in particular in Europe. However, unlike in the *World Energy Outlook (WEO)-2021* (IEA, 2021a), which projected growth, gas-fired generation is now expected to stay at broadly the same level until 2050. This is the result of a shift in perceptions about the role of natural gas that stems from the current energy crisis and record prices for natural gas in all major markets. In the NZE Scenario, natural gas-fired generation increases slightly in the near term as a result of coal-to-gas switching, but peaks by 2025. Even as output falls, however, natural gas-fired capacity remains a critical source of power system flexibility in many markets.

Unabated coal met almost half of the increase in electricity demand in 2021, with its share of total electricity generation exceeding 36%. Coal-fired power plants under construction at the start of 2022 represented over 175 GW of capacity with many more plants in the planning stage. In the STEPS, coal-fired power plant capacity reflects this and continues to grow, peaking by 2025. Coal-fired generation, however, is projected to enter a decline and falls more rapidly as 2030 approaches. Unabated coal accounts for 26% of global electricity generation in 2030, declining to 12% by 2050. Most advanced economies are pursuing coal phase-out policies and they cut unabated coal use in the power sector by 60% from 2021 to 2030. Coal use increases by 3% to 2030 in emerging market and developing economies, but it then also enters a long-term decline.

Coal sees the largest impact among all fuels from the fulfilment of announced pledges by governments. In the APS, unabated coal declines steeply from 2025 onwards, with its share in electricity generation dropping to 23% by 2030 and just 3% in 2050. In advanced economies, unabated coal generation falls nearly 80% by 2030 and is phased out completely by 2050. In emerging market and developing economies, unabated coal use continues to rise until 2025 before declining significantly, driven mostly by net zero emissions pledges in China, India and Indonesia. In the NZE Scenario, no unabated coal plants beyond the ones already under construction are commissioned. The share of unabated coal in global electricity generation declines rapidly to 12% in 2030 and falls to zero by 2040. CCUS retrofits play an important role in mitigating emissions from the relatively young coal fleet in emerging market and developing economies.

Box 6.2 ▻ Will electricity systems be more resilient to climate risks in the future?

In addition to other threats to electricity security, global power systems faced a number of climate-related challenges over the last year. Heatwaves and droughts were significant in many parts of the world, e.g. China, Europe, India, Myanmar, Pakistan, Sri Lanka, South Africa and the United States. As a result, the availability of hydropower and cooling water for thermal power plants was reduced, straining the ability of electricity systems to meet demand, including for space cooling. Very cold temperatures also affected natural gas infrastructure and caused electricity outages in countries including the United States. Other extreme weather events caused damage to electricity infrastructure and extended outages. For example, the 2021 Atlantic hurricane season brought the third-highest number of named storms on record, impacting Latin America and the Caribbean in particular, while devastating flooding from heavy rains in 2022 affected millions of people, notably in Bangladesh, India, Nigeria and Pakistan.

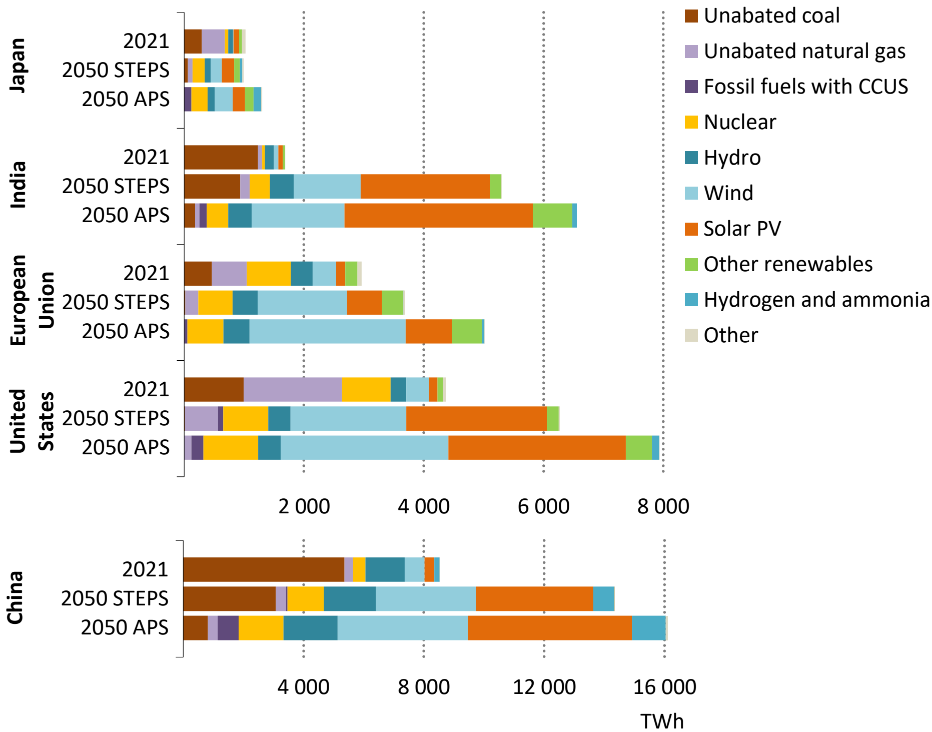
Climate risks are set to increase in all scenarios due to rising global temperatures, changing rainfall patterns, rising sea levels and extreme weather events. Changes in the electricity sector will reduce exposure to some of these risks, but increase exposure to others. The electrification of heating and cooling in all scenarios will place more strain on electricity grids during extremely hot or cold periods. Electricity demand for cooling is set to increase strongly in emerging market and developing economies in particular, rising nearly fourfold from 2021 to 2050 in the STEPS. Electric heating expands fastest in emerging market and developing economies too, where the related consumption of electricity more than doubles to 2050 in the STEPS. In both cases, energy efficiency efforts in the APS cut the electricity demand growth for heating and cooling to 2050 seen in the STEPS, reducing the strain on electricity networks during peak demand periods. While adding to overall electricity demand, the expansion of EVs has the potential to help alleviate the impacts of extreme hot and cold weather by helping to smooth demand patterns through smart charging and vehicle-to-grid arrangements.

In electricity supply, the resilience of fossil fuel infrastructure, particularly for natural gas, remains critical for electricity security even as the use of fossil fuels declines (see Chapter 4). However, the shift away from unabated fossil fuels in all the scenarios is likely to increase resilience by reducing their use of cooling water. The increase in nuclear power in all scenarios partly offsets this reduction in cooling water demand, but it also reduces dependence on imported fossil fuels. The expansion of solar PV and wind in all scenarios improves the resilience of electricity systems to some climate impacts, but it also increases their exposure to seasonal weather patterns such as long periods of cold and low wind in Europe. Electricity security will depend on having sufficient flexibility available at all times. Flexibility will be especially important in the APS and NZE Scenario, where solar PV and wind play a much larger role than in the STEPS (see section 6.6). There are a number of effective steps that can be taken to improve the climate resilience of electricity systems, and thus to avoid outages, minimise repair costs and facilitate clean energy transitions. These include steps to assess risks, incorporate climate resilience in energy and climate plans, identify cost-effective measures, incentivise utilities to take action, implement resilience measures and evaluate and adjust them to continuously improve system resilience (IEA, 2021b).

Electricity supply by region

The electricity supply mix differs from region to region, reflecting available resources, policy choices and the relative economic competitiveness of various power generation technologies. Most power sector investment today is driven by policies, which play a major role in shaping the development of regional power mixes over the outlook period. A common trend across all regions is the expanding contribution from wind and solar PV generation, driven mainly by declining costs and robust policy support in many countries (Figure 6.10).

Figure 6.10 ▷ Electricity generation by source, key region and scenario, 2021 and 2050



Electricity supply is set to shift away from unabated fossil fuels in all major markets, as renewables, nuclear, hydrogen, ammonia and carbon capture scale up

Note: Other renewables includes bioenergy and renewable wastes, concentrating solar power and marine power. Other includes non-renewable waste and other sources.

In **China**, unabated coal-fired electricity generation accounts for more than 60% of electricity supply and is still expanding, but the peak is approaching in all scenarios. In the STEPS, unabated coal starts to decline before 2030 and falls by over 40% from its peak by 2050. In the APS, coal use falls faster, with its share of the generating mix declining to 9% by 2050, nearly half of it from plants equipped with CCUS. Overall, China sees a profound transformation of its electricity supply mix over the period to 2050, with steps towards this set out in 14th Five-Year Plan to 2025. While total generation in 2050 rises by two-thirds in the STEPS and nearly doubles in the APS, the share of low-emissions sources increases to 76% in the STEPS and close to 95% in the APS, up from 34% today. By far, the most significant growth is from wind and solar PV. In the STEPS, these two technologies account for 80% of all additional capacity installed between 2021 and 2050. With the world's largest new build programme, nuclear power too is set to rise significantly: the STEPS projects the construction of more than 120 GW of additional nuclear capacity on top of the more than 50 GW which is operational today.

In **India**, the primary challenge is how to meet rising electricity demand with renewables and nuclear on a large enough scale to reduce the use of unabated coal-fired generation, which provides nearly three-quarters of electricity supply today. In both the STEPS and the APS, coal generation is projected to continue rise in absolute terms, peaking around 2030, though its share of electricity generation declines. Expanding renewables is the central means of meeting demand growth and limiting coal use, with solar PV leading the way and wind also playing an important part. The APS shows that meeting current pledges in full calls for continued expansion of renewables and a scaling up India's nuclear fleet so as to enable an almost complete phase-down of unabated coal-fired electricity generation by 2050, while also maintaining grid reliability.

In the **United States**, the electricity sector is continuing its transition away from coal. The Inflation Reduction Act supports the accelerated deployment of wind and solar PV, among other technologies, which leads to a long-term reduction in natural gas use as well. In the STEPS, unabated coal almost disappears from the electricity generating mix by 2050, with its share dropping to below 1% from nearly 23% today. At the same time, strong growth in renewables leads to gas-fired generation peaking before 2030 and then falling rapidly: it is nearly two-thirds lower than today by 2050. Recent policy changes also provide support for lifetime extensions for the ageing fleet of nuclear power plants. In the APS, the United States pursues its ambition of net zero emissions electricity around 2035 through accelerated deployment of renewables, CCUS, hydrogen and ammonia together with an expansion of nuclear power, including small modular reactors.

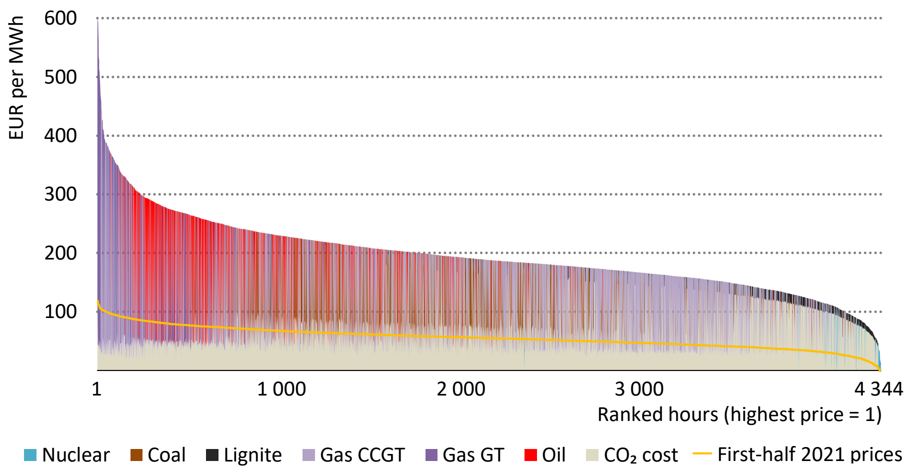
In the **European Union**, an emphasis on energy security and reducing reliance on imported natural gas is expected to speed up the deployment of renewables. In the STEPS, the combined share of wind and solar PV in the generation mix rises from 18% today to 42% in 2030 and 56% in 2050, with wind and solar PV accounting for more than 70% of all new power capacity installed between 2021 and 2050. The expansion of solar PV and wind could offer a degree of protection for consumers from market fuel price volatility of the kind currently being experienced (Spotlight). In the APS, the near term and medium-term expansion of renewables is even more rapid. In the long-run, the European Union moves towards an electricity system dominated by onshore and offshore wind, with both accounting for more than 40% of total generation in 2050 in the STEPS and over 50% in the APS and NZE Scenario.

SPOTLIGHT

Are high electricity prices here to stay in the European Union?

Retail electricity prices in the European Union were about 30% higher on average for residential consumers in the first-half of 2022 than they were a year before. This increase reflects high wholesale electricity market prices in the European Union, which soared to EUR 200 per megawatt-hour (MWh) on average during the first-half of 2022 - more than three-times the average in the first-half of 2021. This is one of the most extreme near-term impacts of the current energy crisis, and it is not confined to the European Union, although it is starkest there: costs to generate electricity are set to rise by an estimated one-third worldwide in 2022 (see Chapter 1).

Figure 6.11 ▷ Hourly wholesale electricity price duration curve and price setting technology in the European Union, first-half of 2022



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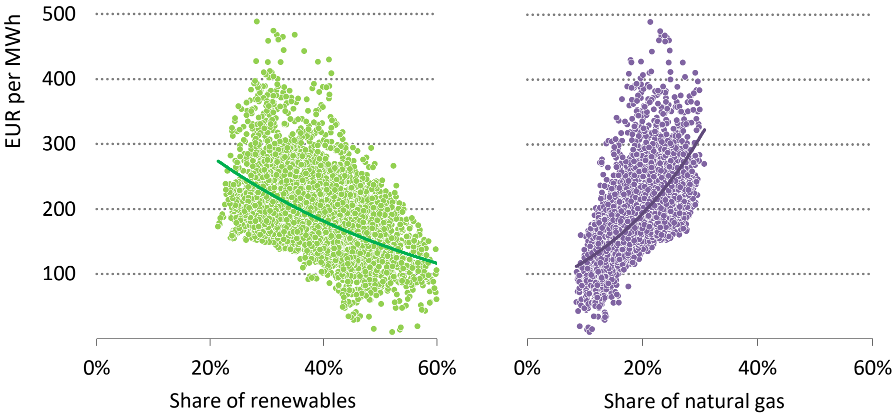
Average EU wholesale electricity prices in the first-half of 2022 were over three-times higher than in the first-half of 2021, with hourly prices set by gas, oil and coal plants

Note: MWh = megawatt-hour; CCGT = combined-cycle gas turbine; GT = gas turbine.

We have carried out an analysis of wholesale electricity prices in the European Union in the first half of 2022. We combined electricity market price data, CO_2 prices, fossil fuel prices, power plant capacities and efficiencies in the Global Energy and Climate Model to determine the price setting technology in each hour. Our analysis indicates that higher fossil fuel prices account for over 70% of the overall wholesale electricity price increase. Higher natural gas prices alone make up about half of the increase, with natural gas-fired power plants setting the price in close to half of hours from January through June (Figure 6.11). Coal and oil prices, which have also been high, set the wholesale electricity price in about 25% and 10% of the hours respectively.

Besides higher fossil fuel prices, we found two other important factors that drove up the price of wholesale electricity in the European Union. First, we estimate that CO_2 prices – at an average of EUR 85/tonne during the first-half of 2022 compared with EUR 45/tonne the previous year – led to about 20% of the increase. Second, we find that the reduced availability of nuclear power, hydropower and other factors accounted for nearly 10% of the increase. In the first-half of 2022, nuclear power produced 17% (62 TWh) less electricity in the European Union than the same period in 2021. In France, in May 2022, 29 out of 56 reactors were offline for regular maintenance, repairs or safety checks. In Germany, 3 reactors operated in 2022, following the closure of 3 reactors at the end of 2021. Hydropower output was meanwhile 24% (47 TWh) lower in the first-half of 2022 compared with the first-half of 2021. Increased grid congestion also contributed to higher prices.

Figure 6.12 ▷ EU hourly wholesale electricity prices by shares of renewables and natural gas in electricity generation, first-half of 2022



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High shares of renewables in electricity supply drove down wholesale electricity prices in 2022, while high shares of natural gas pushed them up

Wind and solar PV reduced the impact of higher wholesale electricity prices on consumers. They provided 23% of total EU electricity generation in the first-half of 2022, mostly under long-term fixed-price contracts, such as feed-in tariffs or power purchase agreements (PPAs). Higher shares of wind and solar PV in generation have put downward pressure on wholesale prices. When the share of renewables was above 40% – in nearly half of the hours from January through June 2022 – the average wholesale electricity was about EUR 170/MWh, 15% below the average of the first-half of 2022 (Figure 6.12). We estimate that the cost of electricity supply would have been EUR 40 billion lower if the contribution of renewables had been at least 40% throughout the first-half of the year.

Several supply-side factors offer potential future relief from such high wholesale electricity prices. Some will make a difference very quickly. The availability of EU nuclear power is anticipated to improve significantly, notably as a result of France's intention to restart all its reactors during the coming winter. Wind and solar PV are set to expand significantly over the course of 2023, adding 45 GW of new capacity – a nearly 10% increase. Other factors will make a difference over the next few years. In particular, fossil fuel prices, and especially natural gas prices, are projected to move lower in the medium term as market tightness moderates. Wind and solar PV are meanwhile expected to continue to grow steadily year after year.

In addition, European Union member states formally adopted emergency measures in October 2022 to mitigate the impact of high electricity prices on consumers while not impairing future investment in low-emissions technologies. Alongside efforts to reduce demand, the European Commission has put forward a proposal for two temporary measures. The first is to introduce revenue caps for low marginal cost power generation, such as nuclear power, lignite and renewables. The second is to seek contributions from surplus profits that have arisen during periods of high prices in upstream oil, gas and coal activities and refining. Together, these measures could generate over EUR 140 billion that could provide financial support measures to households, especially vulnerable ones, and hard-hit companies to mitigate the impacts of high energy prices and help the reduction of energy consumption (European Commission, 2022).

Consumers can take a number of actions to mitigate wholesale electricity prices and their impacts. To the extent that customers are able to reduce their electricity demand, it will reduce their energy bills. It will also help indirectly to reduce prices for everyone: lower overall demand means less need to call on the most expensive power plants. The European Commission has proposed a voluntary target of reducing overall electricity demand by 10% or more, and a mandatory reduction of demand during peak price hours by at least 5%. We estimate that this scale of reductions would have saved at least EUR 30 billion in the first-half of 2022.

Other actions by consumers can also make a difference. Energy efficiency measures, such as improving home insulation or purchasing more efficient appliances, offer permanent reductions in demand. Behavioural changes, e.g. moderating the use of space heating, can offer permanent or temporary reductions. Major industrial consumers may also be able to mitigate the impacts of high wholesale electricity prices through the use of long-term PPAs with producers and through hedging strategies.

Japan approved its Sixth Strategic Energy Plan in October 2021, outlining its electricity mix plans for 2030 and its ambition to achieve carbon neutrality by 2050. A key element is to restart its nuclear reactors and lift the share of nuclear in the electricity mix back to 20% by 2030. Raising the share of renewables in the mix is also important, from 23% in 2021 up to

36-38% in 2030. Another element is retrofitting coal plants to co-fire with ammonia; Japan is the only country deploying this technology at significant scale in the STEPS.

Other emerging market and developing economies also face the challenge of meeting rapidly rising electricity demand while limiting the use of fossil fuels, particularly when they are imported. In **Southeast Asia**, unabated coal-fired generation continues to expand in the STEPS, although its share in the electricity mix slowly declines. With the implementation of announced pledges in full, unabated coal generation falls 60% by 2050 in the APS, and its share of generation drops from more than 40% today to 6% in 2050. **Africa** experiences extremely rapid growth in electricity production over the period, with generation almost tripling by 2050 in the STEPS and quadrupling in the APS. Renewables account for most of the incremental generation. In the APS, solar PV makes the biggest contribution, though wind and hydropower also see significant growth. In-depth analyses and projections for Africa are provided in the recent *Africa Energy Outlook 2022* (IEA, 2022e). The power systems of many countries in **Central and South America** are dominated by hydropower. In both the STEPS and the APS, rising shares of wind and solar PV account for most of the new capacity added over the outlook period.

6.4 CO_2 emissions from electricity generation

The electricity sector emitted 13 Gt CO_2 emissions in 2021, or over one-third of the global energy-related total, but its emissions are set to decline over the coming decades in all three scenarios. In the STEPS, global annual CO_2 emissions from electricity generation fall more than 10% by 2030 and around 40% by 2050. In the APS, emissions drop around 80% by 2050. Emissions fall faster in the APS because of more rapid reductions in the use of coal and natural gas. Emissions from coal-fired power plants decrease by almost 85% from 2021 to 2050 in the APS compared with over 45% in the STEPS (Table 6.4). CO_2 emissions from the use of natural gas in the electricity sector over the same period fall by more than 50% in the APS, whereas they remain broadly stable in the STEPS. In the NZE Scenario, annual CO_2 emissions fall rapidly and reach zero by 2040.

Table 6.4 ▷ CO_2 emissions from electricity generation by source and scenario, 2010-2050 (Mt)

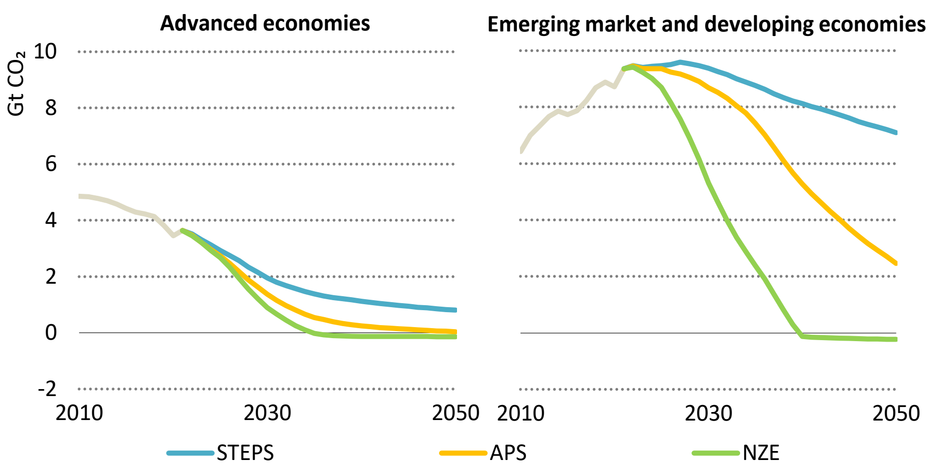
			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Coal	8 342	9 670	8 324	5 242	7 423	1 442	4 179	27
Natural gas	2 186	2 798	2 678	2 407	2 380	1 278	1 969	36
Oil	751	523	333	242	286	140	135	2
Bioenergy and waste	5	4	4	8	-31	-362	-65	-434
Total (net)	**11 285**	**12 996**	**11 338**	**7 899**	**10 057**	**2 498**	**6 218**	**-369**
Total CO_2 captured	-	1	7	96	81	1 484	304	1 479

Notes: Mt = million tonnes. CO_2 emissions include CO_2 removals such as captured and stored emissions from the combustion of bioenergy and renewable wastes.

In **advanced economies**, efforts to phase out coal in electricity generation reflect national and sub-national policies, as well as collective initiatives such as the Powering Past Coal Alliance and the Global Coal to Clean Power Transition Statement. Annual CO_2 emissions from coal-fired power plants in advanced economies decrease from 2021 levels by more than 60% in 2030 in the STEPS, and by 80% in the APS. As a result of this shift away from coal, natural gas becomes the main source of CO_2 emissions from 2030 in both the STEPS and the APS. After 2030, net electricity sector emissions continue to fall with the fulfilment of announced pledges bringing the total in the APS down to 40 Mt CO_2 in 2050.

For most **emerging market and developing economies**, there is a big and growing gap in future years between emissions reductions based on stated policies in the STEPS and those which fulfil all announced pledges on time in the APS. The APS leads to nearly 60 Gt CO_2 emissions avoided cumulatively from 2021 to 2050 compared to the STEPS, although this is still far short of what is needed in the NZE Scenario (Figure 6.13).

Figure 6.13 ▷ Annual CO_2 emissions from electricity generation for regional groupings by scenario, 2010-2050

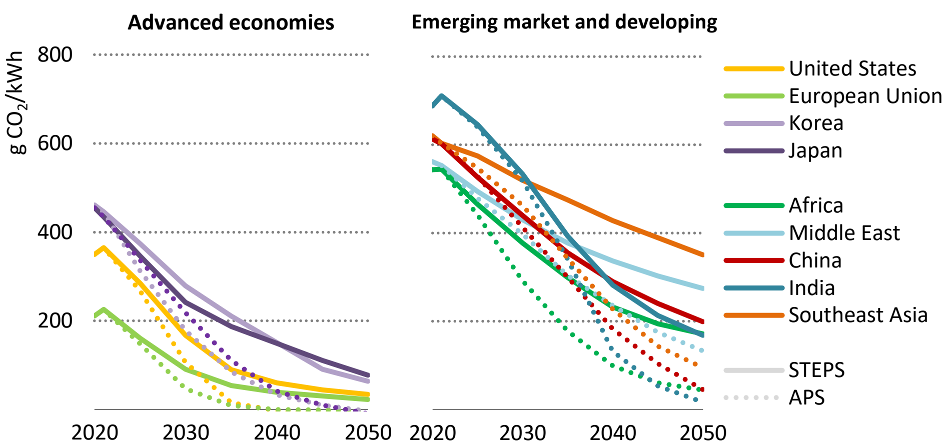


Electricity sector CO_2 emissions fall in all scenarios, but the different pathways in the STEPS and APS illustrate the importance of countries fulfilling their pledges on time and in full

Additional pledges and announcements over the last year have helped close the electricity sector emissions gap between the APS and NZE Scenario. In advanced economies, the *WEO-2021* estimated that the APS would cover 70% of the gap between the STEPS and the NZE Scenario in terms of cumulative emissions to 2050. Our updated assessment indicates that now the gap between the STEPS and NZE Scenario has narrowed due to stronger action in the STEPS, and deeper reductions in the APS still close about 70% of the remaining gap to the NZE Scenario. In emerging market and developing economies, the pledges in the APS now close almost 40% of the gap between the STEPS and NZE Scenario, up from 15% in the *WEO-2021*.

The global average CO_2 intensity of electricity generation declines in all scenarios from its level of 459 grammes of carbon dioxide per kilowatt-hour (g CO_2 /kWh) in 2021, falling by 2030 to 330 g CO_2/kWh in the STEPS, 280 g CO_2/kWh in the APS and 165 g CO_2/kWh in the NZE Scenario. By 2050, the average intensity of electricity generation ranges from 160 g CO_2/kWh in STEPS to slightly below zero in the NZE Scenario. However, countries start from different places in 2021 and their pathways vary. In general, the rapid growth of power systems in emerging market and developing economies and higher use of unabated coal result in an average CO_2 intensity of electricity generation that is 70% higher than the average in advanced economies (Figure 6.14). In advanced economies, while stated policies lead to significant reductions in annual emissions, announced pledges lead to faster reductions, with the United States and the European Union reaching net zero emissions electricity by 2040, and Japan and Korea by 2050. A number of emerging market and developing economies have also pledged to reach net zero emissions, and this leads in the APS to deep reductions in the CO_2 intensity of electricity by 2050 in Africa, China, India, Middle East and Southeast Asia.

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



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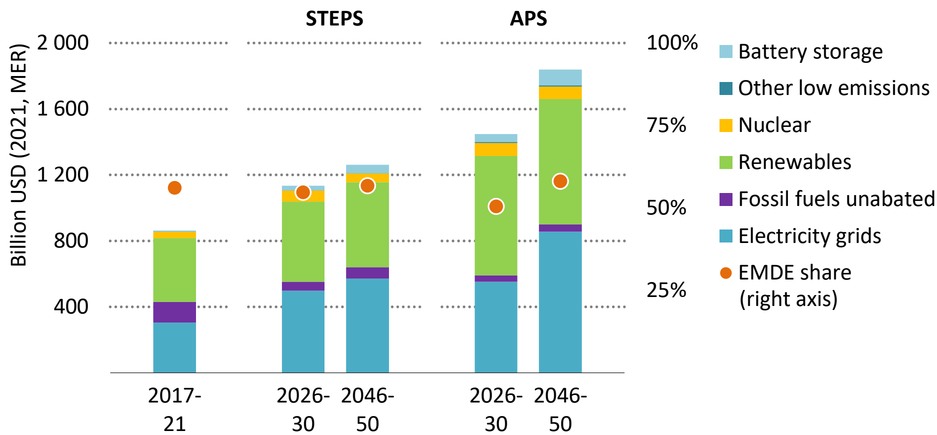
CO_2 intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

6.5 Investment

Global power sector investment rose 7% in 2021 as economies rebound in the wake of the Covid-19 pandemic. Such investment is expected to rise an additional 6% in 2022 to nearly USD 1 trillion. Investment continues to rise in all three scenarios. In the STEPS, an average of around USD 1 trillion per year is invested over the next decade, which represents an increase of more than 10% over the 2017-21 period (Figure 6.15). By 2050, annual investment in the power sector nears USD 1.1 trillion. Investment is concentrated in regions where energy transitions are at a more advanced stage, and more than 70% of power sector investments are in advanced economies and China. As energy transitions in emerging market and developing economies gather pace, the balance starts to change. Emerging market and developing economies represent around 50% of global power sector investment by 2030. In the APS, investment increases by around 30% from current levels to reach an annual average of USD 1.2 trillion over the next decade and USD 1.8 trillion by 2050. In the NZE Scenario, investments rise to USD 1.7 trillion per year over the next decade.

Figure 6.15 ▷ Average annual investment in the power sector by type and scenario, 2017-2050



Power sector investment is set to increase; up from an annual average of USD 860 billion in the 2017-21 period, with renewables and grids representing the largest shares

Note: MER = market exchange rates; EMDE = emerging market and developing economies.

Despite a rise in costs in recent months, renewable energy technologies such as wind and solar PV remain the cheapest option for new power capacity in many countries, even without taking into account the exceptionally high prices seen in 2022 for coal and gas. Accordingly, these technologies attract a large share of money being committed. Investment in renewables amounts to an average of USD 480 billion per year from 2022 to 2030 in the STEPS and around USD 630 billion per year in the APS. Annual global investment in nuclear power also increases from USD 30 billion during the 2010s to over USD 60 billion by 2030 in the STEPS and USD 80 billion in the APS. In faster transitions, other low-emissions fuels and technologies such as CCUS take a progressively larger share of investment in the power sector, reaching an annual average of USD 7 billion by 2050 in the APS. Investment in unabated fossil fuel power plants drops to around USD 50 billion 2030 in the STEPS and around USD 40 billion in the APS.

Transmission and distribution grids capture a rising share of total power sector investment in recognition of their critical role in supporting modern electricity systems and clean energy transitions. This investment supports the expansion, modernisation and further digitalisation of transmission and distribution networks. Battery storage gains ground as a source of power system flexibility, with annual investment increasing more than threefold to USD 33 billion by 2030.

Key themes

6.6 Power system flexibility is key to electricity security

Flexibility needs

6

Power system flexibility[2] needs are driven primarily by the rising share of variable wind and solar PV in electricity generation and changes in electricity demand profiles. Rising shares of non-dispatchable wind and solar PV increase the variability of the net load (the load that remains after removing wind and solar production from electricity demand), while the electrification of additional end-uses, e.g. electric heating, road transport or industrial processes, raises peaks and increases the hourly, daily and seasonal variability of electricity demand.[3] Although seasonal variations play an increasingly important role in systems characterised by rising shares of variable renewables, the change in net load from one hour to the next remains a useful indicator for flexibility needs and is used in this analysis.

All three scenarios see a significant rise in the share of variable renewables in power systems worldwide. In the STEPS, the combined share of wind and solar PV in the electricity mix doubles by 2030 and exceeds 40% by 2050. In the APS, where all announced emissions reduction pledges and renewable energy targets are met in full, it rises to nearly 30% by 2030 and close to 60% by 2050. This significantly raises the demand for additional system flexibility to balance electricity supply and demand continuously and to maintain grid stability. In the STEPS, hour-to-hour flexibility needs more than triple by 2050. In the APS, the needs double by 2030 and increase more than 3.5-times by 2050, while they more than quadruple between today and 2050 in the NZE Scenario.

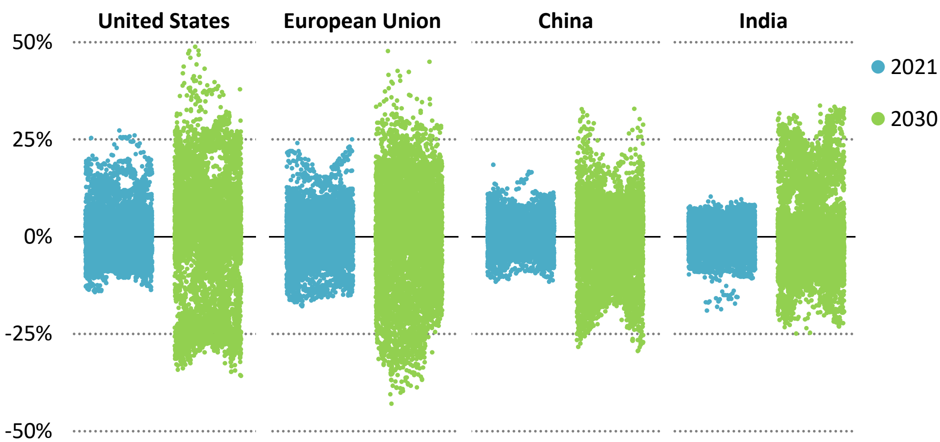
The relative change is biggest in systems which start from a low base but see the rapid introduction of variable renewables. In India, for example, flexibility requirements rise threefold in the APS by 2030 and sixfold by 2050, while in China they double by 2030 and rise 3.5-fold by 2050 (Figure 6.16). The United States and the European Union also see dramatic

[2] Flexibility is defined as the ability of a power system to reliably and cost effectively manage the near instantaneous, hourly, daily, weekly and seasonal variability of demand and supply. It ranges from ensuring the instantaneous stability of the power system to supporting long-term security of supply.

[3] The electrification of additional end-uses also raises the potential to provide flexibility through demand-side response measures.

increases in the need for flexibility to 2030 as the share of variable renewables in the power mix rises to almost 45% in the former and 50% in the latter.

Figure 6.16 ▷ Hour-to-hour flexibility needs in the United States, European Union, China and India in the APS, 2021 and 2030



Hour-to-hour flexibility needs rise significantly by 2030 in major markets, driven by increasing shares of variable renewables and changes in demand patterns

Note: Flexibility needs are represented by the hour-to-hour ramping requirements after removing hourly wind and solar PV production from hourly electricity demand, divided by the average hourly demand for the year.

Flexibility supply

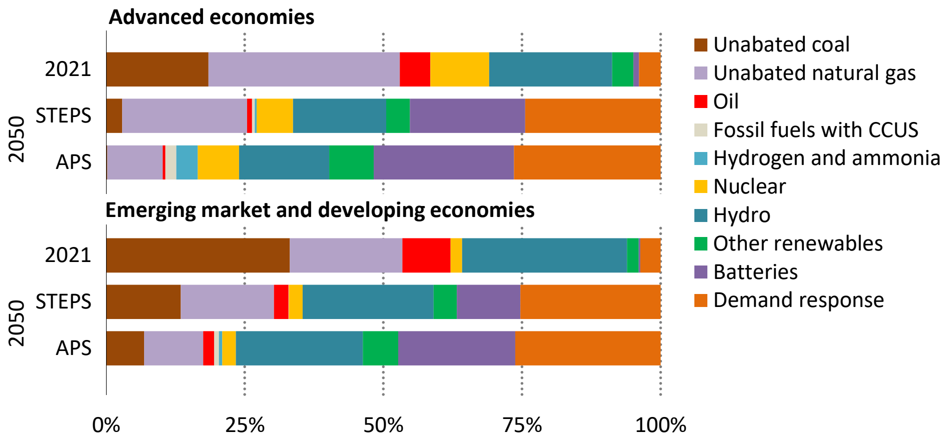
The provision of flexibility in power systems is a cornerstone of electricity security today and in the future. There are four main sources of flexibility: power plants, grids, demand-side response and energy storage.[4]

Thermal power plants provide most of the flexibility required to maintain the reliability of power systems today, with the remainder supplied mainly by hydropower (including pumped storage). By 2050, the rise of renewables means that the share of thermal power plants in the overall supply of flexibility declines from around two-thirds today to around a third in the STEPS and a quarter in the APS (Figure 6.17). The technology mix of the remaining fleet of thermal power plants changes considerably over the outlook period, especially in advanced economies. There is a move away from less flexible, base load thermal generation such as coal-fired power plants to more flexible technologies such as gas turbines, which are able to start and ramp up or down much faster, making them a more suitable match with high shares of variable renewables. In countries with nuclear generation, it remains an important, low-emissions source of flexibility and provides stability to power grids. In the APS, plants that

[4] While solar PV and wind are able to provide some flexibility through curtailment, doing so raises their levelised cost and could negatively impact their profitability depending on compensation.

co-fire hydrogen or ammonia and fossil fuel power plants with CCUS also enter the flexibility supply mix, mostly in advanced economies. While unabated coal continues to play a significant role as a provider of system flexibility in emerging market and developing economies in the STEPS, it is almost completely phased out in advanced economies.

Figure 6.17 ▷ Flexibility supply by source, region and scenario, 2021 and 2050



The provision of power system flexibility becomes less reliant on unabated fossil fuels over time, moving towards low-emissions sources, battery storage and demand response

Power grids and interconnections can help even out fluctuations in demand and in the supply of weather-dependent variable renewables such as wind. They do so by connecting generators dispersed over a wide area within and between countries and regions. They thus help reduce the demand for flexibility from other sources while at the same time connecting further potential providers of flexibility. Certain grid assets, such as high voltage direct current (HVDC) interconnections, can also provide flexibility services, including fast active and reactive power and voltage control (see section 6.7).

Demand-side response helps to align consumption with available supply, thus reducing the need for other sources of flexibility. With the projected increase in the use of electricity by air conditioners, heat pumps, EVs, electrolysers and other potentially flexible sources of demand, there is potential for significant load shifting in all three scenarios. In 2050, demand-side response provides roughly a quarter of power system flexibility in both advanced economies and emerging market and developing economies in the STEPS and APS. Tapping this potential, however, will require significant investment in digital infrastructure, as well as in technologies such as thermal storage that help decouple electricity consumption from final demand. Regulatory frameworks will also need to evolve in order to enable suppliers to offer tariffs that reward demand response to end-users, and to permit aggregators, industrial consumers and other potential providers of demand-side response to offer flexibility in electricity, capacity and ancillary service markets.

Energy storage, in particular battery energy storage, is set to play an increasingly important role in system flexibility. Battery storage is projected to be the fastest growing source of power system flexibility in all scenarios over the outlook period. Battery systems are modular, which allows them to be deployed and scaled up rapidly in almost any location. In addition to energy storage, utility-scale batteries can offer important system services, for example by helping with the restoration of grid operations following a blackout, supporting short-term balancing or providing operating reserves. Their provision of localised flexibility may also reduce the need for investment in new transmission and distribution infrastructure.

Although dwarfed by the projected increase in battery storage capacity, other storage technologies play contributing roles in system flexibility as well. With around 160 GW of installed capacity globally, pumped storage hydro is the largest source of electricity storage today, and it is set to expand further over the next ten years (IEA, 2021c). Other grid-level storage options include compressed and liquid air energy storage, gravity storage, and hydrogen and ammonia. Hydrogen and ammonia in particular hold significant promise as sources of seasonal storage for large amounts of renewable energy (IEA, 2021d).

As the power generation mix evolves, ensuring an adequate supply of flexibility will be critical. However, current market designs are sending weak signals for investment in flexibility, and this could present a risk to electricity security in clean power systems characterised by high shares of variable renewables. Policies and regulatory frameworks need to evolve in order to bring about the levels of investment in new sources of flexibility seen in the APS and NZE Scenario. Legacy regulations that could potentially diminish the economic case for various types of flexibility should be reviewed and reformed if necessary.

In countries with liberalised electricity markets, several options could help better incentivise investment in sources of flexibility. These include decreasing the market settlement period, i.e. the interval in which electricity is traded; reforming market gate-closure, i.e. the time between the last trade and the physical delivery of the electricity, to bring it closer to real time; introducing capacity remuneration mechanisms; and further opening of ancillary service markets. A recent IEA report provides more information on design choices to tailor power markets for tomorrow's electricity systems (IEA, 2022f).

In addition to adapting market designs, there is a strong case for considering flexibility in long-range energy planning and considering options to incentivise the deployment of flexible capacity through instruments that improve long-term revenue visibility. For example, so-called hybrid auctions for renewables and storage could provide the necessary revenue stability for investment in storage.

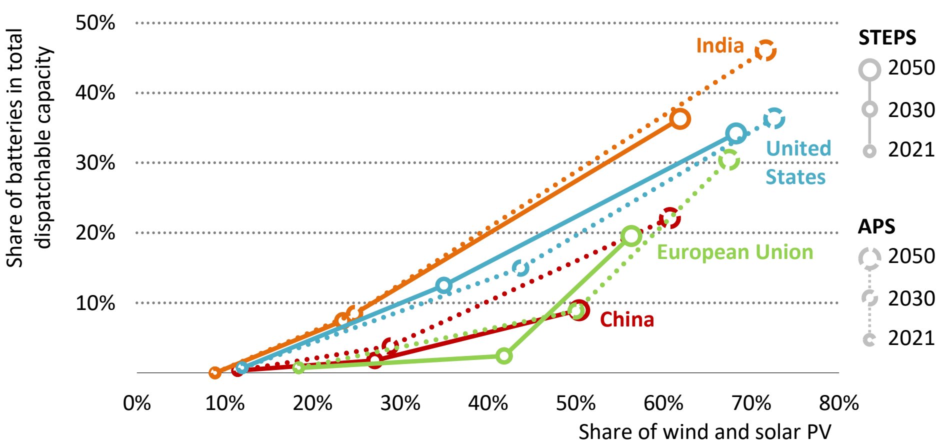
Focus on battery storage

Installed battery storage capacity, including both utility-scale and behind-the-meter systems, totalled more than 27 GW at the end of 2021. For the second year in a row, capacity additions increased strongly in 2021, rising to more than 9 GW (nearly 90% higher compared to 2020). The pace of deployment is set to pick up significantly: global battery storage capacity increases nearly 50-fold in the STEPS, rising to more than 1 000 GW by 2050. In the APS, this doubles to more than 2 000 GW, with more than 400 GW installed by 2030. The strongest growth occurs in the NZE Scenario, which sees about 780 GW installed in 2030 and more than 3 500 GW by 2050.

The increase in battery storage capacity is underpinned by a steady decline in their costs which is brought about by continuing innovation in battery chemistry and economies of scale. There is some risk in the short and medium term that difficulties related to availability and affordability of specific critical minerals needed to produce batteries could slow the decline in cost, but there are options to mitigate these concerns (see section 6.8).

6

Figure 6.18 ▷ Share of batteries in total dispatchable capacity and share of variable renewables in electricity generation for selected regions by scenario, 2021-2050



Battery storage capacity rises in tandem with the share of wind and solar PV, helping to provide flexibility and security for power systems

Battery storage capacity expansion is closely correlated with the rising share of variable renewables in power systems. This highlights its role as an important source of additional flexibility as renewables are scaled up and traditional providers of flexibility such as coal-fired power plants are retired. Since batteries are primarily for short duration storage, they are well suited to smooth the daily cycle of solar PV-based electricity generation (battery storage volumes commonly range from one to eight hours of storage at full capacity, with most systems currently at the lower end of the range). Behind-the-meter battery systems are often paired with rooftop solar, for example. Regions with high shares of solar PV relative to wind, such as the United States or India, thus tend to see higher relative levels of battery deployment than regions in which wind power predominates, such as China or the European Union (Figure 6.18).

In the STEPS, the United States maintains its position as the leading market for battery storage, with installed capacity rising from more than 7 GW in 2021 to nearly 370 GW by 2050. In the APS, China becomes the largest market for battery storage with installed capacity rising from close to 6 GW today to 570 GW in 2050. China's share of batteries in total dispatchable capacity remains low in relative terms compared to other regions, but its market is huge in absolute terms.

The installed capacity of battery storage rises faster relative to renewables capacity in the APS than in the STEPS. This reflects the greater urgency shown in the APS outlook to provide additional flexibility to the grid and lower battery storage costs that come with that: as higher numbers of batteries are deployed, learning effects and improved economies of scale drive down the cost of battery packs and the other components constituting the balance of system. Spillover effects from the EV industry, which is by far the largest user of batteries, also play an important role.

To get on track for the levels of battery storage capacity in the APS or NZE Scenario, policies and regulatory frameworks will have to evolve to reflect the importance of the contribution made by battery storage to different system services. For storage assets, ownership is often an important question: typically, storage is considered a generation asset and grid operators are not allowed to own it. This could impede progress. A potential solution might be to allow transmission or distribution system operators to procure storage services from third parties, for example through tenders or local flexibility markets.

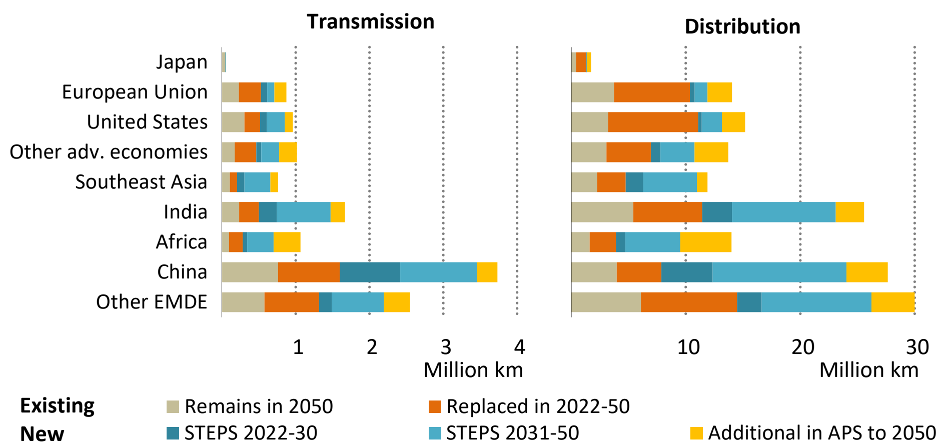
6.7 Electricity networks are the backbone of clean power systems

Electricity transmission and distribution systems currently include around 80 million kilometres (km) of lines. The way in which these are developed and operated will determine the economic viability and reliability of the entire electricity system as demand grows and as energy transitions accelerate in the coming years. Most electricity systems were originally designed and operated by vertically integrated utilities with a focus on maintaining reliable local supply. The liberalisation of many electricity markets changed this arrangement by splitting the integrated utilities into separate grid and generation services. The rising share of variable renewables in the generation mix and alterations in the way that electricity systems operate, e.g. in terms of demand management, however are now changing requirements for the interface between the distribution and transmission grids, raising questions about how best to meet the challenges ahead.

Grid infrastructure development

The electricity network – the essential link between generation and demand – continues to expand in all three scenarios. In the STEPS, 13 million km of distribution lines and about 1.6 million km of transmission lines are constructed by 2030 (Figure 6.19). By 2050, more than 45 million km of distribution lines and a further 4 million km of transmission lines are added along with primary equipment, power transformers and associated control and protection equipment, increasing the existing grid by more than 80%. In the APS, the expansion of the network proceeds even more rapidly, with 14 million km of distribution lines and 1.8 million km of transmission lines added by 2030.

Figure 6.19 ⊳ Grid development by type, region and scenario, 2022-2050



Electricity networks need to be expanded and replaced in all regions, providing opportunities for modernisation to accommodate tomorrow's power systems

Note: Adv. = advanced; EMDE = emerging market and developing economies.

The need for new capacity in the transmission grid has two main causes. First is rapid growth in electricity demand, which increases by one-quarter before 2030 in the APS and more than doubles by 2050. Second is the rapid rise in new sources of generation and demand. The strong growth of renewables, often more distant from existing grids to tap high quality resources, add to the growth of transmission around the world.

In emerging market and developing economies, over 14 million km of new lines are built in the STEPS by 2030. Rising demand accounts for over 90% of this enlargement. Almost a third of the total expansion takes place in China (5.3 million km). Some of these new lines take the form of large-scale ultra-high voltage electricity transmission links over distances of up to 3 300 km to connect remote solar PV and wind power installations. Many emerging market and developing economies make significant progress in expanding access to electricity, notably in Africa (IEA, 2022e) and Southeast Asia (IEA, 2022g). Indonesia has already raised access rates from two-thirds of the population a decade ago to nearly 100% today.

In advanced economies, where electricity networks are well developed and generally older, there is more focus on replacement and less on new lines. Almost 21 million km of grid lines have to be renewed in advanced economies until 2050, including over 7 million km in the European Union and more than 8 million km in the United States. This corresponds to two-thirds of those networks in place today.

Lines, cables and transformer capacity will remain the mainstays of electricity networks, but investment in digital technologies is also critically important. Most operational decisions today are based on load flow analysis in local monitoring systems. This approach to system operations works well when the power flows from centralised generation capacity to consumers are largely predictable within a local or national framework. Integration of energy flows over longer distances and the rise of variable generation sources is changing the level of predictability of electricity flows through the system. Depending on the equipment, these power flows can lead to system conditions that are more dynamic, leading to local line overloads. Digital technologies have a key part to play in meeting the challenges that arise from these changes.

New monitoring and control devices and the corresponding software can provide system information in real time. Dynamic line assessment sensors placed throughout the network can help transform the stationary assessment of larger power supply regions into real-time measurements and uncover the dynamics of power flows in a broader and meshed system, while smart meters can improve the visibility of load flows. Real-time knowledge of system health allows fuller utilisation of existing resources, enables networks to operate closer to their true limits without sacrificing reliability, and makes it easier to contain system failures into smaller areas and prevent cascading power outages. Higher levels of co-operation and knowledge sharing between transmission and distribution grid operators will help to enhance energy security, as will the sharing of best practices relating to the co-ordinated operation and planning of transmission and distribution systems and data exchange between operators.

The ability to act on the basis of a detailed view of a broad network area depends on digital technologies such as Static Synchronous Compensator and Thyristor Controlled Series Compensation, both of which are part of the family of flexible alternating current transmission devices. These allow control of power flows, voltage levels and other stability characteristics nearly in real time, while generating corresponding reactive power that further increases power transmission capacity and stabilises the grid. HVDC is another important technology in this context that can help system operations by transporting large amounts of electricity while offering full bi-directional load flow control and black start capabilities.

Grids support secure energy transitions

Successful clean energy transitions depend on modern electricity networks, and their development requires long-term vision and planning. For example, large projects involving transmission systems can often take a decade or longer to complete. Such long lead times put a premium on strategic thinking and accurate estimates of future supply and demand so that tomorrow's networks are ready to meet the requirements placed on them and do not act as a bottleneck in clean energy transitions.

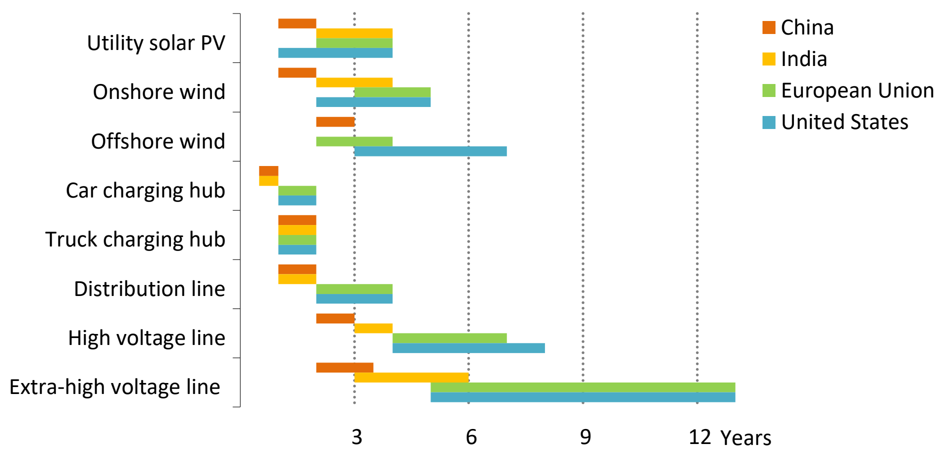
To ensure security of supply, grid development must be considered at the system level, taking account of increasing electricity demand and rising levels of variable renewables. Energy from utility-scale wind or solar PV installations, which are often located far from densely populated cities and other demand centres, will need to be transferred over long distances through a network that may have been designed for a different type of operation. Networks are complex systems with many variables; keeping them up-to-date is a never-ending challenge. For example, when the network plan in Germany was updated in 2019, just two years after its previous revision, the need for more than 100 new reinforcement measures was identified. Failure to plan ahead sufficiently can lead to transmission bottlenecks. This was experienced recently in Viet Nam, which announced in early 2022 that it would not connect any new solar PV or wind projects for the rest of the year, and also in Mongolia, where 12% of the electricity generated by wind turbines in 2021 could not be transported to end-users.

Electricity network projects, especially high voltage interconnections, are very complex in terms of both permitting and construction. Line route plans and reports have to be drawn up covering the entire length, conditions and specifications have to be assessed, and stakeholders must be engaged. People living near proposed line routes may oppose their development.

Typical permitting and construction times for power lines vary widely. The visual impact of high voltage power lines often produces a concerted level of local resistance. It is not unusual for the permitting and construction of a single extra-high voltage overhead power line (>220 kilovolt [kV]) to take 5-13 years, depending on the length of the line and other factors, especially in advanced economies (Figure 6.20). Lower voltage level projects often take 4-7 years. Distribution grid projects are usually completed within four years. As an example for an advanced economy, in Germany, out of the 1 655 km of line projects approved in a 2009 network development plan, less than 50% were operational a decade later. The use of underground cables instead of overhead power lines can help deal with concerns about visual and environmental impacts, especially in advanced economies, but cables add significantly to costs. They generally have been used primarily for low voltage power lines, but are now increasingly being deployed for high voltage lines of up to 525 kV.

There are a number of ways to address the challenge of electricity network development. The likelihood of success is increased where there is effective long-term grid planning incorporating forward planning in supply and demand, where there is clarity about the roles and responsibilities of regulatory authorities, network operators and investors, and where the number of permits required is reduced to the minimum necessary through integrated procedures which set the clear requirements for substations in all regions of the country. Effective and binding deadlines are important in order to give network operators and investors legal certainty with regard to the timely completion of approval procedures. This implies adequate staffing levels and professional competence on the part of the regulatory authorities. High priority projects can be accelerated by the designation of so-called "infrastructure corridors" with provision for quick initial permitting decisions. The importance of network-wide co-ordination has already been recognised in countries such as Australia, Japan and United States, while the European Union has agreed on a new Trans-European Networks for Energy Regulation that offers the prospect of accelerated permitting procedures and funding support for over 150 power transmission and storage projects of common interest.

Figure 6.20 ▷ Typical deployment time for electricity grids, solar PV, wind and EV charging stations



Electricity grid deployment is complex, involves many stakeholders and can take many years, which makes advanced planning critical to support clean energy transitions

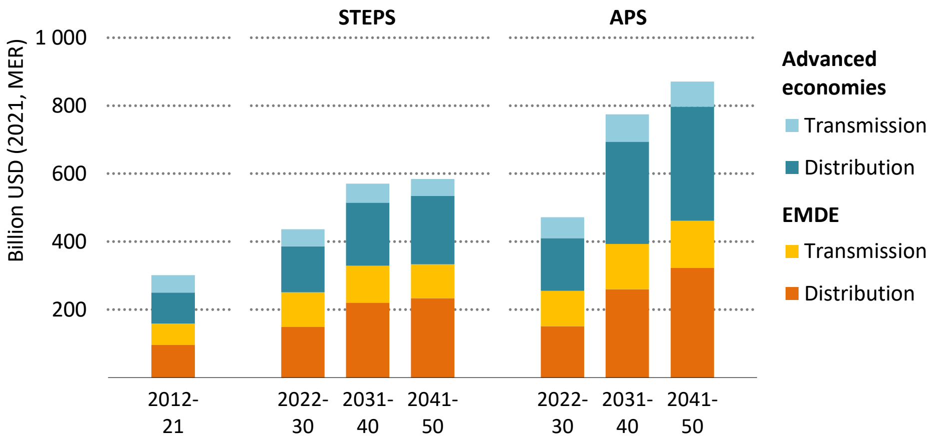
Notes: Ranges reflect typical projects commissioned in the last three years. Distribution line = 1-36 kV overhead line; transmission is split between high voltage line = 36-220 kV overhead line and extra-high voltage line = 220-765 kV overhead line. To date, India has not developed offshore wind projects.

Source: IEA analysis.

Grid investment

In the STEPS, annual grid investment rises to USD 550 billion by 2030 compared with USD 300 billion per year from 2012 to 2021, and to about USD 580 billion in the 2030s and 2040s (Figure 6.21). This increase reflects rising levels of electricity demand, the need for systems to adjust to expanding levels of variable renewables generation capacity, and the development of smart grids. Grid investments in advanced economies rise till 2040 to about USD 250 billion per year where they remain stable and are largely focussed on ensuring grid reliability during the transition to a decarbonised power sector that needs to be increasingly flexible while meeting rising levels of demand and maintaining affordability and resilience. In emerging market and developing economies, investments rise from about USD 135 billion to over 330 billion by 2030, and stabilise at about this level through 2050, as demand for energy grows rapidly and more of that demand is served by electricity as well as extending access to millions of people for first time. Most grid investment in emerging market and developing economies today is made by the public sector, and the rising levels of investment required in the future underline the case for finding ways of attracting some proportion of this investment from the private sector.[5]

Figure 6.21 ⊳ Average annual electricity grid investment by type and scenario, 2012-2050



Annual grid investment ramps up from the recent average of USD 300 billion per year to an average of USD 580 billion in the 2030s in the STEPS and USD 770 billion in the APS

Note: MER = market exchange rates; EMDE = emerging market and developing economies.

[5] For further information concerning attracting private investment in emerging market and developing economies, see *Africa Energy Outlook 2022* (IEA, 2022e).

In the APS, grid investment rises to USD 630 billion by 2030 and USD 830 billion by 2050, with distribution grids accounting for the largest share. This represents a marked step up from the levels seen in the STEPS. Investment in advanced economies falls after 2040 as full decarbonisation is nearly achieved and electricity demand growth slows and efficiency measures take effect. Meanwhile it continues to rise in emerging market and developing economies, driven by electricity demand more than doubling from 2021 to 2050 in the STEPS and APS. Large interconnections remain a major investment focus, with projects under construction or planned in Africa, Australia, China, Europe, India and North America.

Regulators and policy makers face the task of ensuring that the necessary grid investment takes place while managing costs and maintaining system stability. Cost allocation frameworks need to ensure fair remuneration for grid operators and investors while protecting consumer affordability. The integration of rising shares of renewables increases the complexity of grid operations and may raise new questions about asset ownership and the distribution of responsibilities. Whatever the overall framework, however, clear vision, long-term energy planning and transparency can help reduce uncertainty for grid operators and investors, facilitating timely and efficient investment in grid infrastructure. Where they exist, regional bodies can also help regulators by promoting better understanding about regional power systems, sharing lessons learned and supporting the development of innovative collaboration models and joint training initiatives.

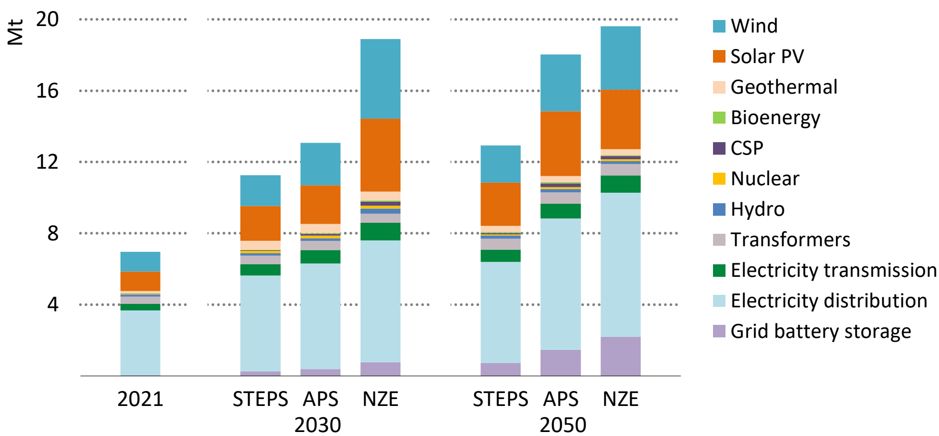
6.8 Critical minerals underpin future clean electricity systems

A low-emissions electricity system differs profoundly from one fuelled by traditional fossil fuel resources. Among others, it depends much more on critical minerals. A solar PV installation requires around six-times more critical mineral inputs (7 000 kilogrammes per megawatt [kg/MW] of installed power capacity) than a natural gas-fired power plant. An onshore wind installation requires nine-times more critical mineral inputs (10 000 kg/MW), and an offshore wind installation requires 13-times more critical mineral inputs (15 000 kg/MW) (IEA, 2021b). At just over 5 000 kg/MW, nuclear power is the least critical mineral-intensive technology among the suite of low-emissions power generation technologies (IEA, 2021b). This implies that a transformation of the electricity system will be inevitably accompanied by expanding demand for these critical minerals. As clean energy transitions gather pace, there accordingly will be a shift of focus from the supply of traditional fuels to the supply of critical minerals (see Chapter 4). Rising mineral prices and volatile supply chains which could be affected by geopolitical events should be seen as warning signs to policy makers to pay closer attention to the importance of these minerals for a secure and sustainable energy transition (IEA, 2022h).

System transition comes with new challenges

The rapid deployment of low-emissions power, electricity grids and grid storage in the APS and NZE Scenario implies rapidly growing demand for critical mineral from the electricity sector. Despite technology innovation leading to material intensity improvements over time, critical mineral demand rises from 7 Mt in 2021 to reach 11 Mt in 2030 and 13 Mt in 2050 in the STEPS. It grows much faster in the APS and NZE Scenario, reaching over 18 Mt in 2050 in the APS and 20 Mt in the NZE Scenario (Figure 6.22). Even in the STEPS, the transitions to low-emissions power, grids and storage lead to cumulative demand for critical minerals this decade being 20% higher than between 2010 and 2020, and cumulative demand after 2030 until mid-century is nearly four-times as large as the demand of the last decade.

Figure 6.22 ▷ Annual demand for critical minerals for low-emissions electricity supply, storage and networks by scenario, 2021-2050



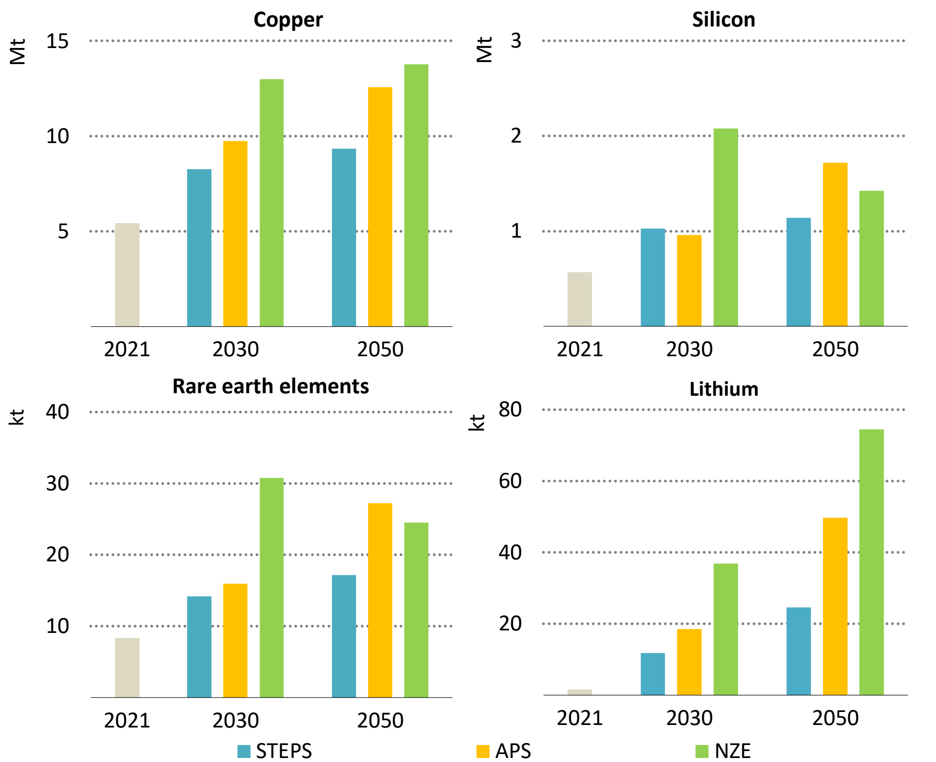
Annual demand for critical minerals in low-emissions electricity generation, battery storage and networks increases almost 200% from 7 Mt today to 20 Mt by 2050 in the NZE Scenario

Note: CSP = concentrating solar power.

Among the minerals which are crucial for the future of power systems are copper, rare earth elements, silicon and lithium. Copper is used extensively in the electricity transmission and distribution grids, but its conductive properties also make it an essential component for low-emissions power generation technologies such as solar PV panels, wind turbines and batteries. Rare earth elements (REEs) are used to manufacture the permanent magnets for the motors of direct drive and hybrid wind turbines (accounting for 30% of wind power installations in 2021). Silicon is used to manufacture solar panels. As deployment of variable renewable technologies increases, the need for storage technologies to complement renewable electricity also rises rapidly. Lithium-ion batteries are the fastest growing storage technology in the world, making lithium indispensable for future electricity systems.

In terms of absolute volumes, copper dominates total demand for critical minerals from the electricity sector: current demand of over 5 Mt per year rises to 10 Mt by 2030 in the APS and 13 Mt in the NZE Scenario (Figure 6.23). Relative to current levels, demand for lithium for battery storage systems rises most sharply, by over 20-fold by 2030 and almost 50-fold by 2050 in the NZE Scenario. Demand for copper, silicon and REEs nearly doubles to 2030 in the APS, and rises by around three-times in the NZE Scenario relative to 2021.

Figure 6.23 ▷ Annual demand for selected critical minerals used in low-emissions electricity supply, storage and networks by scenario, 2021-2050



More copper for grids, rare earth elements for wind turbine motors, silicon for solar panels and lithium for battery storage are required to transition to low-emissions power systems

Notes: Mt = million tonnes; kt = kilotonnes. In this figure, battery storage is limited to utility-scale and home energy storage and does not include demand for EV batteries. Copper demand excludes demand for EV motors. Lithium demand excludes demand for EV batteries.

Support for R&D is crucial to achieve mineral intensity improvements and mineral alternatives

Copper and aluminium currently account for around 16% and 4% respectively of total grid investment costs (IEA, 2021b). To reduce raw material costs, grid operators could switch from copper in underground cables to use aluminium, which is less expensive. Increased use of aluminium in underground cables could reduce copper demand nearly 45%. Recent developments in cable insulation technology also widen the possibility of higher transmission capacity using the same amount of conducting materials.

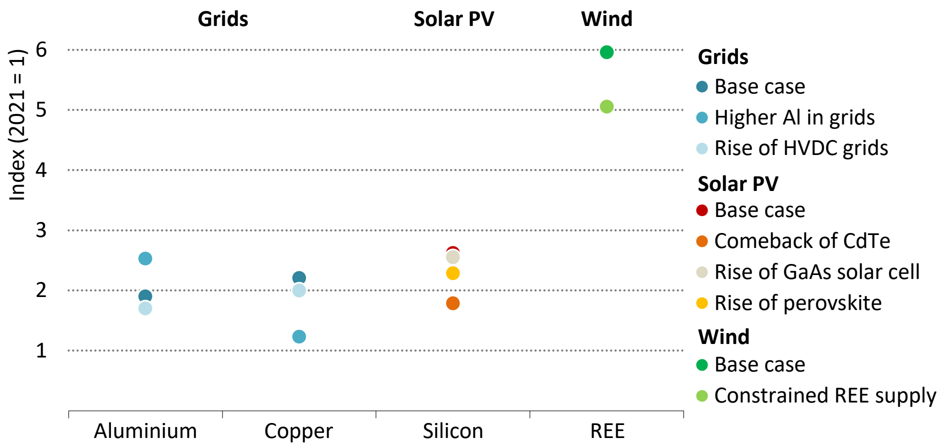
Today's electricity networks are largely operated using an alternating current (AC) system, which require a minimum of three wires per cable to transmit electricity. HVDC systems use two wires, which implies a direct saving on metal demand of at least one-third compared to AC systems. HVDC systems are also capable of transporting more electricity than AC systems, which could reduce copper and aluminium demand as well as the extent of a need for grid expansion. Wider adoption of HVDC systems could raise costs, but would reduce both aluminium and copper demand by around 10% each by 2050 in the NZE Scenario.

Crystalline silicon (c-Si) modules dominate the solar PV market today, accounting for around 95% of global capacity additions. A slowdown in production of crystalline polysilicon in China over the last year has created a bottleneck in the solar PV supply chain, leading to a quadrupling of polysilicon prices (IEA, 2022i). Nevertheless, innovation in the manufacturing and design of c-Si solar panels over the past decade has contributed to major improvements in material intensity; since 2008, silicon intensity has more than halved as wafer thickness has diminished substantially, and silver use has been cut by 80%. During the same period, module costs have declined by 80%, leading to spectacular growth in solar PV deployment worldwide. While c-Si modules are expected to continue to dominate the market, further R&D work on alternative technologies such as cadmium telluride (CdTe), perovskite or gallium arsenide (GaAs) solar cells could see these technologies achieve increasing market shares to 2050.

Global installed wind power capacity has nearly quadrupled over the past decade, spurred by an average 40% reduction in costs and strong policy support in more than 130 countries. Average rated capacity for wind turbines has also increased considerably over the last decade, almost doubling for onshore wind turbines and shooting up even more rapidly for offshore wind turbines: the most recent offshore wind turbine designs are 10-14 MW, and plans for up to 20 MW turbines are in the pipeline. These changes have important implications for the use of materials. On a kilogramme per megawatt basis, a turbine of 3.45 MW contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine (Elia, 2020).

Material intensity depends not only on turbine size, but also on turbine type. The rapid expansion of wind power generation brings with it more demand for the rare earth elements required to manufacture the permanent magnets for many of the motors. In the NZE Scenario, demand for REEs in wind, neodymium and praseodymium in particular, is projected to triple by 2050, driven by a shift from technologies using induction generators in favour of those using permanent magnet generators. Given concerns about competing for REE supply with EV motors, rising prices and geopolitical events, further R&D efforts are needed to develop non-magnet technologies or hybrid configurations with smaller magnets or permanent magnets without REEs to reduce overall REE demand (IEA, 2021b). Successful R&D could lead to significant reductions in demand for REEs (Figure 6.24).

Figure 6.24 ▷ Demand for selected minerals used in electricity networks, solar PV and wind relative to 2021 in alternative technology cases in the NZE Scenario, 2050



Enhanced R&D efforts could help commercialise technologies that provide substitutes for certain critical minerals or reduce the amount of minerals required per unit of power

Note: Al = aluminium; CdTe = cadmium telluride; GaAs = gallium arsenide; REE = rare earth element; HVDC = high voltage direct current systems.

Recycling and reuse could reduce the burden on primary supply to meet demand

Metal recycling has the potential to be a significant source of secondary supply to meet the growing demand for critical minerals, although it comes with its own set of challenges. Recycling comprises the physical collection and separation of metals and the metallurgical processes to recover them. It includes multiple pathways and a wide range of technologies and practices.

Recycling metals used in the energy transition will not only ease the burden on their primary supply via mining, but better treatment of waste streams will reduce the risk of several hazardous materials entering the environment and polluting land and water resources. Although recycling will not eliminate the need for significant investment in primary supply, a slightly reduced burden on mining through recycling will eventually lead to lower social and environmental impacts from mining.

By mass, 95% of solar panel components are recyclable, but only around 10% of end-of-life solar panels are currently being recycled. With average lifespans of about 25 years, many solar panels worldwide are now approaching the end of their lives. In the NZE Scenario, capacity retirements for solar PV increase almost 150-fold from 3 GW in 2030 to around 400 GW in 2050. By mass, 90% of the components of a wind turbine are recyclable, and like solar panels their lifespan is about 25 years. In the NZE Scenario, capacity retirements for wind turbines increase from 16 GW in 2030 to 240 GW in 2050. Further policy efforts are needed to boost recycling of metals and to ensure that at the end of their useful life that solar panels and wind turbines do not end up in landfills.

It has proved possible to achieve high rates of recycling for metals such as aluminium, iron and nickel and, in some cases, copper when simple, bulk products are involved or when the raw material is relatively easy to collect from industrial applications. This suggests that these metals have relatively high potential for continuous recycling, including from clean energy technology waste streams. The same is not true for other energy transition minerals such as REEs, lithium and cobalt. High levels of recycling focused on the metals needed for clean energy technologies depend on further investment and R&D, as well as on international collaboration and co-operation between various manufacturers.

Targeted policies in support of recycling of solar panels, wind turbines and batteries, including minimum recycled content requirements, tradeable recycling credits and virgin material taxes have the potential to incentivise the recycling of energy transition minerals and to drive the rise of secondary supplies (Söderholm, 2020). Policy intervention and investment in R&D both need to be stepped up considerably in order to ensure a circular economy is created for low-emissions electricity generation technologies.

The immensely rapid progress in innovation and corresponding cost declines for EV lithium-ion batteries over the last decade have brought spillover benefits for grid-scale battery storage systems. There is now scope for the automotive industry to provide a second type of benefit for grid storage. This stems from the growing pool of EV batteries which could have second-life applications in energy storage. Spent EV batteries tend to have terawatt-hours of unused energy that no longer meet the standards for use in an EV but can be used for other applications (Söderholm, 2020). The amounts of unused energy involved are significant: these spent batteries typically maintain about 80% of their total usable capacity. Initial trials for second-life batteries have already begun, but a number of technological and regulatory challenges remain for their application to grow at scale. Clear guidance on the repackaging, certification, standardisation and warranty liability of used EV batteries will be needed to overcome these challenges. The proposed update of the European Union Battery Directive is attempting to tackle some of these issues, for example through requirements for minimum levels of recycled metals in batteries, new targets for recycling and open information requirements that enhance battery traceability.

Outlook for liquid fuels

A combustible mix

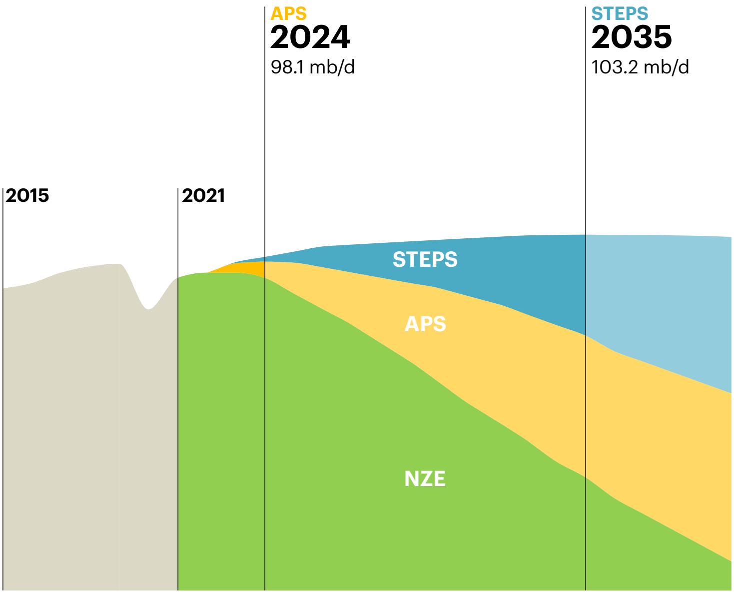
SUMMARY

- The oil market today is grappling with huge near-term and long-term uncertainties. Fears of recession loom large over the immediate prospects for demand, although China could boost oil use as it emerges from renewed lockdowns. Sanctions on Russia and dwindling spare capacity cast a shadow over the adequacy of supply. High prices are generating a historic windfall for the oil and gas industry, accompanied by hesitation on how this can best be invested given the likelihood of structural shifts in oil use in the decades to come.
- Our scenarios provide different perspectives on the strength of these shifts and their implications. In the Stated Policies Scenario (STEPS), global oil demand rebounds and surpasses 2019 levels by 2023, despite high prices; demand peaks in the mid-2030s at 103 million barrels per day (mb/d). In the Announced Pledges Scenario (APS), stronger policy action brings forward the peak in oil demand to the mid-2020s. In the Net Zero Emissions by 2050 (NZE) Scenario, faster global action to cut emissions means oil demand never returns to its 2019 level and falls to 75 mb/d by 2030.
- Around 10% of cars sold in 2021 were electric. This rises to 25% in the STEPS and to 60% in the NZE Scenario by 2030. Electric and fuel cell heavy trucks struggle to gain market share in the STEPS, but they comprise 35% of trucks sold in 2030 in the NZE Scenario. Road transport oil demand increases by 1.5 mb/d between 2021 and 2030 in the STEPS, but falls by 13 mb/d in the NZE Scenario.
- Aviation and shipping consumed 10 mb/d of oil in 2021, which is 20% less than before the Covid-19 pandemic. In the STEPS, economic growth drives up trade and travel, and demand grows by 4 mb/d between 2021 and 2030. In the APS, action is taken to increase the use of alternative fuels and cut emissions to achieve the climate goals of governments and targets set by industry organisations, and demand increases by 3 mb/d to 2030. In the NZE Scenario, behaviour changes and increases in low-emissions liquid fuels mean oil demand barely increases to 2030.
- The chemical sector was the only sector in which oil use increased in 2020, and it is set to account for a rising share of oil use in each scenario. Around 70% of oil used as a petrochemical feedstock is currently used to produce plastics. A number of countries are announcing policies to ban or reduce single-use plastics, improve recycling rates and promote alternative feedstocks. Global average recycling rates for plastics increase from the current level of 17% to 27% in 2050 in the STEPS, 50% in the APS, and 54% in the NZE Scenario.
- In the STEPS, rising demand and declining output from existing sources of production mean that new conventional upstream projects are required to ensure that supply and demand stay in balance. Around USD 470 billion annual upstream investment is

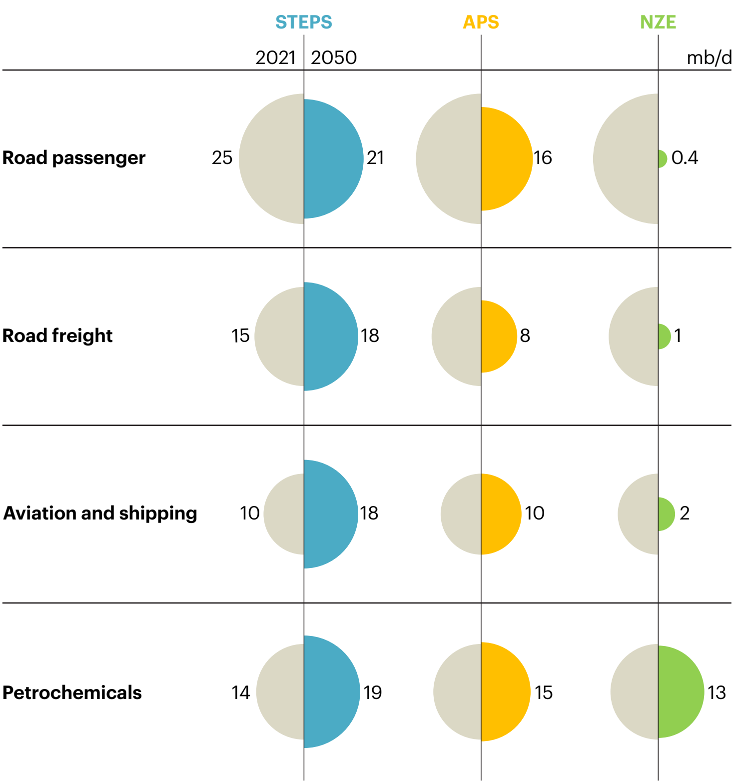
spent on average to 2030, which is 50% more than has been invested in recent years. In the APS, demand is lower, but there is still a need for new conventional projects, and USD 380 billion is invested annually on average to 2030. In the NZE Scenario, declining fossil fuel demand can be met without the need for the development of new oil fields, but with continued investment in existing assets, and this requires USD 300 billion annual average upstream investment to 2030.

- The impact of the Covid-19 pandemic and the low level of investment in recent years mean there are few new resources under development and few discovered resources available to be developed. New oil resources discovered in 2021 were at their lowest level since the 1930s. The implications of this vary by scenario. In the STEPS, the largest increases in production to 2030 come from US tight oil, Middle East members of OPEC, Guyana and Brazil.
- High oil prices and energy security concerns are encouraging some countries to revisit the case for issuing exploration licences for new domestic oil projects. Such licences are unlikely to provide any relief in the short term: in the past it has taken 20 years on average to move from a new exploration licence to the start of production. Projects with shorter lead times and quick payback periods – such as tight oil and projects to extend production from existing fields – are better candidates for making good any short-term shortfalls in supply. They play an important role in all our scenarios.
- Global refining capacity fell in 2021 for the first time in more than 30 years. As demand rebounded in 2022 and oil product exports from Russia and China have fallen, refining margins surged to record highs. In the STEPS, rising demand for diesel and kerosene means markets are likely to remain very tight for a number of years. In the APS, strong policy measures to curb demand significantly reduce this tightness. The APS and the NZE Scenario see major changes in the composition of product demand, requiring refiners to adapt refinery configurations and business models, and to invest more heavily in emissions reductions, hydrogen and biofuels.
- Disruption to food supply chains and high fertiliser prices mean liquid biofuel costs have soared. A growing focus on ensuring sustainability meanwhile has led to increasing attention being paid to advanced liquid biofuels that do not directly compete with food and feed crops, and that avoid adverse sustainability impacts. Liquid biofuels grow from 2.2 million barrels of oil equivalent per day (mboe/d) in 2021 to 3.4 mboe/d in the STEPS, 5.5 mboe/d in the APS and 5.7 mboe/d in the NZE Scenario in 2030.
- Low-emissions hydrogen-based liquid fuels offer an alternative to oil, but they currently have high costs of production and suffer from limited enabling infrastructure. The development and deployment of new projects over the next decade will be essential to lower costs and improve performance so that these fuels can play a significant role in the future.

When does oil demand peak...

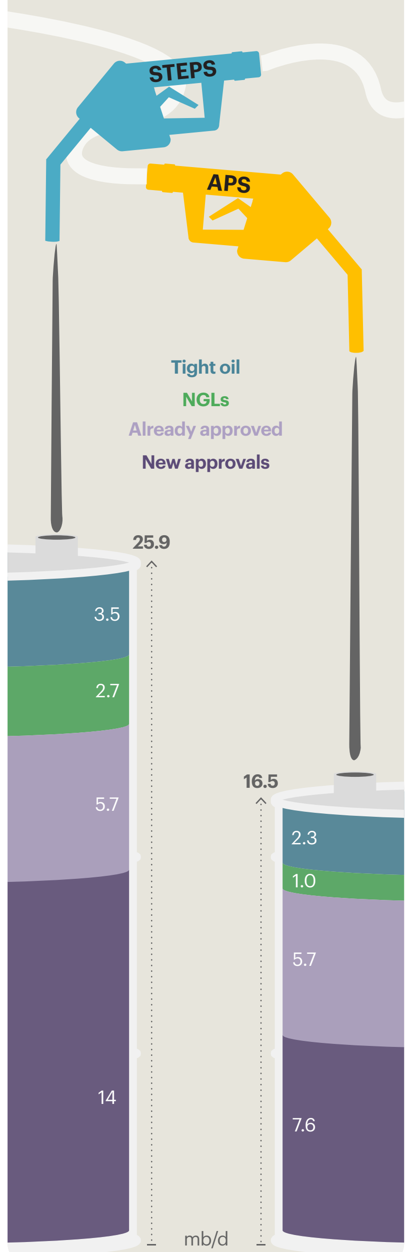


Peaks in oil demand rest on changes in transport. Oil use in petrochemicals is harder to shift.



...and what new supplies are needed

Oil demand increases by 8 mb/d in the STEPS and falls by 1.5 mb/d in the APS between 2021 and 2030. Production from existing fields drops by 18 mb/d over this period, leaving a large gap in 2030 that needs to be filled by new sources of supply.



Introduction

The situation for oil markets today could hardly be more different from what it was in 2020. Two years ago, lockdowns imposed in response to the Covid-19 pandemic caused a huge oversupply of oil, leading prices to collapse to an average of USD 44/barrel. Today, global supply is struggling to keep pace with demand, with many producers bumping up against capacity constraints and Russia's invasion of Ukraine sharply accentuating market tightness. Prices have soared to an average of USD 105/barrel so far in 2022.

Global oil use is subject to sharply conflicting pressures. Some sectors, notably aviation, are still recovering from the shock of the pandemic. Others, such as the chemical sector, have remained robust throughout. Road transport, which has traditionally been the heartland of oil consumption, is undergoing structural changes, especially for personal mobility; nearly one-in-ten passenger cars sold worldwide in 2021 was an electric vehicle. And now high prices – and their economic impacts – are contributing further to near-term uncertainty.

On the supply side, the major near-term question regards Russia and the extent to which tighter sanctions will force a reduction in output. Behind that lies a host of strategic questions for other producers, including members of the Organization of Petroleum Exporting Countries (OPEC), over how much of current windfall revenues they will invest in large-scale new production assets. For the moment, the reaction of producers to higher prices has been relatively muted. Upstream investment is expected to rise by around 10% in 2022, but this remains well below the pre-pandemic level of investment in 2019, and most of the rise stems from cost inflation rather than an increase in activity.

The global energy crisis has also put the spotlight on refining, where a deficit of available capacity led to oil product prices in 2022 rising even more than crude oil prices; and on the biofuels sector, where higher oil prices would normally encourage new production, but disruption to food supply chains and high fertiliser prices are complicating the picture.

Where do we go from here? This chapter looks at three scenarios for guidance. As ever, they provide different answers to this question. In the Stated Policies Scenario (STEPS), robust oil demand growth leads to demand in 2030 of 102 million barrels per day (mb/d). In the Announced Pledges Scenario (APS), demand soon peaks and drops to 93 mb/d in 2030. In the Net Zero Emissions by 2050 (NZE) Scenario, demand drops rapidly to 75 mb/d in 2030. Against this backdrop, this chapter also examines in detail three key issues that will shape the future of oil markets:

- **What do recent bans and recycling policies mean for plastics?** Oil demand for petrochemicals has been strong, but might this be undercut by new policy initiatives?
- **Are new conventional oil projects part of the answer to today's energy crisis?** Is there a need for new conventional oil projects to balance markets?
- **What do tight oil product markets mean for refining?** How much of a buffer does the system have and how might sanctions and embargoes affect oil trade?

Scenarios

7.1 Overview

Table 7.1 ▷ Global liquids demand and supply by scenario (mb/d)

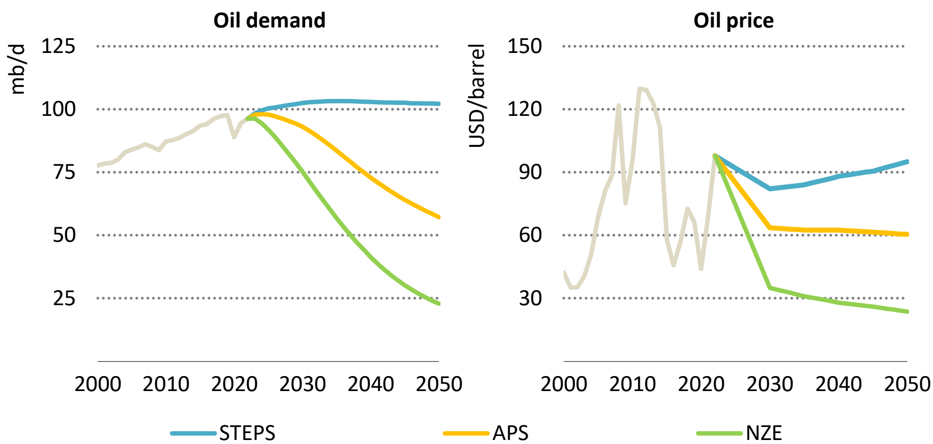
			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Road transport	36.5	40.5	41.9	39.0	37.8	17.3	27.5	1.3
Aviation and shipping	9.9	9.9	14.0	18.1	12.8	9.5	10.0	2.0
Industry and petrochemicals	17.2	20.5	23.7	25.5	21.5	18.1	20.1	13.4
Buildings and power	12.4	11.4	9.3	7.0	8.3	3.7	6.5	0.6
Other sectors	11.2	12.2	13.6	12.5	12.6	8.6	11.1	5.6
World oil demand	**87.2**	**94.5**	**102.4**	**102.1**	**93.0**	**57.2**	**75.3**	**22.8**
Liquid biofuels	1.2	2.2	3.4	5.3	5.5	9.2	5.7	5.7
Low-emissions hydrogen-based fuels	-	-	0.0	0.2	0.2	3.2	0.9	5.6
World liquids demand	**88.4**	**96.7**	**105.8**	**107.6**	**98.7**	**69.5**	**81.9**	**34.1**
Conventional crude oil	66.8	60.1	62.5	62.6	56.8	31.0	44.2	12.6
Tight oil	0.7	7.4	10.9	9.9	9.7	6.7	9.2	1.6
Natural gas liquids	12.7	18.2	20.9	19.3	19.2	13.9	16.4	6.1
Extra-heavy oil and bitumen	2.6	3.7	4.4	6.2	4.1	3.4	3.3	2.0
Other production	0.6	0.9	1.2	1.4	1.0	0.3	0.3	0.0
World oil production	83.4	90.3	99.9	99.3	90.7	55.3	73.5	22.2
OPEC share	40%	35%	36%	43%	36%	43%	36%	52%
World processing gains	2.2	2.3	2.5	2.8	2.3	1.9	1.8	0.6
World oil supply	**85.5**	**92.6**	**102.4**	**102.1**	**93.0**	**57.2**	**75.4**	**22.8**
IEA crude oil price (USD[2021]/barrel)	**96**	**69**	**82**	**95**	**64**	**60**	**35**	**24**

Notes: mb/d = million barrels per day; STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Other production includes coal-to-liquids, gas-to-liquids, additives and kerogen oil. Historical supply and demand volumes differ due to changes in stocks. Liquid biofuels and low-emissions hydrogen-based liquid fuels are expressed in energy equivalent volumes of gasoline and diesel, reported in million barrels of oil equivalent per day. See Annex C for definitions.

In the **STEPS**, global oil demand surpasses 2019 levels by 2023, undeterred by high oil prices. Demand peaks in the mid-2030s at 103 mb/d and then declines slightly to 2050 (Table 7.1). There is continued growth in the use of oil for aviation and shipping, as a petrochemical feedstock, and as fuel in heavy trucks, but from the mid-2030s this is more than offset by declining oil use in other sectors, especially in passenger cars, buildings, and power generation. It is assumed that production from Russia in the near term falls by 2 mb/d due to European and US sanctions, and that in the long term it remains well below projections made prior to its invasion of Ukraine. The largest increases in production to 2030 come from the United States, Middle East members of OPEC, Guyana and Brazil. The OPEC share of oil production rises from 35% in 2021 to 36% in 2030 and 43% in 2050. The supply of liquid biofuels more than doubles to 2050, and there is also a small increase in low-emissions hydrogen-based fuels. Upstream oil investment rises from current levels to offset losses in supply and meet rising demand and, as markets rebalance, the oil price falls from the very high levels in 2022 to around USD 82/barrel in 2030.

In the **APS**, stronger policy action leads global oil demand to peak in the mid-2020s, just above the level of demand in 2019, before dropping to 93 mb/d in 2030 (Figure 7.1). Demand then falls by around 40% between 2030 and 2050, with passenger cars, road freight and industry responsible for the largest reductions. The use of oil as a petrochemical feedstock increases by 0.9 mb/d between 2021 and 2050, and this is one of the few areas where oil demand rises in this scenario. Lower demand eases the task of offsetting the near-term reductions in Russian oil production, but from 2030 onwards it leads inexorably to falls in production in nearly all producer countries. The oil price falls to just under USD 65/barrel in 2030 and continues to decline slowly thereafter as demand falls.

Figure 7.1 ▷ Global oil demand and crude oil price by scenario



Demand peaks in the mid-2030s in the STEPS, in the mid-2020s in the APS, and policy-led declines in demand in the NZE Scenario mean a radically different future for oil markets

Notes: STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; mb/d = million barrels per day.

In the **NZE Scenario**, oil demand never returns to its 2019 level. Demand falls by 2.5% each year on average between 2021 and 2030, and by just under 6% each year from 2030 to 2050. Reductions in oil use in road transport are particularly significant, and assume that policy makers mandate a strong global push towards cleaner alternatives: no new cars with internal combustion engines are sold after 2035 and nearly all trucks sold from 2040 use electricity or hydrogen. The global effort to increase recycling of plastics pushes the rate from 17% in 2021 to 54% in 2050. Around 11 million barrels of oil equivalent (mboe/d) of low-emissions liquid fuels are consumed in 2050, mainly in aviation and shipping.[1] Even with the rapid decline in oil demand in the NZE Scenario, there is a need for continued investment in existing production assets, but the declines are sufficiently steep to avoid the need for any new long lead time conventional fields. The oil price is increasingly set by the operating cost of the marginal project and it falls to around USD 35/barrel in 2030 and to USD 24/barrel in 2050.

7.2 Oil demand by region and sector

Table 7.2 ▷ Liquids demand by region and scenario (mb/d)

			STEPS			APS		
	2010	2021	2030	2040	2050	2030	2040	2050
North America	22.2	21.4	20.5	17.8	16.2	18.2	10.8	6.9
United States	17.8	17.7	16.7	14.1	12.6	15.0	8.4	5.0
Central and South America	5.5	5.3	5.5	5.8	5.8	4.8	3.5	2.4
Brazil	2.3	2.4	2.4	2.5	2.4	2.0	1.4	0.9
Europe	13.9	12.4	10.9	8.6	7.1	9.2	4.7	2.7
European Union	10.6	9.2	7.7	5.8	4.5	6.5	3.1	1.7
Africa	3.3	3.8	5.0	6.7	8.5	4.9	5.8	6.1
South Africa	0.5	0.5	0.6	0.7	0.7	0.5	0.4	0.3
Middle East	7.1	7.7	8.9	10.4	10.9	8.0	8.4	7.9
Eurasia	3.2	4.1	4.2	4.5	4.5	4.1	4.0	3.9
Asia Pacific	25.0	33.3	38.2	38.7	36.7	35.1	28.1	20.6
China	8.8	15.1	16.2	14.3	12.5	15.2	11.0	7.6
India	3.3	4.7	6.7	8.4	8.3	5.9	5.4	3.9
Japan	4.2	3.3	2.7	2.1	1.7	2.4	1.3	0.7
Southeast Asia	4.0	4.9	6.7	7.4	7.4	6.0	5.2	3.9
International bunkers	7.1	6.6	9.3	10.4	12.4	8.6	7.5	6.8
World oil	**87.2**	**94.5**	**102.4**	**102.8**	**102.1**	**93.0**	**72.9**	**57.2**
Liquid biofuels	1.2	2.2	3.4	4.6	5.3	5.5	8.7	9.2
Low-emissions hydrogen-based fuels	0.0	0.0	0.0	0.1	0.2	0.2	1.2	3.2
World liquids	**88.4**	**96.7**	**105.8**	**107.5**	**107.6**	**98.7**	**82.8**	**69.5**

Notes: Liquid biofuels and low-emissions hydrogen-based liquid fuels are reported in million barrels of oil equivalent per day. See Annex C for definitions.

The last few years have been very volatile ones for oil markets. Oil demand fell by nearly 9 mb/d in 2020 and rose by around 5.5 mb/d in 2021. Demand in 2021 surpassed 2019 levels in only a few countries, including China, Poland, Sweden and Kazakhstan. Oil use in passenger cars in 2021 was about 5% lower than pre-pandemic levels globally, and in aviation it was around 30% lower.

[1] Low-emissions liquid fuels include liquid biofuels and low-emissions hydrogen-based liquid fuels, including ammonia, methanol and other synthetic liquid hydrocarbons.

Oil prices increased steadily during 2021 and jumped to USD 105/barrel in the first-half of 2022 following Russia's invasion of Ukraine. A number of countries, including the United States and Indonesia, have seen gasoline prices increase by more than 30% between 2019 and the first-half of 2022, and gasoline prices at the pump have surpassed USD 2/litre in more than 20 countries (equivalent to more than USD 7.5/US gallon). Several governments have introduced measures to reduce prices at the pump, for example by reducing taxes and excise duties (Chapter 2). The IEA set out a *10-Point Plan to Cut Oil Use* (IEA, 2022a) for consumers in advanced economies that could quickly reduce oil demand by around 2.7 mb/d in order to help alleviate some of the current market tightness (Chapter 5). Despite growing pressures and uncertainties, global oil demand is set to increase by 1.7 mb/d in 2022 as economic and transport activity rebounds.

In the **STEPS**, oil demand surpasses 2019 levels by 2023 and increases to 102 mb/d in 2030 (Table 7.2), with China, India and Southeast Asia together accounting for more than 60% of the increase in global demand. In advanced economies, demand falls by 3 mb/d to 2030, mainly because of reductions in road transport, and only a few countries see demand exceed 2019 levels. In emerging market and developing economies, demand increases by 8 mb/d to 2030 as car fleets expand and the use of oil use as a petrochemical feedstock rises rapidly. Demand peaks globally in the mid-2030s as reductions in advanced economies (a drop from 2030 to 2050 of 10 mb/d) just outweigh growth in emerging market and developing economies (6 mb/d increase) and international bunkers (3 mb/d increase).

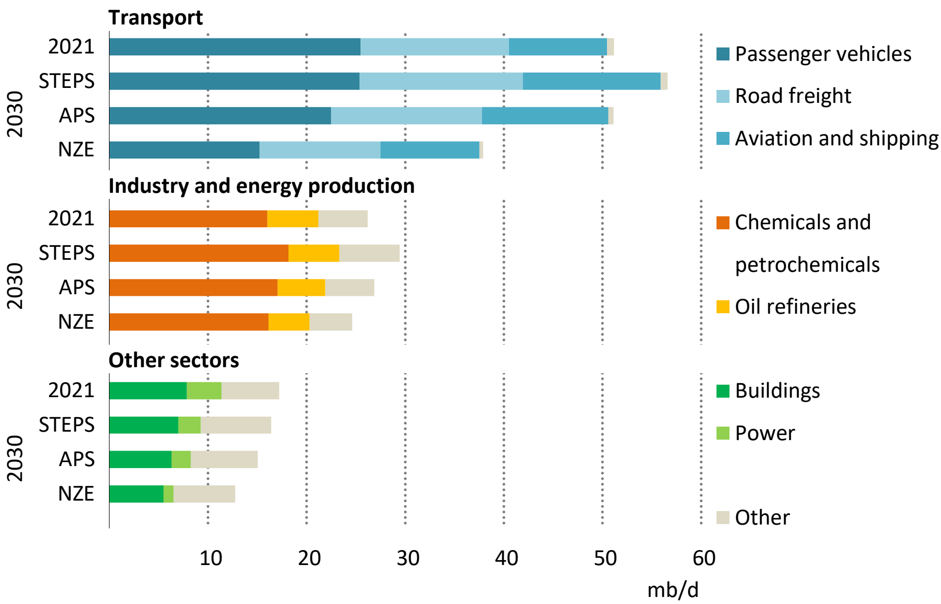
In the **APS**, global oil demand peaks in the mid-2020s at 98 mb/d. Faster electrification in the transport and buildings sectors helps governments to deliver on their climate pledges, while the use of oil for petrochemical feedstocks grows more slowly than in the STEPS. Oil demand in advanced economies falls by around 7.5 mb/d between 2021 and 2030 and increases by 4 mb/d in emerging market and developing economies.

In the **NZE Scenario**, strong policy action worldwide means global oil demand never recovers to its 2019 level and it falls by nearly 20 mb/d between 2021 and 2030. There is a 15 mb/d decrease in demand in advanced economies to 2030 and a 5 mb/d decrease in emerging market and developing economies.

Demand trends to 2030

There are 1.3 billion **passenger cars** on the road today and they accounted for nearly 25% of global oil demand in 2021 (Figure 7.2). Despite high gasoline and diesel prices, demand is set to increase slightly in 2022 as the world economy recovers from the Covid-19 pandemic. The outlook to 2030 varies by scenario: demand is broadly flat in the STEPS and falls by nearly 3 mb/d in the APS. Electric car sales grow faster in the APS than in the STEPS and this is responsible for around 50% of the difference between the two scenarios in 2030; stronger fuel economy improvements in the APS account for another 25% of the difference (see Chapter 5). In the NZE Scenario, 60% of cars sold worldwide are electric in 2030 and oil demand falls by around 9.5 mb/d.

Figure 7.2 ▷ Oil demand by sector and scenario to 2030



IEA. CC BY 4.0.

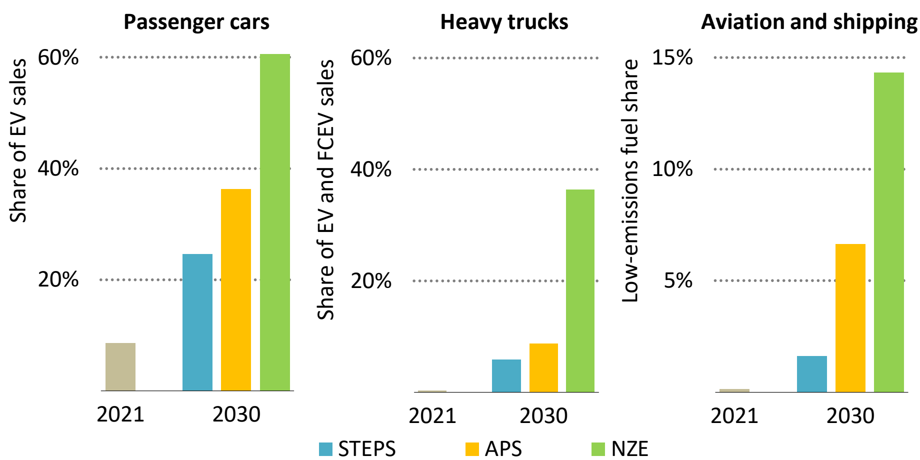
Road transport remains by far the most important sector for oil demand, and it sees the biggest changes to 2030

Notes: Passenger vehicles = cars, buses and two/three-wheelers.

Road freight accounts for more than 15% of global oil demand today. Rising demand for freight transport causes oil demand to rise by 1.5 mb/d to 2030 in the STEPS and by 0.3 mb/d in the APS despite increases in the uptake of electric and fuel cell heavy-duty trucks and liquid biofuels. The NZE Scenario sees a 3 mb/d reduction in demand to 2030.

Aviation and shipping both experienced increased oil demand in 2021. In aviation, oil use rose to 5 mb/d, but this was still 30% lower than in 2019. In shipping, maritime trade rebounded strongly from the lows in 2020 and oil use rose to around 5 mb/d in 2021, meaning that both sectors used broadly equivalent amounts of oil in 2021. All the scenarios take account of expected increases in trade and travel stemming from the 35% growth in the size of the global economy to 2030. In the STEPS, this leads to a 4 mb/d increase in oil use in aviation and shipping to 2030. In the APS, various policies – including the European Union ReFuelEU Plan and targets to increase the use of sustainable aviation fuels in the United States – reduce this increase to 3 mb/d to 2030. In the NZE Scenario, demand only increases marginally to 2030 as behaviour changes slow activity growth in aviation (see Chapter 3) and the uptake of low-emissions liquid fuels increases (Figure 7.3).

Figure 7.3 ⊳ Growth in alternatives to oil in transport by scenario to 2030



Moves away from oil use in all transport modes are evident in the STEPS and APS, but these fall far short of what is needed to meet the climate goals embodied in the NZE Scenario

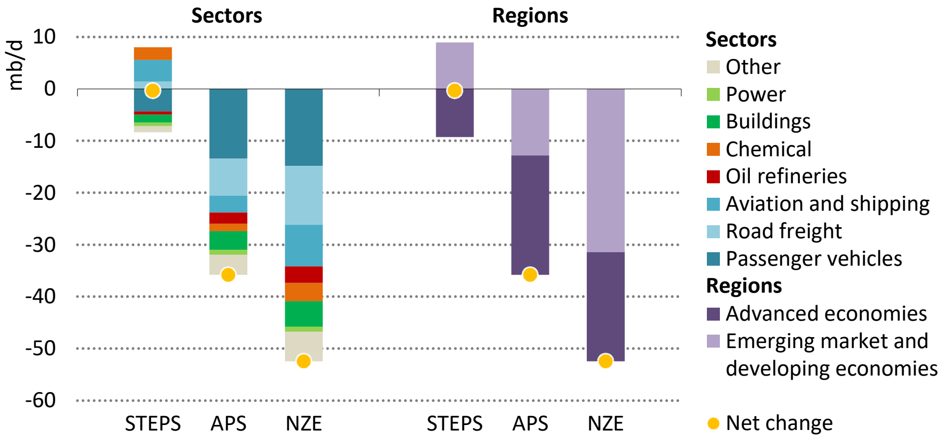
Notes: EV = electric vehicle; FCEV = fuel cell vehicle; heavy trucks = medium- and heavy-freight trucks. Low-emissions fuels include biofuels, low-emissions hydrogen and hydrogen-based fuels.

The **chemical** sector was the only sector in which oil use increased in 2020, and it now accounts for around 15% of global oil demand. An increasing number of countries have introduced or announced policies to reduce single-use plastics and improve recycling levels, but demand nevertheless grows by more than 2 mb/d in the STEPS between 2021 and 2030, and by more than 1 mb/d in the APS. In the NZE Scenario, demand only rises marginally to 2030 thanks to strengthened reuse and recycling strategies for plastics globally, backed by targeted policies that lead to much lower plastic demand per capita levels (see section 7.8).

The **buildings** sector accounts for just under 10% of oil use today. Demand falls in advanced economies as an increasing number of countries and jurisdictions have banned sales of new fossil fuel boilers. It is however set to grow in emerging market and developing economies as a result of increasing demand for liquefied petroleum gas (LPG), especially for cooking in Asia and Africa. Net oil use in buildings decreases globally by almost 1 mb/d in the STEPS, by 1.5 mb/d in the APS, and by nearly 2.5 mb/d in the NZE Scenario. The decrease in the NZE Scenario occurs even though it incorporates universal access to clean cooking by 2030.

Oil use for **power generation** has fallen by around 30% since 2010 and currently stands at around 3.5 mb/d, with Middle East countries accounting for 40% of this total. With strong growth in renewables, demand to 2030 falls by one-third in the STEPS, by 45% in the APS, and by 70% in the NZE Scenario.

Figure 7.4 ⊳ Change in oil demand by scenario, 2030-2050



Oil demand in the STEPS falls only marginally from its peak in 2035; it falls much more sharply in the APS as current climate pledges are met on time and in full

Notes: Other = rail, pipeline transport, non-specified transport, agriculture, oil and gas extraction, non-energy use and industry apart from use in the chemical sector.

In the **STEPS**, global oil demand levels off in 2035 at around 103 mb/d and then drops by around 1 mb/d to 2050 (Figure 7.4). Demand reductions in road transport, buildings and power after 2030 are offset by growth in feedstocks, aviation and shipping. By 2050, policy support and falling battery costs mean that around 40% of cars and 10% of heavy trucks on the road are electric or fuel cell vehicles. Efficiency measures and the use of alternative fuels curtail the growth of oil use in shipping and aviation. Between 2030 and 2050, global international shipping activity doubles while oil use increases by 25%, and international aviation activity increases by two-thirds while oil use increases by 40%. Oil use as a petrochemical feedstock increases by 2.5 mb/d between 2030 and 2050 as growth in emerging market and developing economies outweighs efforts to reduce and recycle plastics.

In the **APS**, oil demand falls by nearly 40% between 2030 and 2050 to 57 mb/d in 2050. Achieving national climate pledges leads to a strong reduction in oil use in transport and this is supported by the electric vehicle targets of manufacturers. Over 70% of passenger cars on the road in 2050 are electric or fuel cell vehicles, and so are 40% of heavy trucks. In the aviation and shipping sectors, the International Civil Aviation Organization requires international airlines to offset emissions growth above 2019 levels (ICAO, 2020), and the International Maritime Organisation has a target to cut emissions from maritime transport by at least half by 2050 (relative to 2008 levels) (IMO, 2018). Achieving these goals in the APS leads to a 25% reduction in oil use in aviation and shipping between 2030 and 2050. Oil use as a petrochemical feedstock also falls slightly between 2030 and 2050 as a result of stronger efforts to reuse and recycle plastics.

In the **NZE Scenario**, strenuous policy efforts to reduce emissions lead to a 6% average annual reduction in oil demand between 2030 and 2050, and demand in 2050 falls to less than 25 mb/d. Three-quarters of this is used as a petrochemical feedstock and in other processes in which the oil is not combusted, such as in lubricants, paraffin waxes and asphalt; a further 10% is used in aviation and shipping. Around 10 mboe/d of low-emissions liquid fuels are consumed in 2050. Most of this is used in aviation and shipping where low-emissions liquid fuels account for 80% of all liquid fuels used in 2050; the share of oil in total final consumption falls to 20% in aviation and 15% in shipping.

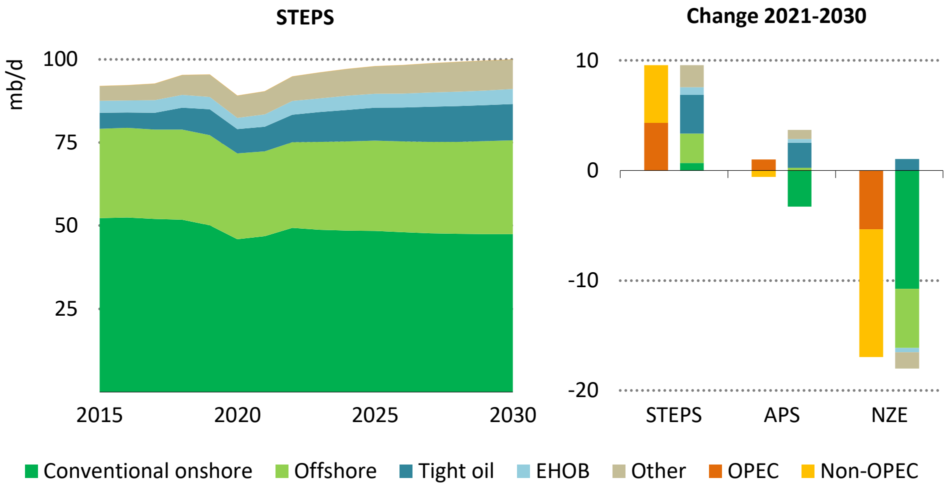
7.3 Oil supply

Table 7.3 ▷ Oil production by scenario (mb/d)

			STEPS			APS		
	2010	2021	2030	2040	2050	2030	2040	2050
North America	14.2	24.4	28.6	27.0	24.6	25.8	19.2	14.7
Canada	3.5	5.6	6.2	6.4	5.5	5.4	4.1	3.2
United States	7.8	16.8	20.7	18.6	16.7	18.8	14.0	10.7
Central and South America	7.4	5.9	9.0	10.1	11.4	8.3	7.7	6.5
Brazil	2.2	3.0	4.5	4.3	5.1	4.4	3.8	3.3
Guyana	0.0	0.1	1.6	2.0	1.1	1.4	1.5	1.0
Venezuela	2.8	0.6	0.8	1.4	2.7	0.7	1.2	1.3
Europe	4.4	3.6	3.1	2.2	1.3	2.7	1.3	0.6
Norway	2.1	2.0	2.0	1.3	0.6	1.9	1.0	0.5
United Kingdom	1.4	0.9	0.6	0.4	0.3	0.5	0.2	0.1
Africa	10.2	7.4	7.0	6.4	6.1	5.8	4.0	2.9
Angola	1.8	1.2	0.9	0.8	0.9	0.8	0.6	0.5
Nigeria	2.5	1.7	1.3	1.3	1.3	1.2	0.9	0.7
Middle East	25.4	27.9	33.9	38.2	40.4	31.2	27.5	22.9
Iraq	2.4	4.1	4.6	5.5	6.2	4.6	3.7	2.7
Iran	4.2	3.4	3.9	4.6	5.0	3.7	4.0	2.8
Kuwait	2.5	2.7	3.3	3.4	3.5	3.0	2.6	2.3
Saudi Arabia	10.0	11.0	13.5	14.8	15.9	12.3	10.9	10.0
United Arab Emirates	2.8	3.6	4.8	5.4	5.5	4.1	3.2	2.5
Eurasia	13.4	13.7	11.9	10.8	10.6	11.2	7.6	5.4
Russia	10.4	10.9	8.8	7.7	7.7	8.5	5.5	3.9
Asia Pacific	8.4	7.4	6.3	5.4	4.8	5.7	3.5	2.2
China	4.0	4.0	3.6	3.1	2.7	3.3	1.9	1.1
Conventional crude oil	66.8	60.1	62.5	62.5	62.6	56.8	41.9	31.0
Tight oil	0.7	7.4	10.9	11.3	9.9	9.7	8.3	6.7
United States	0.6	6.9	9.9	9.7	8.6	8.8	7.8	6.2
Natural gas liquids	12.7	18.2	20.9	19.9	19.3	19.2	15.9	13.9
Canada oil sands	1.6	3.4	3.9	3.8	3.7	3.5	2.8	2.2
Other production	1.6	1.3	1.7	2.6	3.8	1.6	1.8	1.6
Total	**83.4**	**90.3**	**99.9**	**100.1**	**99.3**	**90.7**	**70.7**	**55.3**
OPEC share (%)	*40%*	*35%*	*36%*	*40%*	*43%*	*40%*	*40%*	*43%*

Note: See Annex C for definitions.

Figure 7.5 ▷ Oil production in the STEPS and change by scenario, 2021-2030



US tight oil, oil produced by OPEC members, and new Brazil and Guyana deepwater oil all play a major part in meeting the near-term increases in demand in the STEPS and APS

Notes: EHOB = extra-heavy oil and bitumen. Other = enhanced oil recovery, Arctic crude, gas-to-liquids, coal-to-liquids, additives and oil shale.

High oil prices and concerns about energy security have led countries around the world to reassess the economic, political and climate impacts of bringing on new sources of domestic oil supply. In the wake of the pandemic and low investment levels in recent years, there is however a limited pipeline of new resources under development and of discovered resources available to be developed. New oil resources discovered in 2021 were at their lowest level since the 1930s. Access to financing has proved challenging, supply chains have become stretched, and costs are rising across the industry.

In the **STEPS**, there is 8 mb/d of demand growth to 2030 and 6 mb/d of production declines in mature producers (Table 7.3). More than 80% of this gap is met through increases in production in Middle East OPEC member countries, US tight oil, and Brazil and Guyana deepwater developments (Figure 7.5). Production from Russia is assumed to fall by around 2 mb/d as European and US sanctions take hold, but declines stabilise as new routes are developed to markets outside Europe, despite continuation of the sanctions. There is a gradual normalisation of the international situation in a number of other major resource-holders subject to sanctions, notably Iran and Venezuela, and production from these countries rises to 2030.

In the **APS**, global oil demand falls back to 2021 levels by 2030, but declines in mature producers means just over 8 mb/d of production increases elsewhere are needed to 2030. Countries with net zero emissions pledges make efforts to minimise emissions from their domestic oil and gas operations and this tends to increase their financing and production costs. Countries without net zero emissions pledges also come under pressure to reduce oil- and gas-related emissions as consumers in export markets start to differentiate imports by the emissions intensity of production. This leads to a 25% reduction in the global average emissions intensity of oil production by 2030 in the APS, compared with a 15% reduction in the STEPS.

In the **NZE Scenario**, falling demand is met without any need to approve the development of new long lead time projects. There is continued investment in existing fields, and this includes some low cost extensions of existing fields, e.g. for example through the use of in-fill drilling, enhanced oil recovery and tight oil drilling, to ensure that supply does not fall faster than the decline in demand. There is also investment to reduce emissions from oil and gas production, and the global average emissions intensity of oil production falls by more than 50% to 2030.

In the **United States**, oil production increases by just under 4 mb/d to 2030 in the STEPS, and total US production in 2030 is around 50% higher than in the next largest producer country (Saudi Arabia). Tight oil operators choose to prioritise returns over aggressive production growth but high prices in the near term encourage increased drilling. Tight oil and natural gas liquids (NGLs) from shale plays account for nearly all of the increase in US production to 2030. In the APS, lower oil and gas prices mean a smaller increase in tight oil and NGLs from shale plays but US production still increases by 2 mb/d to 2030.

In **Russia**, oil production in the STEPS is assumed to decline by 2 mb/d to 2030 as sanctions take hold. Russia has been under sanctions since 2014 but the financial and technology restrictions bite much harder now. As access to technologies, oil field service expertise, equipment and assets is removed, Russia struggles to maintain production in existing fields and to develop large new fields in the Arctic, tight oil and other offshore areas. In the APS, lower prices and fewer export opportunities mean Russian production in 2030 is around 2.5 mb/d lower than in 2021.

In **Canada**, oil production rises by 0.6 mb/d to 2030 in the STEPS. The increase comes from extra-heavy oil and bitumen (EHOB) projects currently under development and from increased tight oil production. No new large-scale EHOB projects are approved for development in the STEPS, but there are some smaller scale extensions of existing projects. In the APS, there are increased efforts to reduce domestic emissions from oil and gas operations and total production falls slightly to 2030.

In **Europe**, production declines by 0.5 mb/d in the STEPS and by 0.8 mb/d in the APS in 2030. New fields brought online in Norway mean its production rises to the mid-2020s before declining to current levels by 2030. The United Kingdom sees some inward investment, but production in 2030 is 0.2 mb/d lower than it is now in both the STEPS and the APS.

Saudi Arabia has recently invested more than USD 18 billion to raise capacity at its Berri and Marjan fields, and is set to make further investments. Together with measures to remove bottlenecks, this spending leads to production rising from around 11 mb/d in 2021 to 13 mb/d in the STEPS (of which 11 mb/d is crude oil) and to 12 mb/d in the APS by 2030.

Iraq roughly doubled its production during the 2010s but has suffered from low capital investment since the 2014 oil price drop, difficulties in ensuring sufficient water for injection, and political disagreements. As a result, it has been unable to expand production further in line with its large resource base. Our scenarios assume that internal relationships are normalised, that progress is made on providing water for oil recovery, and that production rises by around 0.5 mb/d to 2030 in both the STEPS and the APS.

United Arab Emirates increased investment to USD 20 billion in 2022 against a backdrop of multiple large discoveries. Production increases by 1.2 mb/d to 2030 in the STEPS from both onshore and offshore fields (including an expansion of the Upper Zakum oil field).

Iran faces limitations on its production as a result of international sanctions. Our scenarios assume a gradual normalisation in relations over time and a rise in production of 0.3-0.5 mb/d by 2030 in the STEPS and APS.

Venezuela faces political uncertainty and economic difficulties. Our scenarios assume a gradual normalisation of the international situation, and a slight rise in output in both the STEPS and APS.

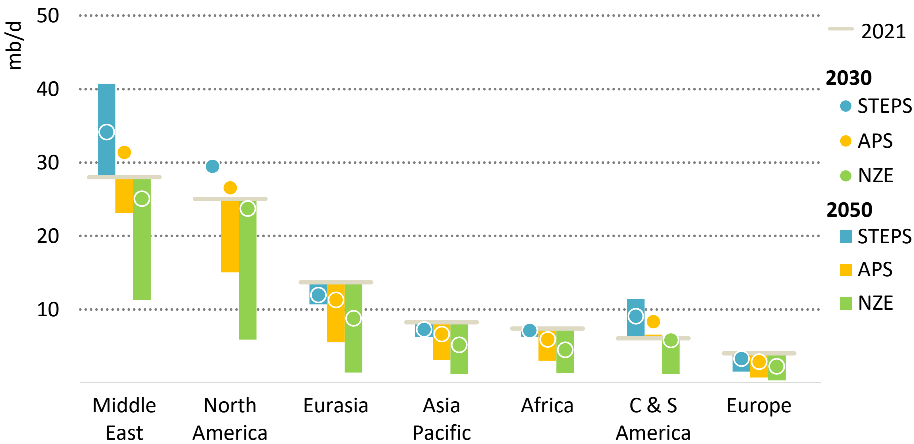
Brazil has invested heavily in recent years in its large pre-salt deepwater fields and it has announced plans to nearly double annual investment between 2021 and 2026. A number of its development projects have suffered from delays and cost overruns, but these projects come steadily online in both the STEPS and APS, and total production grows by 1.4 mb/d to around 4.4 mb/d in 2030. As a result, Brazil accounts for around 45% of global deepwater production in 2030 in both scenarios.

Guyana has seen a number of major deepwater discoveries in recent years and companies have been looking to develop these quickly. Production began at its Liza field in 2019 only four years after it was discovered and is continuing to ramp up. Overall production increases by around 1.5 mb/d to 2030 in the STEPS and APS.

Argentina has been looking to expand production from its tight oil plays and the government has eased capital control restrictions to encourage inward investment. Total production increases marginally in the STEPS and APS as increases in tight oil production are offset by declines in conventional oil production.

African members of OPEC have seen a 30% drop in production since 2010, with output in both Angola and Nigeria beset by technical and operational difficulties. Both countries are now developing new deepwater fields, but compensating for declines from existing fields looks unlikely as investment in supply has been 45% lower since 2016 compared to the 2010-15 period. Accordingly, production by African members of OPEC between 2021 and 2030 falls by 1 mb/d in the STEPS and by 2 mb/d in the APS.

Figure 7.6 ▷ **Changes in oil production by region and scenario, 2021-2050**



Increases in the Middle East and Central and South America offset declines elsewhere in the STEPS after 2030; both the APS and NZE Scenario see declines in all regions

In the **STEPS**, demand remains largely flat between 2030 and 2050. As a result, investment in new supply is needed chiefly to compensate for underlying declines in existing sources of production. The largest declines in production to 2050 are in North America (Figure 7.6). As the most productive US tight oil areas become depleted, US production drops by 4 mb/d between 2030 and 2050. Without new large-scale projects, EHOB production in Canada starts to decline over this period. Global deepwater production grows to 9.5 mb/d in 2035, supported by new output from Brazil and Guyana, before declining to around 7.5 mb/d in 2050. Production in Russia declines by just over 1 mb/d between 2030 and 2050. OPEC members increase their production by 7 mb/d between 2030 and 2050 to offset declining output elsewhere. One third of the increase in OPEC production comes from Saudi Arabia, with Venezuela providing a further 25% and Iraq 10%; there are declines in production from African members of OPEC. OPEC's share of the global oil market increases to 43%, its highest level since 1979.

In the **APS**, demand declines by around 2.5% each year on average between 2030 and 2050, and this means that much lower levels of new production are required than in the STEPS. The biggest fall in production takes place in the United States over this period (8.5 mb/d) as conventional fields mature and lower prices mean less investment in tight oil and shale gas. There are also declines in Russia (4.5 mb/d) and Canada (2 mb/d). Among members of OPEC, Iraq and Saudi Arabia see some of the largest declines. Overall OPEC production falls by just under 9 mb/d, but its share of the market still increases to 43% in 2050.

In the **NZE Scenario**, demand declines by around 6% on average each year between 2030 and 2050. Production accordingly falls in all regions and the oil price drops to very low levels (USD 25/barrel in 2050). Oil production is increasingly concentrated in resource-rich countries due to the large size and slow decline rates of their existing fields. OPEC's share of a much smaller oil market increases to 52% in 2050, higher than at any point in the history of oil markets. The combination of falling demand and a low oil price results in a sharp drop in income and GDP in many fossil fuel producers, including some where revenues from oil and gas sales often cover a large share of public spending on essential services. The oil price in the NZE Scenario would in principle be sufficient for some of the lowest cost producers to cover the cost of developing new fields, but we assume that they do not do so as this would lead to even lower prices and might herald greater market volatility depending on the resilience of these countries to such a sharp contraction in income.

7.4 Oil trade[2]

Table 7.4 ▷ Oil trade by region and scenario

	STEPS						APS			
	Net imports (mb/d)			Share of demand			Net imports (mb/d)		Share of demand	
Net importer in 2021	2021	2030	2050	2021	2030	2050	2030	2050	2030	2050
China	12.3	13.0	10.6	78%	75%	76%	12.2	6.9	75%	82%
European Union	9.7	8.9	5.7	93%	95%	92%	7.6	2.0	95%	93%
Other Asia Pacific	6.4	10.0	13.5	70%	82%	87%	9.3	7.9	83%	87%
Japan and Korea	5.8	5.5	4.1	96%	98%	98%	5.0	2.3	98%	97%
India	4.1	6.2	8.0	87%	89%	92%	5.4	3.8	90%	90%
Other Europe	0.3	0.9	2.2	7%	25%	67%	0.7	0.9	21%	60%
	Net exports (mb/d)			**Share of production**			**Net exports (mb/d)**		**Share of production**	
Net exporter in 2021	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Middle East	19.6	24.3	28.5	70%	72%	71%	22.4	14.4	72%	63%
Russia	7.2	5.3	4.4	66%	61%	58%	5.1	1.0	60%	27%
Africa	3.4	1.7	n.a.	46%	25%	n.a.	0.6	n.a.	11%	n.a.
North America	2.5	7.9	7.7	10%	27%	31%	7.3	7.5	28%	51%
Caspian	2.0	2.0	1.4	72%	66%	49%	1.8	0.4	64%	26%
Central & South America	0.4	3.1	5.0	8%	34%	44%	3.1	3.8	37%	59%

Note: n.a. = not applicable.

[2] Trade figures reflect volumes traded between regions modelled in the *World Energy Outlook* and do not include intra-regional trade. Oil trade includes both crude oil and oil products.

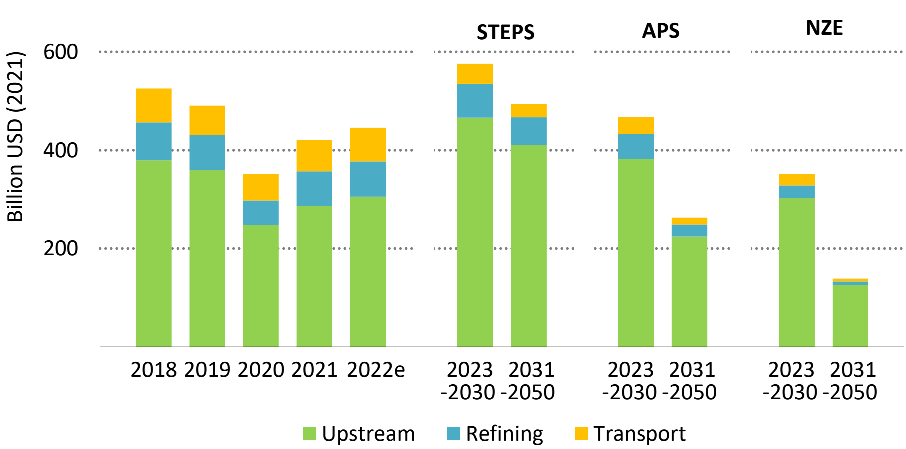
In the **STEPS**, the European Union ban on imports from Russia and the sanctions imposed on Russia together result in a major reorientation of oil trade. Russian net oil exports drop by 25% to 2030 and by more than 40% to 2050 (Table 7.4). The Middle East increases exports to help offset this reduction and its share of global export markets rises from 52% in 2021 to 60% in 2050. North America overtakes Russia to become the world's second-largest oil exporting region in the mid-2020s. China remains the world's largest oil importer to 2050 although its imports peak and fall slightly from 2030 onwards. India's oil imports double between 2021 and 2050. Despite ample crude supply, countries in Central and South America and Africa increasingly import oil products due to a lack of domestic refining capacity.

In the **APS**, a number of countries including large producers such as the United States and Brazil cut demand faster than supply, and this enables them to increase exports by more than in the STEPS. This means a smaller share of the market for producers in the Middle East, and their share of export markets in 2050 is lower than in the STEPS. China's imports in 2050 are around one-third lower than in the STEPS; India's imports peak in the 2030s and fall below the current level by 2050.

In the **NZE Scenario**, oil imports fall across the board. Around 10 mb/d of oil is still traded globally in 2050, most of which takes the form of exports from the Middle East and North America to demand centres in the Asia Pacific region.

7.5 Oil investment

Figure 7.7 ▷ Average annual investment in oil by scenario



Oil investment to 2030 in the APS is broadly in line with the levels seen in recent years; much lower demand in the NZE Scenario can be met without new long lead time projects

Note: 2022e = estimated value for 2022 based on IEA (2022b).

Total oil investment is expected to increase to around USD 450 billion in 2022, around 25% more than in 2020. After years of relative stability, cost inflation has raised upstream costs sharply, largely as a result of increased material costs, and this has significantly diminished the impact of higher spending on activity levels.

In the **STEPS**, average annual oil investment to 2030 is USD 580 billion, which is 30% higher than the average since 2018 (Figure 7.7). Meeting the increase in oil demand to 2030 while also offsetting declines from existing sources of supply requires annual average upstream oil investment of USD 470 billion to 2030. Between 2022 and 2050, cumulative upstream oil investment is USD 12 trillion, and there is a further USD 2.5 trillion of investment in transport and refining. Cumulative clean energy investment to 2050 meanwhile reaches USD 60 trillion.

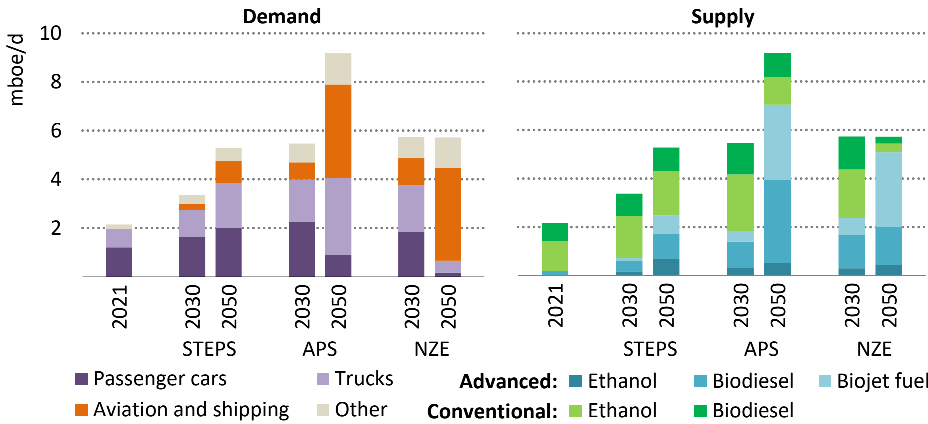
In the **APS**, aggregate average annual oil investment to 2030 is USD 470 billion, which is broadly similar to levels over the past five years. Although demand peaks in the mid-2020s, declining production in existing sources of supply means that investment is needed at both new and existing fields, and average annual upstream oil investment is USD 380 billion. Cumulative upstream oil investment between 2022 and 2050 is USD 7.5 trillion, and a further USD 1.5 trillion is invested in oil transport and refining. These levels of investment are dwarfed by cumulative clean energy investment to 2050, which totals USD 95 trillion.

In the **NZE Scenario**, annual oil investment averages about USD 350 billion to 2030. The surge in clean energy technology deployment means that oil demand falls at a rapid rate, and that makes it possible to meet demand without any new oil exploration or development of long lead time projects (see section 7.9). Reducing oil investment to this level would lead to a very different outcome if done in advance of – or instead of – the huge scaling up in clean energy spending and consequent reduction in oil demand that features in this scenario (see Chapter 4).

7.6 Liquid biofuels

Over 80 countries have liquid biofuel blending mandates in place today. The drop in the oil price in 2020 and changes in government priorities following the pandemic mean a number of targets and plans have been delayed or scaled back, including in Indonesia, Malaysia, Thailand and Brazil (IEA, 2021). Prices for biofuels have doubled since 2020 as a result of increases in feedstock and energy costs stemming from Russia's invasion of Ukraine and other disruptions to global crop production. During the first-half of 2022, the price of conventional biofuels averaged USD 270 per barrel of oil equivalent (boe) in the United States (around USD 70/boe higher than average US gasoline prices at the pump) and USD 335/boe in Europe (similar to European average gasoline prices at the pump). Prices of advanced biofuels have increased by 70% since 2020 and have so far averaged between USD 350-400/boe in 2022.

Figure 7.8 ▷ Liquid biofuel demand and supply by scenario



Liquid biofuel use increases in all scenarios, more than doubling to 2030 in the APS and NZE Scenario, with increasing shares produced from non-food crop feedstocks

Note: Other includes other transport, industry, buildings and agriculture.

In the **STEPS**, demand for liquid biofuels grows from 2.2 mboe/d in 2021 to 3.4 mboe/d in 2030 and 5.3 mboe/d in 2050 (Figure 7.8). This comes mainly from blending mandates for passenger cars that lead to an increase in the use of ethanol, which is produced using advanced feedstocks. Passenger cars consume 50% of total liquid biofuels in 2030 and almost 40% in 2050. Ethanol comprises 55% of total biofuels production in 2030, down from 60% today.

In the **APS**, demand for liquid biofuels increases to 5.5 mboe/d in 2030 with much higher use of liquid biofuels in road transport in the United States, China, India and Canada. After 2030, increasing sales of electric cars mean that liquid biofuels demand plateaus in road transport, and a much higher share is used in aviation and shipping. In 2050, total liquid biofuels consumption is over 9 mboe/d, 75% of which consists of advanced biofuels. Around 40% of this total is consumed in aviation and shipping, and liquid biofuels provide just over 25% of total fuel use in aviation.

In the **NZE Scenario**, demand for liquid biofuels increases to 5.7 mboe/d in 2030 and then remains around this level to 2050. The high penetration of electric cars and trucks leads to a significant reduction in biofuels consumption in road transport after 2030, and more of the limited supply of sustainable bioenergy available is used in the form of solid bioenergy in power generation and in industrial applications where electrification is challenging. As a result, demand for liquid biofuels in 2050 is 40% lower than in the APS. In the NZE Scenario, around 90% of liquid biofuels produced in 2050 are advanced biofuels and 75% are consumed in aviation and shipping. More than 40% of the fuel used in aviation in 2050 takes the form of liquid biofuels (Box 7.1).

Box 7.1 ▷ Policy support needed for advanced liquid biofuels

Over 90% of liquid biofuels produced today are "conventional" biofuels produced from food crop feedstocks. These feedstocks include sugar cane ethanol, starch-based ethanol, fatty acid methyl ester, straight vegetable oil and hydrotreated vegetable oil produced from palm, rapeseed or soybean oil. There is growing interest in the use of alternative feedstocks that can avoid the potential sustainability concerns associated with some conventional biofuels. These advanced biofuels are produced from non-food crop feedstocks, provide a large reduction in life cycle greenhouse gas (GHG) emissions compared with fossil fuels, and do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. The production of advanced liquid biofuels increases in all scenarios, but is critically dependent on:

- Developing sufficient quantities of sustainable feedstocks such as municipal solid waste, wheat straw and non-food crops. This implies comprehensive waste management policies and regulations to enhance collection, sorting and pre-treatment, together with a robust certification system to ensure that feedstocks are sustainable.
- Demonstrating and scaling up ways of deriving sustainable feedstocks from non-food energy crop production on non-arable and degraded land. Sisal, for example, grows on semi-arid lands and is often used in the textile industry in processes that produce large amounts of organic waste. This waste could be turned into liquid biofuels and could generate additional streams of income for textile companies.
- Regulatory stability to support the long-term investments needed to scale up production. The number of producers of advanced biofuels is small today, and new investors need visibility on policies and plans so that they can assess market potential.

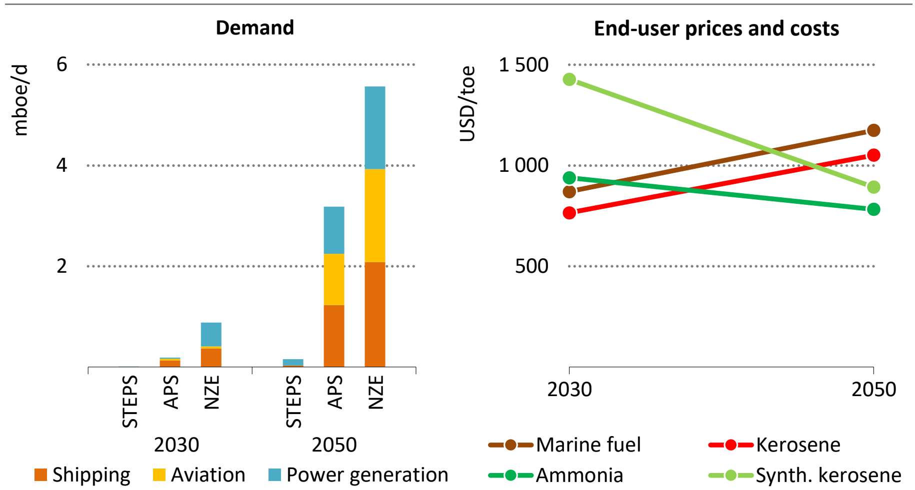
7.7 Low-emissions hydrogen-based liquid fuels

Low-emissions hydrogen-based liquid fuels include ammonia, methanol and other synthetic liquid hydrocarbons made from hydrogen with very low-emissions intensity.[3] They offer an alternative to the use of oil, can often use existing infrastructure and combustion equipment, and are expected to gain market share in sectors such as aviation and shipping that will otherwise struggle to reduce oil demand. However, they currently have high costs of production, suffer from limited enabling infrastructure, can involve large energy losses from production to consumption, and in some cases need to be handled more carefully than traditional liquid fuels.

[3] Hydrogen-based synthetic hydrocarbons need to be made using a non-fossil source of CO_2, such as biogenic or atmospheric CO_2, to be a low-emissions fuel. Sourcing this CO_2 can add considerably to overall costs.

The future uptake of low-emissions hydrogen-based liquid fuels depends crucially on finding ways to reduce production costs. Cheaper renewable energy and carbon capture, utilisation and storage (CCUS) will make a big difference, but dedicated projects are also needed to improve low-emissions hydrogen and ammonia production technologies and to reduce efficiency losses across the value chain. There has been recent progress on this front. The largest power generation company in Japan, JERA, issued a tender in 2022 for up to 0.5 Mt of low-emissions ammonia (around 5 thousand barrels of oil equivalent per day [kboe/d]) to replace 20% of the coal at a large power plant unit from 2027. Maersk, a leading shipping company, has commissioned 19 methanol-fuelled container ships and it is studying how to ensure that the methanol they use is produced from sustainable biomass. In Germany, a 350 tonne per year plant for the production of synthetic kerosene opened in 2022 next to an existing synthetic methane plant and a source of CO_2 from biogas upgrading.

Figure 7.9 ▷ Low-emissions hydrogen-based liquid fuel demand by scenario and the declining cost gap with oil products in the NZE Scenario



Rapidly rising demand for hydrogen-based liquid fuels helps bring down costs through economies of scale and innovation, while prices of oil products rise

Notes: mboe/day = million barrels of oil equivalent per day; toe = tonne of oil equivalent. Synth. kerosene = synthetic kerosene. Ammonia and synthetic kerosene costs are the average levelised production costs for the Middle East and China. Final prices of marine fuel and kerosene include CO_2 prices and other levies.

In the STEPS, there is limited uptake of hydrogen-based fuels globally to 2030, reflecting the low level of current policy support for their use (Figure 7.9). In the APS, more progress is made, with 0.2 mboe/d of low-emissions hydrogen-based fuels being used globally for transport in 2030. In the NZE Scenario, this figure rises to 0.4 mboe/d, most of which is used in shipping. Achieving the levels of use seen in the APS and the NZE Scenario will require rapid progress on standards, notably for the safe transport and use of ammonia. There are likely to be large regional variations in production costs for low-emissions hydrogen-based fuels, and international trade will depend on international co-operation on standards.

Progress between 2030 and 2050 obviously depends crucially on what is achieved by 2030, including on deployment, innovation and economies of scale that help to narrow the cost gap with oil products, as well as on standards. In the NZE Scenario, the steps taken by 2030 lay a solid foundation for the future. Taking into account the cost of CO_2, the cost of producing low-emissions hydrogen-based fuels in the NZE Scenario is lower than the price of maritime fuel in the 2030s in a number of regions, and lower than the price of aviation fuel in the 2040s. Nearly 6 mboe/d of low-emissions hydrogen-based liquid fuels are consumed in 2050, roughly evenly split between aviation, power generation and shipping. This rests on the production of 120 million tonnes of low-emissions hydrogen fed by 1.2 terawatts of renewable power capacity (equivalent to 70% of today's global installed solar and wind capacity) as well as 0.5 gigatonnes (Gt) CO_2 per year of CCUS capacity.

Key themes

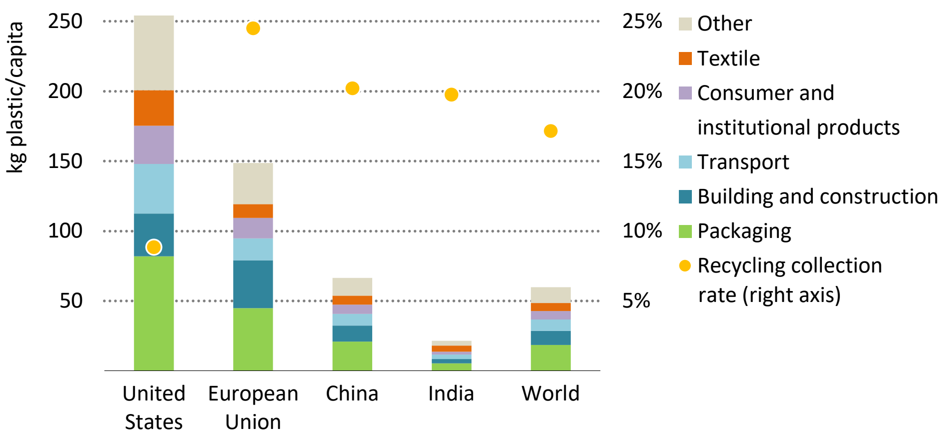
7.8 Oil use in plastics

Petrochemicals are integral to modern societies. They are used for plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents and tyres, among many other things. They also feature in many parts of the modern energy system, including solar PV panels, wind turbine blades, batteries, thermal insulation for buildings and electric vehicle parts. The chemical sector today uses around 15 mb/d of oil and is set to be a major source of future demand growth. In this section, we look at the drivers of petrochemical feedstock demand – with a particular focus on plastics – and at recent policy and technology developments that could reduce oil use in petrochemicals.

Around 90% of the oil consumed in the chemical sector today is used as a feedstock: the remainder provides heat and energy for production processes. Oil that is used as a petrochemical feedstock is converted into chemical products: this limits direct CO_2 emissions from its use, although in some instances the final products are eventually combusted and this can result in a higher level of emissions. Around 70% of oil feedstock (10 mb/d) is used to produce plastics, demand for which has grown rapidly in recent years. Demand for plastics varies significantly between countries: for example, more than 250 kilogrammes (kg) of plastic is used per capita every year in the United States and less than 25 kg of plastic per capita is used each year in India (Figure 7.10). Around 30% of the use of plastics today is for packaging.

Plastics are very useful. However, they do have downsides in terms of emissions from their production, they account for a significant share of overall oil use in a number of countries, and result in large amounts of waste, for example, plastic waste can end up in water streams in the form of microplastics. The use of feedstock based on low-emissions hydrogen-based fuels and bioenergy, for example produced by converting bioethanol to ethylene, could help reduce emissions and oil dependency, but they are currently expensive, require large quantities of sustainable bioenergy, and do not solve issues related to plastic waste.

Figure 7.10 ▷ Plastic demand per capita and recycling collection rates, 2019



Packaging represents the biggest use of plastics in nearly all regions; plastic demand per capita and plastic recycling collection rates vary widely

There is growing momentum behind policies and initiatives that aim to reduce plastic use. Particular attention is being paid to single-use plastics, which are commonly used for packaging and food utensils, and more than 60 countries so far have taken relevant action. This includes China, which has restricted the production, sale and use of plastic bags as well as some other disposable plastic products, and India, which has banned the production, sale and use of 19 single-use plastic items.

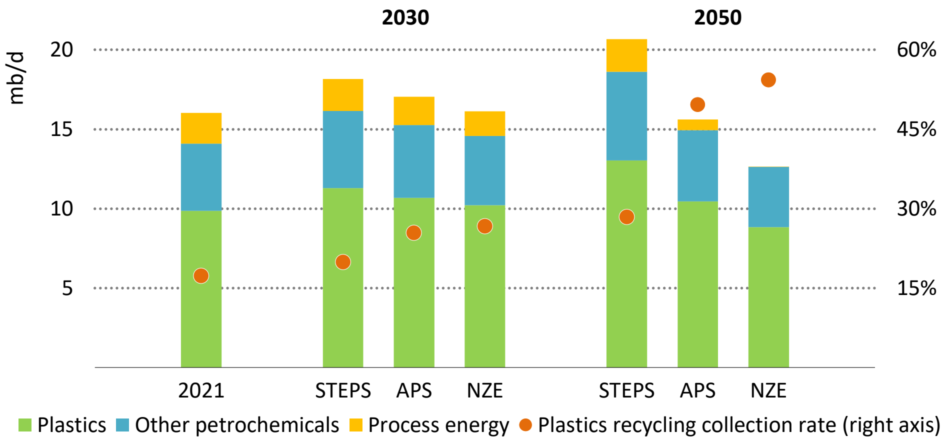
Recycling of plastics is another option to cut down on waste and emissions. Globally, 17% of plastic waste[4] is collected for recycling today although there are large differences between regions: for example, 25% is collected for recycling in Europe and less than 10% in the United States. Recycling rates for plastics are much lower than recycling rates for steel (80%), aluminium (80%) and paper (60%). This is because of the complex processes required to remove impurities and avoid discolouration of recycled plastic material and because processing facilities are capital intensive. Advanced sorting and recycling techniques are being developed to help solve these challenges, including chemical recycling and pyrolysis-based waste-to-feedstock. Policy makers are also looking to boost recycling rates through taxes, subsidies, landfill regulations and charges, and international treaties (Table 7.5).

[4] Plastic waste includes all post-consumer plastic waste with a life span of more than one year.

Table 7.5 ▷ Selected recent policies addressing consumption and recycling of plastics

Region	Policy name	Description	Year
Global pledges and treaties			
United Nations	End Plastic Pollution: Towards an international legally binding instrument	Establishes an Intergovernmental Negotiating Committee to develop an international legally binding instrument on plastic pollution, including in the marine environment.	Announced March 2022, targeting end-2024
G7 and beyond	Ocean Plastics Charter	Sets goals on plastics related to product design, recycling, education and innovation, which have been endorsed by multiple countries and companies.	Launched in 2018
Bans			
China	Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Wastes	Prohibits and restricts the production, sale and use of non-degradable plastic bags and other disposable plastic products.	In force since September 2020
India	Plastic Waste Management Amendment Rules	Prohibits the manufacture, import, stocking, distribution, sale and use of identified single-use plastic items, including cutlery, foodservice ware, stirrers, plastic flags, candy sticks, etc.	In force since July 2022
European Union	Directive on single-use plastics	Prohibits certain single-use plastics (cotton bud sticks, cutlery, plates, straws, stirrers, sticks for balloons and some food and beverage containers) and limits the use of others.	In force since July 2021
Canada	Single-use plastics prohibition regulations	Prohibits the manufacture, import, sale and export of six categories of single-use plastics: checkout bags, cutlery, foodservice ware made from or containing problematic plastics, ring carriers, stirrers and straws.	In force in stages from December 2022 to June 2026
Recycling targets			
European Union	Packaging Directive	Targets a plastic packaging recycling rate of 50% by 2025 and 55% by 2030.	Announced 2018
Investment in recycling of plastics			
Japan	Advanced plastic recycling in National Budget 2021	USD 55 million allocated to support the development of advanced plastic recycling equipment.	Announced 2021
United States	Department of Energy R&D funding for plastics	USD 13.4 million awarded in R&D funding to seven projects for next-generation plastic technologies. Aims include more upcycling of recycled plastics and the development of new plastics that are more recyclable and biodegradable.	Announced 2022
Denmark	Innovation Fund Green Mission: Circular economy with focus on plastics and textiles	Co-financing in research and innovation related to reuse, recycling and reduced consumption of plastics.	Call for funding in 2022

Figure 7.11 ▷ **Oil use in the chemical sector by scenario**



IEA. CC BY 4.0.

Oil use as petrochemical feedstock falls in the NZE Scenario due to alternative feedstocks and more recycling, but still accounts for more than half of global oil demand in 2050

In the **STEPS**, policies to scale up recycling, limit single-use plastics, and invest in waste management and recycling facilities result in an increase in recycling collection rates from 17% in 2021, to 20% in 2030 and 27% in 2050 (Figure 7.11). This is not enough to counterbalance the strong growth in demand for primary plastics; oil use as a petrochemical feedstock for plastics rises by 3 mb/d between 2021 and 2050.

In the **APS**, there is a much stronger push for recycling of plastics in fulfilment of countries' net zero emissions pledges, and the global average recycling collection rate increases to 25% in 2030 and 50% in 2050. Demand for oil as a petrochemical feedstock to produce plastics nonetheless rises by around 0.5 mb/d between 2021 and 2050.

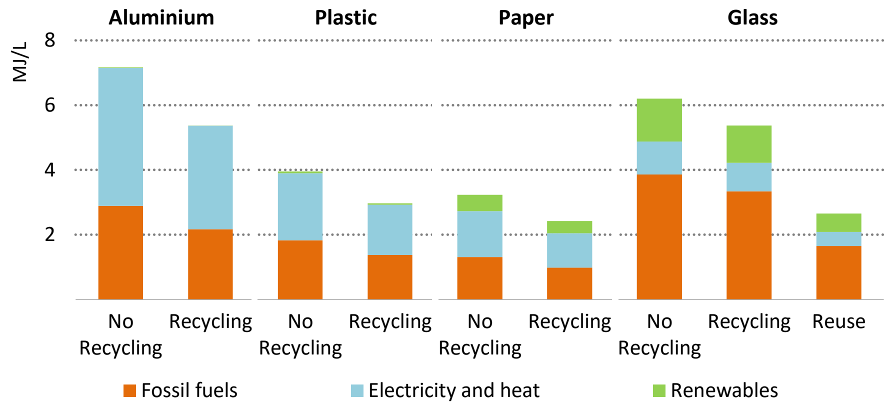
In the **NZE Scenario**, the global average recycling collection rate increases to 26% in 2030 and 54% in 2050; oil use as a petrochemical feedstock falls by 1 mb/d between 2021 and 2050. Total oil use in the chemical sector, including oil that is currently used for process energy, falls by just over 20% between 2021 and 2050. This is a much shallower decline than in all other sectors: oil use in passenger cars falls by 98% over this period, for example. As a result, the chemical sector ends up accounting for more than half of global oil demand in the NZE Scenario in 2050.

Box 7.2 ▷ What's the sustainable choice for packaging drinks?

Most drinks come in plastic bottles, aluminium cans, paper-based packaging or glass bottles. We explore here how the different options compare on the basis of a life cycle assessment of energy and emissions of each of these options in the European Union (Samuel Schlecht, 2020) (Carmen Ferrara, 2021).

In the absence of recycling, the answers are fairly simple. Paper-based packaging and plastic bottles require about 3-4 MJ/litre and are the least energy-intensive to manufacture (Figure 7.12); glass bottles are next, requiring about 70% more energy to produce; and aluminium cans require the highest amount of energy to produce. The associated CO_2 emissions follow the same hierarchy, but vary depending on the balance of fuels and electricity used in each process as well as on the location of the manufacturing facilities. The production of aluminium, for example, is electricity-intensive. A can produced in France generates less than half of the emissions of a can produced in Poland because of the different emissions intensity of electricity in each country.

Figure 7.12 ▷ Energy content of various packaging types in the European Union



Plastic bottles and paper-based packaging options use 35-75% less energy per litre of packaged drink than aluminium cans and glass bottles

Notes: MJ/L = megajoule per litre; reuse is the energy required to transport, wash, sterilise and dry an existing glass bottle.

Introducing recycling and reuse makes comparisons much more complex. Aluminium is one of the most recycled of all materials worldwide. Using recycled aluminium brings down the energy required to produce a new can by around one-quarter. Glass bottles can be recycled, which requires around 15% less energy than making a new one, or reused, which requires less than half the energy of making a new bottle. Our analysis indicates that reusing a glass bottle five times requires less energy than producing five new plastic bottles, while reusing a glass bottle ten times requires less energy than producing paper-based packaging for ten drinks.

Price naturally plays a significant role in determining the choices made by manufacturers and consumers. Plastics bottles are four- to five-times cheaper than glass bottles and they retain a cost advantage even with reuse schemes. Many glass reuse schemes have declined or been discontinued for this reason. Taxes or incentives to reduce plastic use and pollution could help reverse this trend. A push for more glass reuse schemes in Europe or a single scheme across Europe, aided by broader standardisation in bottle design, would also improve resource use and cut waste. This would need to be combined with efforts involving retailers and consumer groups to increase the use of reusable bottles and their return.

7.9 Are new conventional oil projects an answer to today's energy crisis?

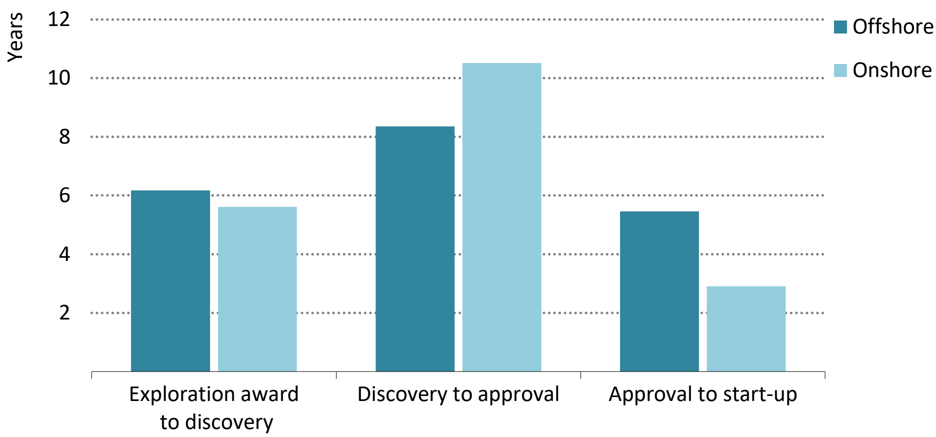
In recent years, oil supply has increased relatively quickly when market conditions have warranted, largely because of the ability of US tight oil production to ramp up relatively fast, as well as the existence of OPEC spare capacity – the traditional buffer for the oil market. But questions are now being asked about whether recent trends for these avenues will prove a good guide to the future. Tight oil operators are now more focussed on returns than near-term production growth, and oil field service providers are hesitant to reinvest in tight oil supply chains. Many members of OPEC are struggling to increase production, and some of the notional OPEC spare capacity buffer is also subject to political constraints.

Here we look at what combination of factors could fill any gap between supply and demand and help the global oil market to stay in balance. We find that the long lead time of conventional projects and the depleted existing pipeline of potential projects mean that new conventional projects are unlikely to provide large-scale relief to the immediate energy crisis. Looking beyond the next few years, the need for new conventional projects to balance the market is contingent on the demand outlook, which varies widely by scenario. In the STEPS, the combination of underlying declines in existing sources of production and rising demand means new conventional projects are needed to ensure a smooth match between supply and demand. In the APS, demand is lower and there is less need for new conventional projects. In the NZE Scenario, declining fossil fuel demand can be met through continued investment in existing production assets without any need for new long lead time oil fields.

Lead times for conventional projects

The development of a typical new conventional upstream oil project occurs in a number of stages. A host country or land owner first announces an intention to allow companies to bid for exploration licences. An interested company (or group of companies) conducts subsurface studies and chooses whether to bid for a licence. After an exploration licence is awarded, the licence holder has to secure further regulatory approvals before exploration activities can take place. If resources are discovered, additional analysis is conducted to decide whether the resources can be produced economically and how best to develop the project. After securing regulatory approval for development, a final investment decision (FID) is taken to develop the project.[5] Physical development work commences and later the project starts producing. Most conventional projects increase production gradually from this point. Production eventually peaks and starts to decline.

Figure 7.13 ▷ Years needed to discover, approve and develop new conventional upstream oil projects since 2010



It takes around 20 years on average from the granting of an exploration licence for a new conventional project to begin production

Note: Includes projects awarded exploration licences since 1980 that started production between 2010-20, weighted by technically recoverable resources.

Source: IEA analysis based on Rystad Energy data.

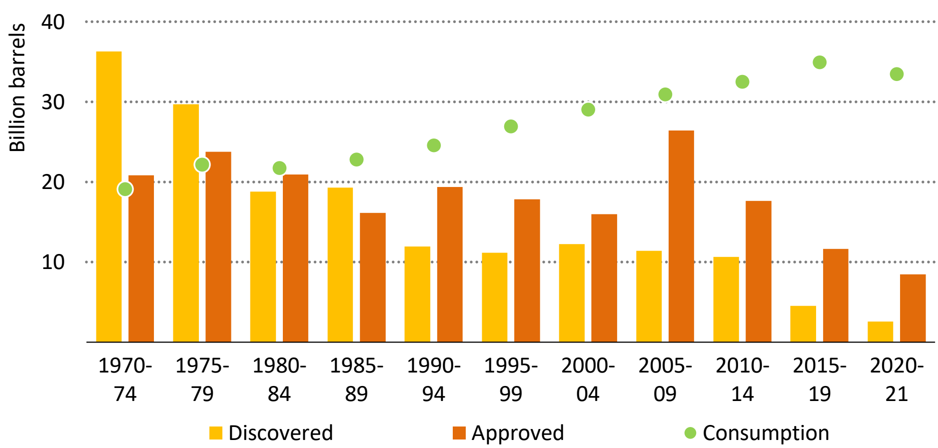
The time required to develop a new conventional oil project can vary substantially and depends on factors such as regulatory oversight and management, political stability, subsurface complexity and whether new facilities and export connections need to be constructed. For conventional upstream projects that have started production since 2010, it took on average around six years from the award of an exploration licence to discovery; nine years from discovery to project approval; and just over four years from approval to first production (Figure 7.13). It then took a further three to five years for projects to ramp up to their maximum level of production after they started producing. Companies have recently tried to focus on projects that can be brought to market relatively quickly. For example,

[5] The point at which a project undergoes its FID is also known as the project "receiving development approval".

offshore projects that started operation since 2019 have taken less than five years to go from approval to start up compared with eight years for similar projects that started up in 2016.

Since the oil price crash in 2014, exploration activity and levels of discoveries have been at historic lows, and relatively few conventional oil projects are now available to be developed (Figure 7.14). Any already-discovered resources that are approved for development could bring some oil to the market within the next few years, but they are unlikely to make an immediate major contribution to the global oil balance. Resources that have not yet been discovered are unlikely to make a meaningful contribution to alleviating the current energy crisis.

Figure 7.14 ▷ Annual average resources discovered, approved for development and consumed since 1970



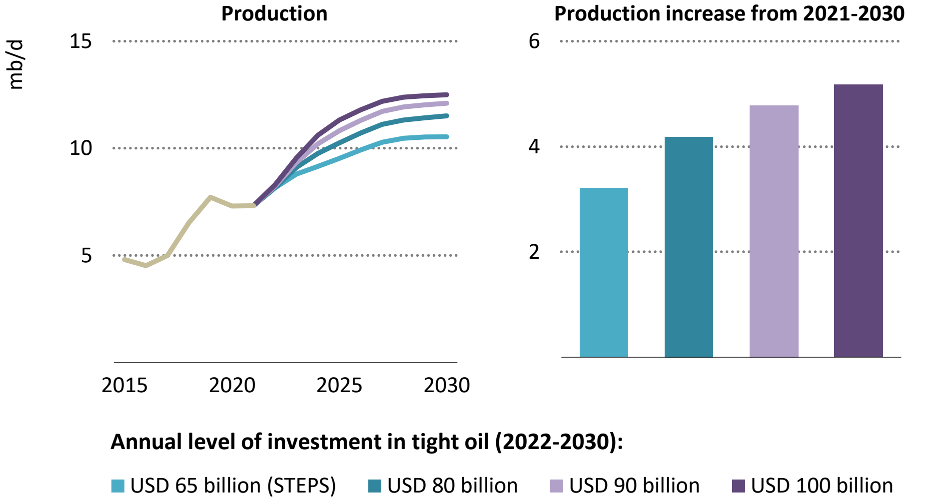
Resource discoveries and new approvals have been at historic lows in recent years and the pipeline of projects available to be developed is now small

Tight oil and OPEC spare capacity

Tight oil has been a key source of new production in recent years, and it met around 85% of the overall increase in global oil supply between 2015 and 2019. It can take as little as three months for a tight oil operator to move from securing development approval to the start of production and tight oil wells produce around 80% of their cumulative production in the first two years of production (compared with less than 10% for conventional wells). However, annual production dipped in 2020 and only rose slightly in 2021 as operators focussed on profitability and capital discipline rather than production growth (Figure 7.15).

In the STEPS, US tight oil production increases by around 3 mb/d over the next five years and annual average investment is around USD 65 billion, which is broadly similar to investment levels between 2015 and 2020. If prices were to be higher than in the STEPS or operators were to focus more on growth, this could lead to a higher level of spending. Without some easing of current tight supply chains, however, any such increases in activity could exacerbate the cost inflation currently being experienced by the industry in the United States.[6] If annual investment were to average USD 100 billion over the period to 2030 – which would be the highest annual level of investment seen in recent years – we estimate that US tight oil production could increase by around 5 mb/d to 2030.

Figure 7.15 ▷ US tight oil production at different levels of investment



Increases in tight oil will be essential to balance demand to 2030: higher investment levels than in the STEPS could lead to more growth, but risks exacerbating cost inflation

Notes: Includes tight crude oil and tight condensate volumes.

Tight oil in other countries also has some scope for growth, but it is limited in scale. Canadian shale plays are generally more suited to natural gas than oil production, though the sector could scale up oil production from plays such as the Duvernay-Montney. Argentina also has scope to increase tight oil output: in the STEPS, its production rises by just under 150 kb/d within the next five years. Tight oil resources also exist in a number of other countries, including Saudi Arabia, United Arab Emirates and China, but new production from these countries is unlikely to contribute meaningful volumes in the immediate future.

OPEC has sustainable crude oil production capacity of around 34 mb/d and produced 28.5 mb/d in the first half of 2022 (a utilisation rate of 84%). Production by OPEC has not exceeded 94% of its capacity since 2000, and a number of countries might struggle to

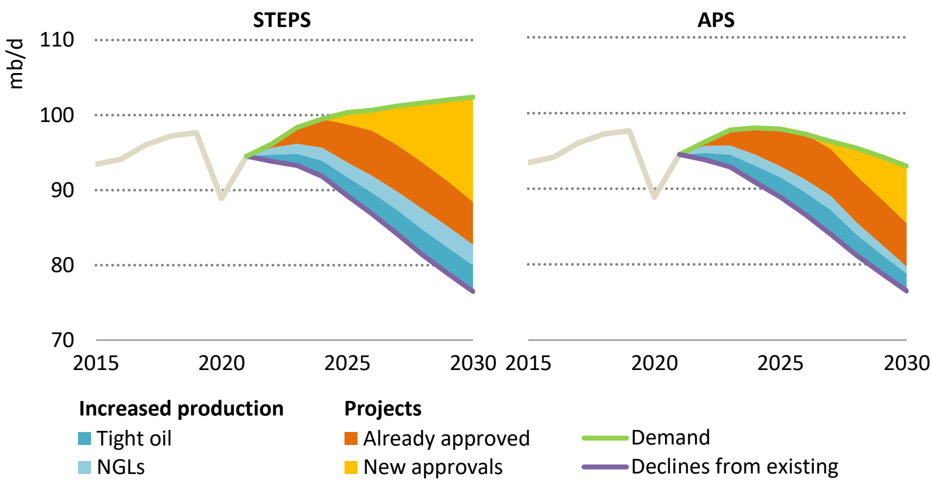
[6] Costs for tight oil production increased by around 15% between 2019 and 2022, mainly because of increases in steel, steel products, aluminium and other raw materials prices (IEA, 2022b).

produce as much oil as they are supposed to be capable of delivering (nameplate capacity). In addition, political unrest in Libya and long-term sanctions on Venezuela and Iran have severely impacted the ability of those countries to maintain production levels over the last decade. It might therefore be a struggle for members of OPEC to produce considerably more than current volumes.

How much new oil supply is needed?

In assessing future supply needs, a key consideration is the level of projected decline in production from existing sources of supply. As fields mature and projects reach the end of their lives, existing sources of oil supply are expected to decline by around 18 mb/d to 2030. Some of this drop is likely to be offset by conventional projects approved for development in recent years, including in Brazil, Saudi Arabia and United States, and these are set to provide around 6 mb/d of new production by 2030. Some increases in NGLs are also likely as a result of changes in natural gas production.

Figure 7.16 ▷ Contribution of increased production of tight oil and NGLs, and new and approved projects in the STEPS and APS



Although tight oil is set to grow strongly, declining output from existing sources of production means new conventional projects are essential in both the STEPS and APS

Note: Already approved = fields that have received an FID, but were not producing at the beginning of 2022.

The trajectory of oil demand is the final element in determining new supply needs. In the STEPS, oil demand rises by 8 mb/d to 2030. Without new long lead time conventional projects, this would mean a major shortfall in supply from the mid-2020s (Figure 7.16). In the APS, global demand peaks in the near future and starts to decline. Conventional upstream projects remain essential to ensure a smooth match between supply and demand: without them, a significant shortfall in supply would emerge by the late-2020s. In the NZE Scenario, demand falls by nearly 20 mb/d to 2030 and no new conventional oil projects need to be approved for development (Table 7.6).

Table 7.6 ▷ Average annual upstream oil investment by scenario

		STEPS		APS		NZE	
	2021	2022-30	2031-50	2022-30	2031-50	2022-30	2031-50
Existing fields	142	216	191	212	137	243	120
New fields	94	189	171	117	62	18	0
Tight oil	70	62	50	53	25	42	5
Total	**305**	**466**	**411**	**382**	**225**	**302**	**126**

Notes: New fields include fields that have received an FID but were not producing at the beginning of 2022, and new approvals.

New long lead time and long-lived conventional projects still carry a number of risks, even if they are needed in the STEPS and APS. They could lock in fossil fuel use that would prevent the world from meeting its climate goals or they could fail to recover their upfront development costs if the world is successful at bringing down demand quickly enough to reach net zero emissions by mid-century. Governments and developers can mitigate some of these risks by ensuring that new projects result in as few direct emissions as possible, for example by ensuring there are no methane leaks, that there is no flaring, that low-emissions options are used to power operations, and that new project developments are linked to CCUS.

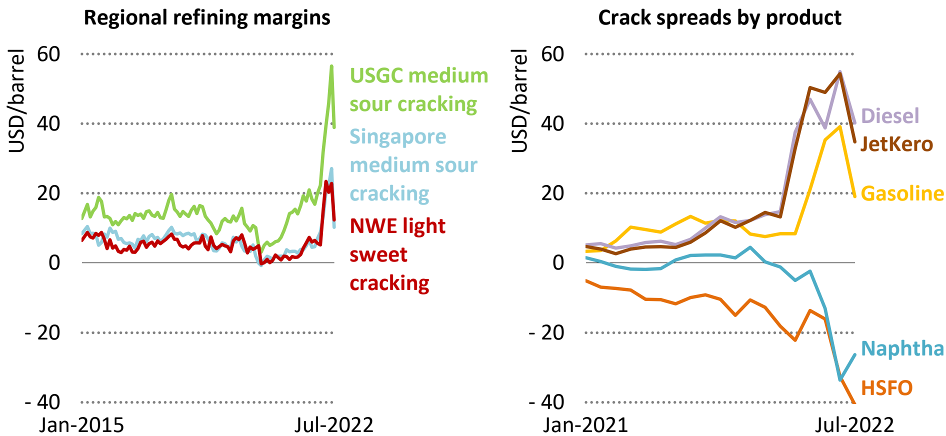
7.10 Refining: immediate and longer term challenges

Immediate challenges: Tightness in product markets and reduced Russian exports

A strong rebound in oil consumption in 2021 following the global Covid pandemic coincided with the first net reduction in capacity in 30 years in the refining sector. New capacity was added in China and the Middle East, but this was surpassed by 1.8 mb/d of capacity retirements. There have also been reduced product exports from Russia and China. Refining margins have surged to record highs in the wake of these developments.

Two other important developments are currently in train. First, oil product exports from Russia, which decreased by 600 kb/d between February and June 2022 as a result of sanctions, are set to decline further when the recently agreed European Union import ban comes into force in 2023. Russia does not play a significant role in gasoline and kerosene markets but it is currently one of the largest exporters of diesel, naphtha, fuel oil, and refinery feedstocks. Second, China has set an explicit goal of phasing out refined product exports by 2025 to reduce emissions from the refining sector. Chinese refined product exports so far in 2022 are 45% below pre-pandemic levels.

Figure 7.17 ▷ Regional refining margins and crack spreads by product



A strong rebound in demand and a reduction in global refining capacity contributed to the recent extraordinary rise in refining margins and crack spreads for transport fuels

Notes: USGC = US Gulf Coast; NWE = northwest Europe. JetKero = jet kerosene; HSFO = high sulphur fuel oil. Product crack spreads are based on northwest Europe indices.

Together with much lower inventories, these factors have combined to create a very tight market. Oil product differentials have risen to record highs across premium transport fuels such as diesel, gasoline and kerosene (naphtha and high sulphur fuel oil have not exhibited the same trends due to weak industrial growth) (Figure 7.17). Product crack spreads fell slightly in July 2022, but they still remain much higher than in the past, especially for middle distillates such as diesel and kerosene.

As things stand, there are few supply-side measures that could tackle the immediate tightness in product markets. One option would be to bring back mothballed refining capacity located in the Atlantic Basin, but this would require major financial commitments and a significant amount of time for repair work. Supply-side tensions may start easing in 2023 as new refineries in Mexico and Nigeria come online[7] and expansion projects in the United States and the Middle East are completed. However, with reduced Chinese and Russian product exports, the global refining system is likely to remain tight for several years to come if middle distillates demand (diesel and kerosene) keeps rising at the current rapid rate.

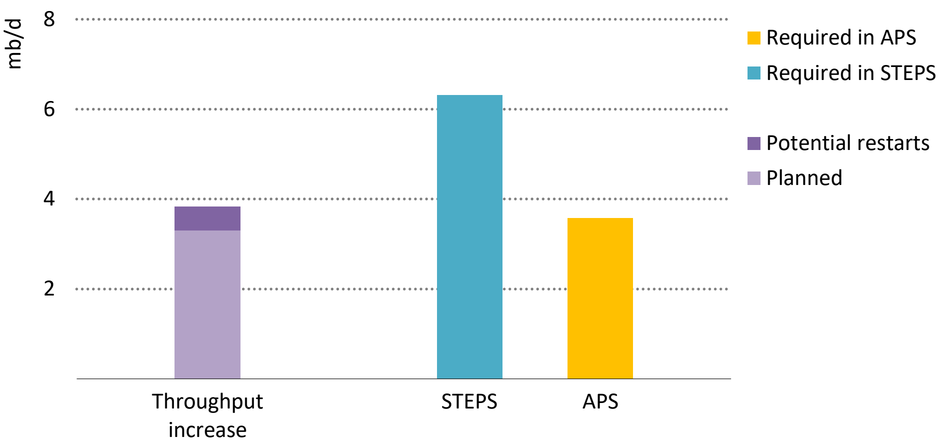
In the STEPS, middle distillates demand (excluding biodiesel, renewable fuels, coal-to-liquids and gas-to-liquids) increases by 2.6 mb/d between 2022 and 2025. Without yield adjustments, this would require more than 6 mb/d of refinery throughput growth (on

[7] Mexico and Nigeria have also initiated rehabilitation programmes to restart mothballed refining assets and increase utilisation rates, although securing financing remains a major hurdle.

average, one barrel of incremental refinery throughput can produce up to 0.3-0.5 barrels of middle distillates). This compares with a likely net capacity increase of 4.2 mb/d over the next three years. Refineries that are currently operating have largely maximised their capacity utilisation, implying that refinery processing may lag behind demand growth. There is some flexibility in the refining system to shift yields from other products to diesel and kerosene as gasoline demand flattens but this may not be enough to plug the remaining gap in middle distillates supply. This brings into sharp focus the importance of demand-side measures to ease product supply tensions.

In the APS, strong policy measures to reduce the use of diesel and kerosene and to revamp idled capacity bring about a significant reduction of the tightness in the middle distillate market (Figure 7.18).

Figure 7.18 ▷ Expected refining throughput growth and required throughput increase to meet middle distillate demand, 2022-2025



Reductions in demand for middle distillates are needed to ease product supply tensions in the coming years

Note: Projected capacity and throughput increase do not include additional yield adjustments. Refineries are assumed to yield 42% of middle distillates.

The effects of sanctions and embargoes on Russian oil trade flows are a key variable that could affect global oil markets in the coming years. Even before Russia's invasion of Ukraine, global oil markets were in a highly volatile phase. Inventories were low after draws since the second-half of 2020, and capacity constraints in the refining sector magnified the impact of supply-demand fundamentals on product prices.

Russia accounted for around 12% of global crude oil and 15% of oil products trade in 2021. Since the invasion, oil markets have had to deal with major changes to global crude oil and product flows in a very short period of time. The United States, Canada, Australia and the

United Kingdom announced plans to ban imports of crude oil and certain oil products from Russia. The European Union, which last year took 35% of its net oil imports from Russia, has also imposed a ban, but has allowed for a six-month phase-in period for crude oil (expiring in December 2022) and eight months for oil products imports (expiring in February 2023). Crude oil imports into Hungary, Slovakia and the Czech Republic via the Druzhba pipeline, seaborne crude oil imports into Bulgaria and refinery feedstock imports into Croatia were given exceptions. These account for 10% of pre-sanction import volumes from Russia. The European Union is also in the process of banning maritime insurance for vessels transporting Russian oil to third countries.

Despite the sanctions already in place, and a fall in Russian exports to the European Union in advance of sanctions there coming into effect, overall Russian crude oil export volumes have not yet dropped significantly. This points to a reallocation of trade flows. Between February and August 2022, India increased Russian crude oil purchases from 0.1 mb/d to 1 mb/d and China increased imports of Russian oil from about 1.6 mb/d to close to 2 mb/d. Given that their combined crude oil import requirements amount to 15 mb/d, there is further scope for both India and China to increase imports of Russian crude oil if they choose to do so. Whether India and China will choose to continue to do so depends on several factors, including geopolitical considerations. Smaller Asian importers may also choose to import some Russian crude oil. A complete cessation of Russian crude oil imports by the European Union would mean that it needs to find around 1.6 mb/d of crude oil from alternative sources in addition to volumes that have already been replaced.

Any reallocation of trade in oil products is likely to be more challenging than for crude oil, not least because oil products trade involves complex operations including storage and blending. No meaningful geographical reallocation of oil product flows has yet taken place. China and India are both oil product exporters and therefore are unlikely to be interested in Russian product imports, while many smaller product importers are likely to find it difficult to negotiate, finance and manage the logistics of long-distance products trade. Russia was also undertaking a refinery modernisation programme to increase yields of gasoline and diesel, but this could see significant delays as sanctions on the provision of refinery technology, catalysts and maintenance services come into effect. Meanwhile the European Union will need to ramp up purchases from alternative providers when its ban on Russian product imports comes into force, and it is likely to turn to the United States, the Middle East and India for these purchases. This will reduce oil product flows to Latin America and Africa and potentially redirect Russian volumes towards these regions.

The ban on maritime insurance could also have a major impact on oil products trade. Most maritime trade insurers and reinsurers are domiciled in the European Union, so the ban could in effect prevent Russian cargo carriers from obtaining insurance. In the past, China and India have provided sovereign insurance for other sanctioned crude oil imports, notably of Iranian oil. However, there are unlikely to be other counterparties in products trade with the same level of financial and operational strength as China and India. If the ban causes the cessation of Russian seaborne oil product exports, this could further strain global product markets.

Western governments are currently considering whether to relax the maritime insurance ban for Russian oil as long as the deals are concluded under a price cap mechanism that aims to curb Russian revenues while allowing oil to flow to international markets.

Longer term challenges: Adapting business models in a decarbonising world

Table 7.7 ▷ World liquids demand by scenario (mb/d)

			STEPS			APS		
	2020	2021	2030	2040	2050	2030	2040	2050
Total liquids	**90.9**	**96.7**	**105.8**	**107.5**	**107.6**	**98.7**	**82.8**	**69.6**
Biofuels	2.0	2.2	3.4	4.6	5.3	5.5	8.7	9.2
Low-emissions hydrogen-based fuels	0.0	0.0	0.0	0.1	0.2	0.2	1.2	3.2
Total oil	**88.9**	**94.5**	**102.4**	**102.8**	**102.1**	**93.0**	**72.9**	**57.2**
CTL, GTL and additives	0.8	0.9	1.1	1.3	1.3	1.0	0.7	0.3
Direct use of crude oil	1.0	0.8	0.5	0.4	0.3	0.4	0.3	0.2
Oil products	**87.1**	**92.8**	**100.8**	**101.1**	**100.5**	**91.6**	**71.9**	**56.7**
LPG and ethane	13.3	13.6	15.6	16.2	15.8	14.4	12.4	10.4
Naphtha	6.4	6.9	7.7	8.6	9.5	7.3	7.4	7.4
Gasoline	21.9	23.6	23.2	21.4	19.3	20.6	13.1	8.2
Kerosene	4.7	5.7	9.2	10.3	11.8	8.7	8.0	7.6
Diesel	25.0	26.5	28.2	28.4	28.2	25.0	18.3	12.6
Fuel oil	5.7	5.9	5.5	5.6	6.3	4.8	3.4	2.5
Other products	10.1	10.6	11.4	10.6	9.6	10.8	9.3	8.0
Fractionated products from NGLs	11.3	11.5	13.4	12.1	11.6	12.7	10.1	8.8
Refinery products	75.8	81.3	87.4	89.0	88.9	78.9	61.8	47.9
Refinery market share	83%	84%	83%	83%	83%	80%	75%	69%

Notes: CTL = coal-to-liquids; GTL = gas-to-liquids; NGLs = natural gas liquids; LPG = liquefied petroleum gas. See Annex C for definitions.

While the refining sector has seen record margins and high utilisation rates in 2022, recent trends may not be a good guide to the future. Gasoline, diesel and kerosene accounted for around three-quarters of total oil demand growth between 2020 and 2022 as economies recovered from the Covid-19 pandemic, while demand for petrochemical feedstocks remained subdued. However, the APS and the NZE Scenario see major changes in the composition of oil product demand in the years ahead, and these require refiners to adapt their configuration and business models (Table 7.7). The share of petrochemical feedstocks such as ethane, LPG and naphtha rises from around 20% of total oil demand today to 30% in 2050 in the APS and to 55% in the NZE Scenario. The share of middle distillates remains around the current level in the APS and halves to 15% by 2050 in the NZE Scenario as electrification and alternative fuels are increasingly adopted in trucks, ships and planes. The share of gasoline falls in both scenarios.

American and European refineries have recently been operating at high utilisation rates and accounted for 45% of the growth in refinery throughput between 2020 and 2022. In the APS and NZE Scenario, however, they lose market share to new refiners in developing economies in Asia and the Middle East. The share of the global refining market accounted for by traditional refining centres (North America, Europe and advanced economies in Asia) shrinks from over 40% today to around 30% by 2050 in the APS and to a quarter in the NZE Scenario (Table 7.8).

Table 7.8 ▷ Refining capacity and runs by region and scenario (mb/d)

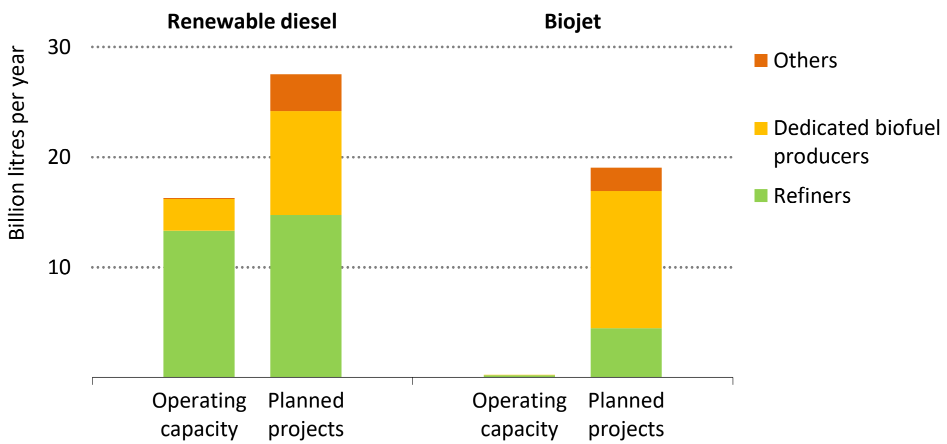
	Refining capacity					Refinery runs				
		STEPS		APS			STEPS		APS	
	2021	2030	2050	2030	2050	2021	2030	2050	2030	2050
North America	21.6	21.1	20.8	20.1	11.1	17.6	18.5	18.1	16.5	7.5
Europe	15.8	14.5	13.3	14.0	6.9	12.0	11.4	9.4	10.2	3.9
Asia Pacific	37.1	40.3	41.5	39.4	28.3	29.2	33.1	34.7	30.5	18.9
Japan and Korea	6.9	6.3	5.8	6.2	3.5	5.2	5.0	4.6	4.6	2.2
China	17.5	19.0	19.0	18.5	11.1	14.2	14.5	14.1	13.4	6.4
India	5.3	6.6	7.8	6.4	5.4	4.8	6.4	7.6	5.7	4.0
Southeast Asia	5.3	6.3	6.8	6.3	6.3	3.7	5.5	6.4	5.1	4.7
Middle East	9.6	11.2	12.0	11.0	9.7	7.6	9.6	10.6	8.5	6.6
Russia	6.9	6.5	6.3	6.1	4.6	5.6	4.0	3.5	3.6	2.4
Africa	3.4	4.5	4.8	4.2	4.2	1.8	3.1	3.9	2.7	2.6
Brazil	2.2	2.3	2.3	2.0	1.6	1.8	2.1	2.2	1.7	1.2
Other	4.6	4.8	4.8	4.7	4.2	2.3	2.9	3.5	2.8	2.6
World	**101.2**	**105.2**	**105.8**	**101.5**	**70.6**	**77.9**	**84.7**	**85.9**	**76.5**	**45.7**
Atlantic Basin	54.1	53.6	52.2	51.0	32.5	40.9	41.9	40.4	37.3	20.1
East of Suez	47.1	51.6	53.6	50.5	38.1	37.0	42.9	45.5	39.1	25.6

Note: Capacity at risk can be found in the online Annex.

Despite today's scramble for oil products, the APS and the NZE Scenario imply longer term pressures for refiners. In the APS, more than half of current refining capacity faces the risk of lower utilisation or closure by 2050, and there are few new capacity additions after projects under construction come online. Those refiners that survive invest to reduce emissions from refining operations, notably via low-emissions hydrogen, CCUS and efficiency improvements.

Many refiners are looking to expand into liquid biofuels, plastic recycling and low-emissions hydrogen to secure new revenue streams. Some refiners have also been actively participating in the production of renewable diesel through co-processing, facility conversion or building new facilities. Traditional refiners, such as TotalEnergies, Eni, Neste and Valero, currently own the majority of operating capacity for renewable diesel, and they also account for a sizeable share of planned capacity (Figure 7.19). This is the case for sustainable aviation fuels as well, although there are now a growing number of dedicated producers. The interest shown by refiners in producing these fuels has been driven by policy measures, including the EU Renewable Energy Directive and the US Blenders Tax Credit, and by the lower capital requirements involved. For example, TotalEnergies is now converting its Grandpuits refinery in France to a bio-refinery because this requires less capital than would be needed to maintain and repair the existing facility. There is also growing interest in chemical plastic recycling and waste-to-feedstock technologies. For example, OMV took a final investment decision at the end of 2021 to expand its pilot plastic waste-to-crude recycling plant at its Schwechat refinery in Austria.

Figure 7.19 ▷ Operating and planned production capacity for renewable biodiesel and biojet fuels by company type



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Refiners are increasingly expanding into the biofuels supply chain, representing around 80% of today's production capacity and over half of planned renewable diesel projects

Today, most investment by refiners is for maintenance, upgrades and expansion into the chemical sector. In the APS and the NZE Scenario, however, emissions reductions, hydrogen, biofuels and plastic recycling account for an increasing share of overall investment. The feedstock landscape is also likely to be more diverse, as an exclusive focus on crude oil widens to encompass biomass and wastes. Looking beyond immediate market conditions, there are growing signs that refiners are going to have to redefine their business model before too long.

Outlook for gaseous fuels

Is natural gas losing steam?

SUMMARY

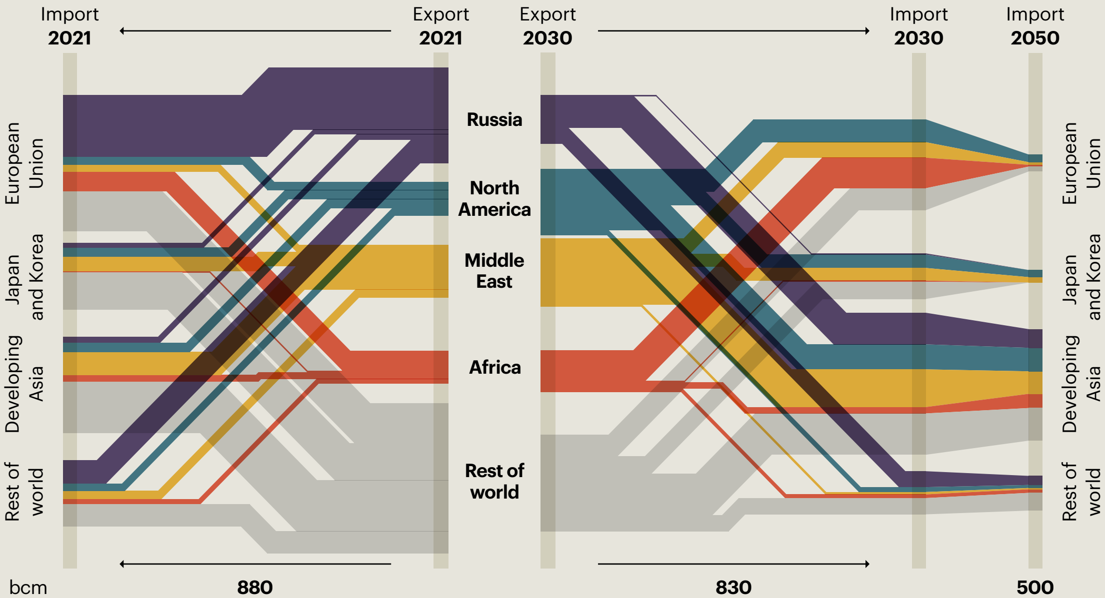
- The traditional arguments in favour of natural gas have focused on its role as a reliable partner for the clean energy transition and its ability to step in to fill the gap left by declining coal and oil. These are currently being tested by the global repercussions of Russia's actions in Europe. In the midst of a global energy crisis, fundamental questions are now being asked about natural gas: how can supply be assured, now and in the future, and at what price?
- The depth and intensity of today's crisis have led to concerns about the future cost and availability of natural gas which have damaged confidence in its reliability and put a major dent in the idea of it serving as a transition fuel. As a result, the era of rapid global growth in natural gas demand is drawing to a close. In the Stated Policies Scenario (STEPS), demand rises by less than 5% between 2021 and 2030, compared with a 20% rise between 2011 and 2020. It then remains flat from 2030 at around 4 400 billion cubic metres (bcm) through to 2050, with growth in emerging market and developing economies offset by declines in advanced economies. In the Announced Pledges Scenario (APS), demand soon peaks and is 10% lower than 2021 levels by 2030. In the Net Zero Emissions by 2050 (NZE) Scenario, demand falls by 20% to 2030, and is 75% lower than today by 2050.
- Global natural gas demand in 2050 in this year's version of the STEPS is 750 bcm lower than projected in last year's version. Half of this downward revision comes from more rapid moves away from unabated natural gas consumption in advanced economies. The United States alone accounts for one-third of the total downward revision: its recent Inflation Reduction Act is set to speed up the deployment of renewables in the power sector and to provide stronger support for efficiency and heat pumps in buildings. The other major downward revision comes from price-sensitive emerging market and developing economies, where high natural gas prices mean that prospects for coal-to-gas switching are now more muted.
- Russian pipeline gas exports to the European Union more than halved over the last year to an estimated total of 60 bcm in 2022. They decline by an additional 45 bcm in the STEPS by 2030, and fall to zero in the APS. Additional liquefied natural gas (LNG) and non-Russian pipeline gas play important roles in making up the shortfall in both scenarios, but the APS sees a stronger surge in wind and solar capacity additions and a bigger push to retrofit buildings and install heat pumps: these help to bring EU natural gas demand down by 40%, or 180 bcm, between 2021 and 2030. The annual investment cost of USD 65 billion is offset over time by lower gas import costs.
- Europe's drive to reduce reliance on Russian imports and a dearth of new gas export projects mean that natural gas prices in importing regions remain high over the next few years in the STEPS and APS, especially in Europe. In the NZE Scenario, rapid

demand reductions in all regions ease the strains on global supplies, and gas import prices fall quickly. Prices come down more gradually in the STEPS and APS from the mid-2020s as gas demand flattens and new supply projects currently under construction come onstream. Declines in domestic demand in the United States open opportunities for higher LNG exports; in both the STEPS and APS, the United States soon overtakes Russia to become the world's largest natural gas exporter.

- Natural gas demand growth in China slows considerably in the STEPS, falling to 2% per year between 2021 and 2030, compared with an average growth rate of 12% per year between 2010 and 2021. Large volumes of LNG have been contracted for the next fifteen years: together with expected supply from existing pipelines and new domestic projects, these more than cover China's demand requirements in the STEPS to 2035.
- High gas prices have dampened prospects for coal-to-gas switching, but they have not extinguished them. In emerging and developing markets in Asia, long-term gas import contracts with prices indexed to oil offer partial protection to consumers from high and volatile gas prices, and in some cases this is buttressed by domestic subsidies. A growing population and robust economic development provide a strong foundation for growth: gas demand in the APS in these emerging markets in Asia rises by 20% to 120 bcm in 2030. Around 70% of this growth is met by imported LNG.
- Rising natural gas demand in parts of Asia alongside European Union efforts to import non-Russian gas underpin LNG demand growth in all scenarios until the mid-2020s, but there are sharp divergences thereafter. In the STEPS, an additional 240 bcm per year of export capacity is needed by 2050 over and above projects already under construction. In the APS, only projects currently under construction are required. In the NZE Scenario, a sharp decrease in natural gas demand globally means that even these projects are in many cases no longer necessary. This highlights a key dilemma for investors considering large, capital-intensive LNG projects: how to reconcile strong near-term demand growth with uncertain but possibly declining longer term demand.
- There are no easy options for Russia in its search for new markets for the gas it was exporting to Europe. Sanctions undercut the prospects for large new Russian LNG projects, and long distances to alternative markets make new pipeline links difficult. In the APS, Russia's share of internationally traded gas, which stood at 30% in 2021, falls by 2030 to less than 15%, and its net income from gas exports (revenue minus costs) falls from USD 75 billion in 2021 to USD 25 billion in 2030.
- Prospects for low-emissions gases look bright. In the APS, low-emissions hydrogen production rises from low levels today to over 30 million tonnes (Mt) per year in 2030. This is equivalent to over 100 bcm of natural gas. The APS also sees a rise in biomethane production that reflects the ambitious targets now being established. Governments have a key co-ordinating role to play in the growth of low-emissions gases, in particular in setting standards and ensuring reliable, long-term demand. At the moment, the 24 Mt per year of projects seeking to export hydrogen or hydrogen-based fuels are running ahead of plans for the corresponding import infrastructure.

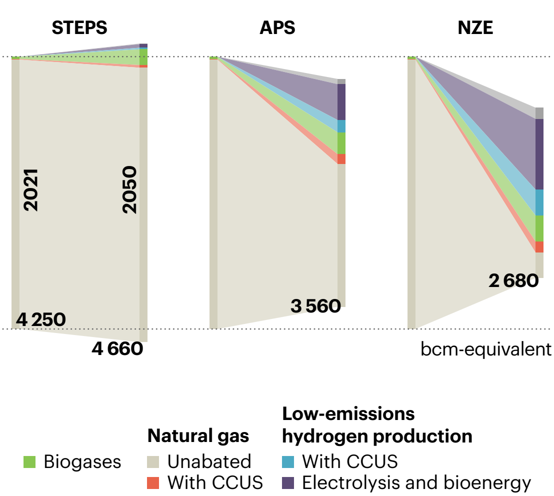
How will global natural gas trade evolve in the APS?

Today's turbulence in gas markets reshapes global gas trade. Russia's exports dwindle and the European Union competes with countries in Asia for LNG supplies. Demand for LNG in Europe then falls steadily as it moves away from gas to meet its climate goals. Developing Asia is the main destination for exports in 2050.



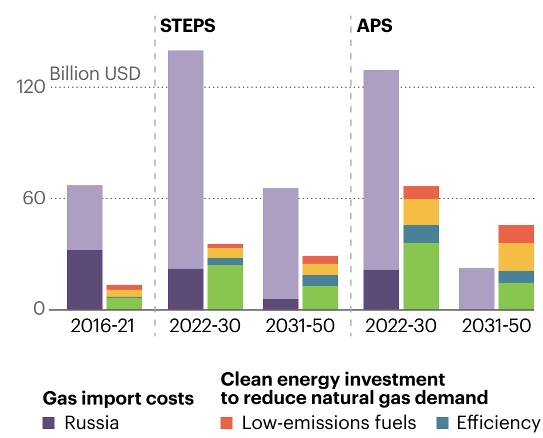
Natural gas may be running out of steam...

The era of rapid growth in natural gas demand is drawing to a close, but doors are opening for low-emissions gases, which get a boost in the APS and flourish in the NZE scenario.



What price tag for reduced EU dependence on natural gas?

In the APS, the European Union doubles down on clean energy, spending USD 65 billion per year to bring natural gas demand down by 60% by 2030. These investments are offset over time by much lower gas import costs.



Introduction

Global demand for natural gas held up better than demand for other fossil fuels during the first year of the Covid-19 pandemic, and then increased by 5% in 2021, double its average growth rate over the past decade. A dearth of new projects, weather-related increases in demand, LNG outages and reduced Russian exports tightened the global gas supply balance from mid-2021 and put upward pressure on prices, especially in Europe where the Title Transfer Facility (TTF) benchmark rose from less than USD 10 per million British thermal units (MBtu) in the first-half of 2021 to over 30 USD/MBtu by December 2021.

Russia's invasion of Ukraine in February 2022 had a huge impact on an already fragile global gas balance. European Union efforts to fill gas storage ahead of the winter have run up against Russia's strategic withholding of gas supply and the prospect of possible supply shortages bringing high levels of market volatility and exceptionally high prices. Europe's TTF benchmark price saw peaks exceeding USD 90/MBtu in 2022, even as the European Union and its partners debate ways to reduce reliance on Russian gas and curtail its revenue from energy sales. The strains on gas supply have also led to energy shortages in several parts of the developing world that rely on imported gas, notably Pakistan and Bangladesh. Major growth markets for gas such as India and China have meanwhile sharply reduced their LNG imports in 2022.

Amid a scramble to squeeze supply out of existing fields and maximise the use of export and import facilities, the crisis has prompted policy discussions about reforming gas markets, better managing supply shortfalls and shielding customers from high and volatile prices. Such issues inevitably involve consideration of the role of natural gas in energy transitions and the contractual structures that might accommodate various visions of the future role of gas.

This chapter examines what our scenarios imply for the future of natural gas. All the scenarios take account of the current gas crisis, while also looking ahead to the longer term. In the Stated Policies Scenario, natural gas demand grows less than 5% over the remainder of the decade, reaching 4 400 bcm in 2030. In the Announced Pledges Scenario, demand plateaus and drops below 4 000 bcm in 2030. In the Net Zero Emissions by 2050 Scenario, demand drops rapidly to around 3 300 bcm in 2030.

Against the backdrop of these three very different views of the future, this chapter also examines three key issues that will shape the future not just of natural gas, but all gaseous fuels:

- **What now for the natural gas balance in the European Union?** What impact will the current crisis have on pipeline and LNG flows, and domestic production in Europe and beyond?
- **What are the prospects for hydrogen?** Interest in low-emissions hydrogen is higher than ever, but what needs to happen to get international hydrogen trade up and running?
- **How long a transition role for natural gas?** How has the crisis affected the prospects for gas in emerging market and developing economies in Asia?

Scenarios

8.1 Overview

Table 8.1 ▷ Global gases by scenario (bcme)

			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Total gas demand	**3 351**	**4 248**	**4 456**	**4 661**	**4 069**	**3 568**	**3 666**	**2 681**
Natural gas demand	**3 329**	**4 213**	**4 372**	**4 357**	**3 874**	**2 661**	**3 268**	**1 159**
Power	1 345	1 633	1 590	1 469	1 422	880	1 177	119
Industry	701	882	1 003	1 116	891	644	802	213
Buildings	757	886	890	852	737	372	486	-
Transport	108	147	159	172	126	58	99	12
Low-emissions H_2 production inputs	-	1	10	32	41	266	145	566
Other	417	664	720	717	658	441	559	248
Natural gas abated with CCUS	*2*	*12*	*24*	*74*	*103*	*420*	*223*	*738*
Losses from low-emissions H_2 production	-	-	*3*	*10*	*13*	*82*	*45*	*175*
Natural gas production	**3 274**	**4 149**	**4 372**	**4 355**	**3 878**	**2 660**	**3 264**	**1 178**
Conventional gas	2 768	2 964	2 962	3 025	2 731	2 016	2 292	827
Unconventional gas	506	1 185	1 410	1 329	1 147	644	972	351
Natural gas trade	**641**	**878**	**944**	**991**	**833**	**497**	**667**	**224**
LNG	275	450	559	649	545	324	443	153
Pipeline	366	428	385	342	288	173	224	71
Low-emissions H_2 demand	**-**	**1**	**21**	**81**	**100**	**752**	**299**	**1 509**
Power	-	-	1	2	14	63	91	200
Industry	-	-	7	20	36	248	84	451
Buildings	-	-	-	3	6	30	10	40
Transport	-	-	2	25	11	158	38	396
Input for H_2 based fuels	-	-	1	11	19	229	60	395
Other	-	1	10	20	15	24	16	27
Low-emissions H_2 production	**.**	**1**	**21**	**81**	**100**	**752**	**299**	**1509**
Fossil fuel-based (with CCUS)	-	1	8	25	29	192	103	406
Electrolytic	-	-	13	56	70	557	195	1 097
Bioenergy-based	-	-	-	-	1	4	1	7
Biogas demand	**22**	**35**	**70**	**244**	**123**	**339**	**199**	**404**
Biogas	21	27	46	102	58	142	59	138
Biomethane	1	8	24	143	65	197	140	267

Notes: bcme = billion cubic metres equivalent; H_2 = hydrogen; CCUS = carbon capture, utilisation and storage; STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Values are reported in bcm equivalent (bcme) accounting for energy per unit of volume of low-emissions gases. Total gas demand includes the total demand for gaseous fuels by users, including power and other transformation sectors, net of any conversions between different gaseous fuels, such as from natural gas to low-emissions hydrogen or low-emissions hydrogen to synthetic methane. Natural gas use in industry includes onsite hydrogen production. Production and demand volumes differ due to stock changes and international bunkers. World trade reflects net trade between regions modelled in the *World Energy Outlook* and therefore excludes intra-regional trade. Other for natural gas demand includes other non-energy use, agriculture and other energy sector. Other for hydrogen demand includes use in refineries, agriculture and biofuels production. See Annex C for definitions.

In the **Stated Policies Scenario** (STEPS), natural gas demand rises at an average rate of 0.4% per year between 2021 and 2030, well below the 2.2% average rate of growth seen between 2010 and 2021 (Table 8.1). Demand reaches 4 400 bcm in 2030 and stays at that level to 2050. A variety of drivers have led to the downward revision in this year's STEPS compared to the *World Energy Outlook 2021 (WEO-2021)*; the global supply squeeze has led to record high prices in several gas markets around the world and the balance is not expected to ease until mid-decade, when large new LNG exports come onstream. This has dampened prospects for demand growth in several emerging gas markets in Asia, and accelerates European efforts to reduce gas demand. There is a faster increase in renewables deployment, a larger uptake of other flexibility options in the power sector, and an acceleration in efficiency, all boosted in particular by the passage of the Inflation Reduction Act in the United States. Coupled with a downward adjustment to GDP growth, global gas demand is 750 bcm lower by 2050 than projected in the *WEO-2021*.

In the **Announced Pledges Scenario** (APS), global natural gas demand soon peaks, and by 2030 is nearly 10% lower than it was in 2021. A modest net increase in demand in emerging market and developing economies between 2021 and 2030 is more than offset by reductions in advanced economies, where gas is gradually replaced by renewables and offset by efficiency gains, notably in the buildings sector. The European Union reduces its natural gas demand by nearly 45% to 2030, easing the task of reducing dependence on Russian imports. By 2050, global natural gas demand is 40% below 2021 levels. Low-emissions gases – hydrogen, biogases and synthetic methane – reach more than 1 000 billion cubic metre equivalent (bcme)[1] by 2050, accounting for almost one-third of total gaseous fuel demand.

In the **Net Zero Emissions by 2050** (NZE) **Scenario**, natural gas demand is over 900 bcm lower in 2030 than in 2021, a drop of around 20%. By 2050, unabated natural gas meets less than 15% of total demand for gaseous fuels; low-emissions gases account for over 70% of total gaseous fuel demand and natural gas used either for non-combustion purposes or equipped with carbon capture, utilisation and storage (CCUS) for the remainder. Around 500 bcm of natural gas is used with CCUS to produce low-emissions hydrogen in 2050, providing around 25% of total hydrogen demand (with most of the rest produced from electrolysis).

Inter-regional natural gas trade increases by 65 bcm in the STEPS between 2021 and 2030, a rate of growth which is one-fifth of the levels of the last five years. An average of 20 bcm per year of new LNG export capacity comes online between 2022 and 2024, well below historical rates of around 35 bcm per year. LNG imports to the European Union double to over 150 bcm by 2025, helping to offset a reduction by over 100 bcm of Russian pipeline supply to the European Union. LNG increases by 90 bcm between 2030 and 2050, even as total global gas demand contracts slightly over the same period. In the APS, global gas trade peaks in the mid-2020s and falls to 470 bcm in 2050, half of 2021 levels. In the NZE Scenario, global gas trade much peaks sooner, and falls to less than 300 bcm in 2050.

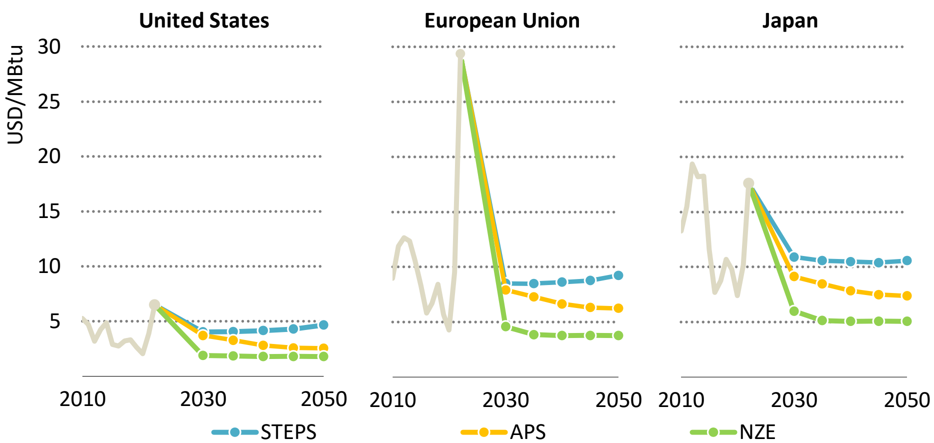
[1] Billion cubic metre equivalent (bcme) represents energy content expressed in standardised units of natural gas volume. For hydrogen, biogas and biomethane it is calculated from the energy content of these fuels and not their volume. A conversion factor of 36 petajoules per bcme is used.

Prices

In the **STEPS**, the weighted average import price of natural gas in the European Union, which is calculated as a composite of prices reported at major EU gas hubs, e.g. the TTF, nationally reported import prices and a calculated oil-indexed reference price, is projected to remain between USD 20-30/MBtu to the mid-2020s. It then gradually falls as more LNG comes online to ease international gas market tightness; prices settle at USD 8.50/MBtu by 2030. Natural gas prices in the United States are projected to come down from recent highs as additional shale gas production comes online. Average prices in importing countries in Asia range between USD 12- 17/MBtu through to 2025, with buyers in northeast Asia partly shielded from higher spot market prices by their use of long-term gas contracts in which the gas price is linked to the price of oil (Figure 8.1).

In the **APS**, robust action to move away from Russian gas exports in line with the Versailles Declaration means that prices in the European Union are slightly higher to 2025 than in the STEPS, but sharper reductions in demand bring them below the level in the STEPS before 2030. As the market rebalances, prices in Asia fall to a USD 9-11/MBtu range.

Figure 8.1 ▷ Natural gas prices by region and scenario



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The speed at which the natural gas price shock recedes varies by scenario, and depends in particular on demand levels and LNG supply dynamics

Note: MBtu = million British thermal units; STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

In the **NZE Scenario**, a sharp drop in natural gas demand globally quickly eases the strains on global supply, leading to gas import prices falling across the board to around USD 7/MBtu on average by 2025. Prices in gas-importing regions subsequently fall further to a floor set by the short-run marginal cost of delivering gas from existing export projects, and average around USD 5/MBtu by 2030.

8.2 Gas demand

Table 8.2 ▷ Gas demand by region in the STEPS and APS (bcme)

			STEPS		APS	
	2010	2021	2030	2050	2030	2050
North America	835	1 106	1 118	820	933	396
United States	678	871	864	575	716	252
Central and South America	147	161	159	179	141	96
Brazil	29	42	34	37	28	17
Europe	698	625	511	395	394	122
European Union	446	421	340	235	242	45
Africa	105	172	215	292	189	193
North Africa	85	132	155	182	137	120
Middle East	391	567	689	833	638	582
Eurasia	578	662	626	635	587	532
Russia	472	543	498	470	470	424
Asia Pacific	576	920	1 043	1 173	983	731
China	110	368	443	442	406	238
India	64	66	115	170	110	102
Japan	95	103	64	43	57	17
Southeast Asia	150	162	203	272	194	177
International bunkers	0	0	11	30	8	8
World natural gas	**3 329**	**4 213**	**4 372**	**4 357**	**3 874**	**2 661**
World low-emissions gases	22	36	91	326	223	1 091
World total gases	**3 351**	**4 248**	**4 456**	**4 661**	**4 069**	**3 568**

Notes: World natural gas and world low-emissions gases do not sum to world total gases because natural gas includes inputs to produce low-emissions hydrogen and low-emissions gases includes the hydrogen as an output. See Annex C for definitions.

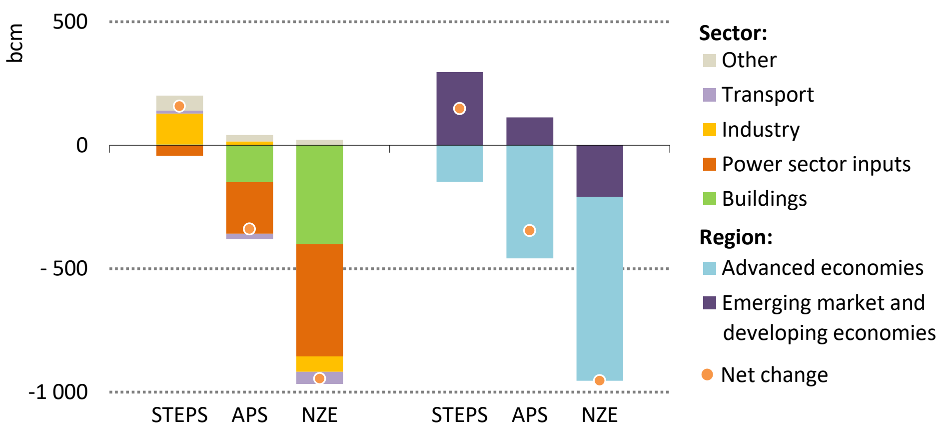
Demand trends to 2030

The **industry** sector drives total natural gas demand growth in the STEPS and accounts for 90% of overall growth between 2021 and 2030. However, many industrial sectors are sensitive to changes in gas prices, and higher equilibrium gas prices contribute to a nearly 30% downward revision to industrial natural gas demand growth between 2021 and 2030 compared to the STEPS projections in the *WEO-2021*. Natural gas demand in industry falls by 2% between 2021 and 2030 in the APS and 7% in the NZE Scenario. Around 35 bcm of coal-to-gas switching props up industry demand in the APS, due to higher carbon prices and policy pressure to shift to less polluting technologies.

The **buildings** sector sees falling demand for natural gas in advanced economies across all the scenarios. In the STEPS, a rapid acceleration in efficiency improvements and broad-based adoption of heat pumps reduces natural gas demand by 65 bcm in advanced economies between 2021 and 2030. In the APS, the rate of decline triples, with gas use in buildings falling by 170 bcm between 2021 and 2030, or 30% of demand in 2021. These reductions however are partly offset by increases in emerging market and developing economies. Globally, natural gas use in the buildings sector stays flat in the STEPS to 2030, declines by 17% in the APS, and falls by 45% in the NZE Scenario.

The **power sector** sees natural gas demand decline slightly, by about 3%, in the STEPS between 2021 and 2030. There is a geographical redistribution of demand; in advanced economies, gas use in the power sector falls over 100 bcm, while in emerging market and developing economies it rises by about 65 bcm. In the APS, faster growth in renewables means that more natural gas-fired power plants move from baseload to flexible providers of electricity generation, meaning less gas is consumed in the power sector even as additional capacity is added for flexibility purposes; there is limited coal-to-gas switching as demand shifts directly to renewables or other low-emissions options. This effect is more pronounced in the NZE Scenario, where power sector gas demand falls by 450 bcm, or 25% of 2021 levels, by 2030 (Figure 8.2).

Figure 8.2 ▷ Change in natural gas demand by sector, region and scenario, 2021-2030



Gas use in industry is more resilient to increased climate ambition than in buildings and the power sector. Gas demand does not increase in advanced economies in any scenario

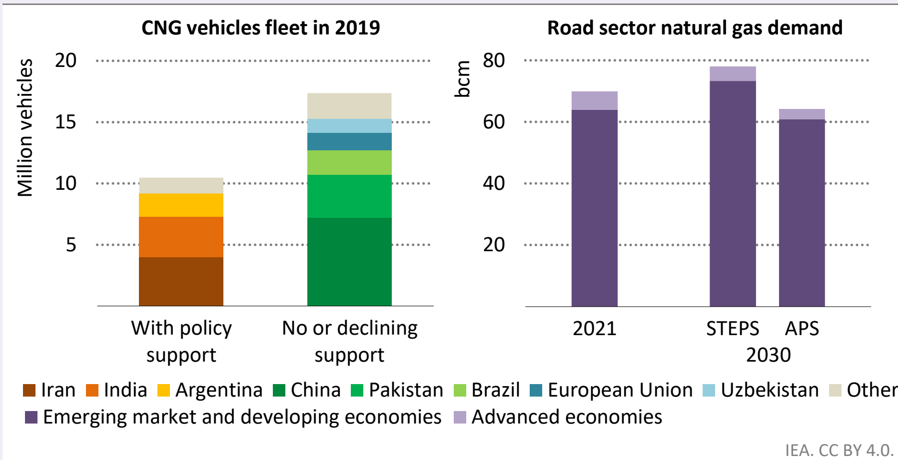
The **transport** sector currently accounts for 3.5% of global natural gas demand, of which about half, 70 bcm, is for road vehicles. Volatile natural gas markets have dampened the policy momentum behind its use as a fuel in road transport (Box 8.1); nonetheless, several countries are exploring the use of biomethane as a transport fuel. Natural gas use in transport is set to increase by 12 bcm by 2030 in the STEPS, mainly due to increased demand in shipping.

Box 8.1 ⊳ A fork in the road for compressed natural gas vehicles

Historically, the price advantage of natural gas compared to oil-based fuels has been the main factor behind rising use of compressed natural gas (CNG) in vehicles, though energy security and air pollution concerns have also played a part. Today 90% of the CNG fleet consists of light-duty vehicles. However, the rising popularity of electric vehicles (EVs), which are more efficient and more effective at avoiding air pollution, has dampened the policy momentum for CNG, leading to a downward revision of over 20 bcm in natural gas demand for road vehicles by 2030 in the STEPS compared to the *WEO-2021*.

In China, the stock of CNG vehicles shrank in 2020 for the first time as incentives for its use came to an end, while growth in the use of LNG for trucks lost momentum in 2021. The large CNG fleet in Pakistan has been challenged by natural gas price increases and supply shortages; the government has responded by banning new CNG filling stations. Gas-based vehicles may also fall foul of bans on internal combustion engine vehicles planned in the European Union as well as in Thailand, unless they are powered by biomethane rather than natural gas. In the United States, the CNG car market has been stagnant for nearly a decade despite policy incentives designed to help it.

Figure 8.3 ⊳ Natural gas demand in the vehicle fleet related to policy support in 2019 and the outlook by scenario



Except in markets with reliable access to ample gas supplies, widespread adoption of CNG vehicles is challenged by high prices and the competitiveness of EVs

Growth, however, is projected to remain strong in those emerging market and developing economies that possess significant natural gas reserves or have access to relatively cheap sources of supply. In Iran – home to 4 million CNG vehicles – supply infrastructure capacity is struggling to keep pace with the popularity of subsidised CNG. Russia has also seen CNG demand rise, and it put in place new targets and subsidies in 2020 to incentivise the use of natural gas as a transport fuel. CNG vehicle sales in India and parts of South America are still rising thanks to government support, including in some cases for bio-CNG. Several other countries, such as Egypt, Israel and Nigeria, are planning CNG support schemes.

In the STEPS, road vehicle gas demand is set to increase by around 10 bcm, to reach almost 80 bcm by 2030, with India accounting for nearly two-thirds of the increase (Figure 8.3). In the APS, natural gas consumption in the road sector declines by 6 bcm, mostly due to a shift towards the use of EVs to help meet net zero emissions targets.

The **Middle East** stands out for the size of its per capita growth in natural gas consumption between 2021 and 2030 in the STEPS, of around 130 cubic metres per capita, driven by growth in the use of gas in power, industry and desalination plants. This offsets a broadly equivalent decline in gas consumption per capita in Europe, which is driven by a nearly 20% reduction in gas use in buildings and a 30% reduction in the power sector. Demand in the Middle East remains relatively resilient in the APS, rising by 70 bcm between 2021 and 2030 compared to 120 bcm in the STEPS.

In the **United States** – the world's largest natural gas consumer – there is modest growth in natural gas demand to the mid-2020s, thereafter demand begins to decline. The Inflation Reduction Act spurs increased deployment of renewables, improved energy efficiency measures and cost declines for heat pumps, leaving natural gas demand in the power and buildings sectors lower by around 45 bcm. Natural gas use in industry and other sectors increases over the same period, leaving overall demand roughly at the same level in 2030 as today. In the APS, total natural gas demand falls at a rate of around 2% per year between 2021 and 2030, with gas use in power falling by nearly 90 bcm.

In **China**, natural gas demand in the STEPS increases by 2% per year between 2021 and 2030, well below the average growth rate of around 12% per year between 2010 and 2021. The coal-to-gas switching which started in the 2010s continues into the 2020s, but at a more moderate pace. The share of gas in the residential sector rises from 12% in 2021 to 16% by 2030, contributing to a reduction in coal use. The majority of industrial demand growth is met by electricity, but natural gas use in industry still increases by around 35 bcm (compared with 75 bcm from 2011 to 2020). In the APS, natural gas demand in China rises less than 1% per year between 2021 and 2030.

In **India**, natural gas demand in the STEPS reaches 115 bcm by 2030. Most of the growth comes from manufacturing and other industry, helped by the expansion of city gas distribution networks. Gas satisfies less than 5% of the increase in total power generation, but this is enough to raise demand by 10 bcm. The use of gas in transport, including both natural gas and biomethane, increase more than twofold, to reach over 10 bcm by 2030. Gas demand trends in the APS are broadly similar to those in the STEPS.

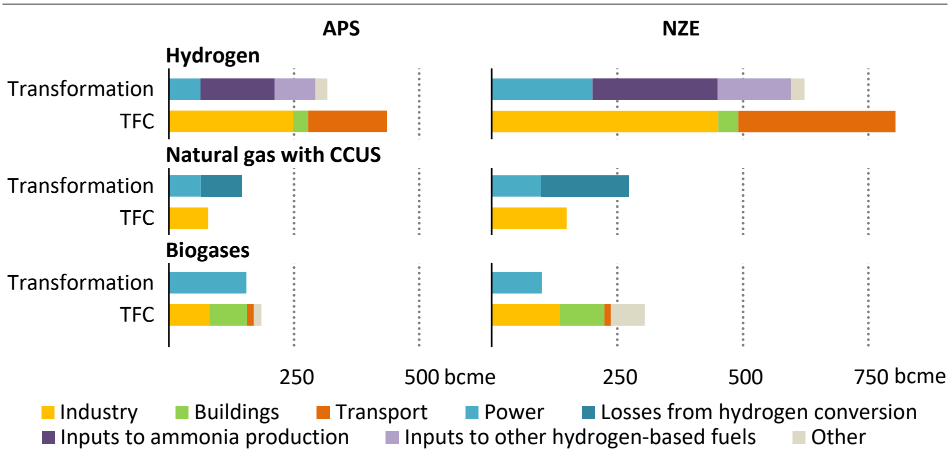
In **Southeast Asia**, natural gas demand rises in both the STEPS and APS at a rate around 2% per year, to reach around 200 bcm by 2030. Power generation accounts for more than half of demand increases while industry accounts for most of the remainder.

Demand trends after 2030

In the **STEPS**, natural gas demand declines slowly from about 22% of global energy demand in 2030 to 20% in 2050. Growth for natural gas in industry, about 120 bcm, offsets more than 90% of the decline in demand arising from growth in renewables and reduced coal-to-gas switching. Natural gas also loses market share after 2030 in residential space heating, ceding ground to district heating and electricity in the form of heat pumps and, in some cases, electric heaters. Solar thermal heating also gains ground in the 2030s, displacing the use of gas to provide hot water. By 2050, global natural gas demand is about 4 400 bcm, or roughly the same level of demand as in 2030.

In the **APS**, the share of natural gas in the global energy mix falls from 23% in 2021 to 15% by 2050. Most of the decline occurs after 2030, and the 2% decline in natural gas demand per year between 2030 and 2040 is comparable to that of coal between 2021 and 2030. Low-emissions gases in the APS meet around 35% of total gaseous fuel demand in industry by 2050 as well as around 20% of total gaseous fuel demand in the power and buildings sectors. Around 80 bcm of the natural gas that is consumed in industrial plants is equipped with CCUS, mainly in the production of petrochemicals and non-metallic minerals. Around 250 bcme of hydrogen is consumed in industry. Around 340 bcme of biogases are used in 2050 across all sectors (Figure 8.4).

Figure 8.4 ▷ Gas flows to meet demand for low-emissions fuels by sector in the APS and the NZE Scenario, 2050



Low-emissions gases and CCUS increase rapidly from a low base in both scenarios and are essential to lower emissions in sectors where electrification options are challenging

Notes: TFC = total final consumption. Other hydrogen-based fuels include hydrogen used in refineries and for biofuel production. Other for biogases includes agriculture, other non-energy use and the other energy sector. To avoid double counting, the energy originating from natural gas that is transferred to low-emissions hydrogen is shown only once, as demand for low-emissions hydrogen. The losses from the hydrogen conversion are estimated only for the merchant hydrogen production.

In the **NZE Scenario**, natural gas demand is 70% lower in 2050 than 2021. Demand falls at a rate of around 5% per year after 2030 (coal declines 8% per year over the same period). In 2050, 190 bcm of natural gas is used in non-combustion sectors such as chemicals, 100 bcm is used in power plants equipped with carbon capture and storage, over 560 bcm is used with CCUS to produce hydrogen and a further 150 bcm is used with CCUS in industry. Total hydrogen production reaches over 1 500 bcme by 2050. Over 25% of the hydrogen produced in 2050 is converted to hydrogen-based fuels such as ammonia, methanol and synthetic hydrocarbons. The remainder is used directly in industry, transport and buildings. Biogases reach more than 400 bcm by 2050; around 65% is biomethane, which is mostly injected into gas networks or otherwise in containers as bio-CNG mainly for use in the transport sector. The overall share of low-emissions gases in total gaseous fuels reaches over 70%, from less than 1% today.

8.3 Gas supply

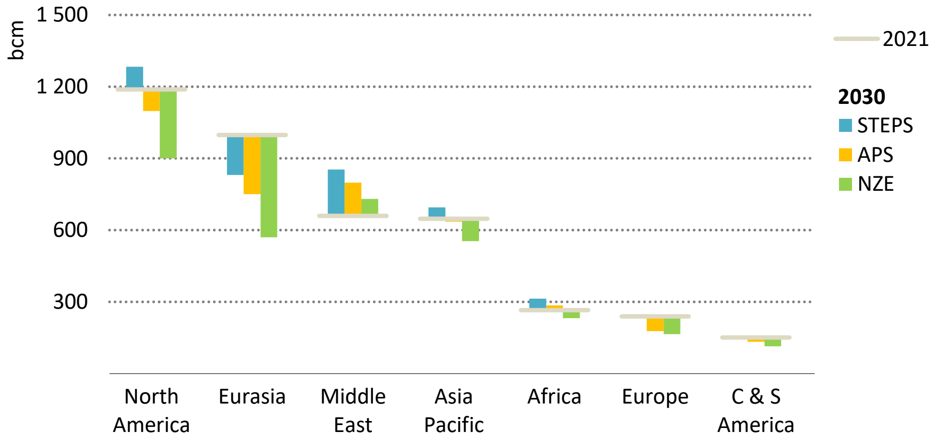
Table 8.3 ▷ Natural gas production in the STEPS and APS (bcm)

			STEPS		APS	
	2010	2021	2030	2050	2030	2050
North America	811	1 189	1 283	1 017	1 098	485
Canada	156	189	189	200	154	87
Mexico	51	31	31	34	31	34
United States	604	969	1 063	784	913	364
Central and South America	160	151	149	195	133	95
Argentina	41	41	53	107	51	60
Brazil	16	25	25	38	19	11
Europe	341	239	247	208	177	65
European Union	148	51	39	34	17	2
Norway	110	119	126	78	80	20
Africa	203	265	313	369	285	239
Algeria	85	103	103	65	97	39
Egypt	57	72	74	58	74	50
Mozambique	3	4	23	83	14	43
Nigeria	33	44	51	57	48	41
Middle East	463	660	853	1 030	798	690
Iran	144	236	248	319	245	154
Iraq	5	12	32	44	29	28
Qatar	121	169	247	326	236	225
Saudi Arabia	73	100	150	191	148	189
Eurasia	807	998	831	857	751	654
Azerbaijan	17	33	35	24	35	29
Russia	657	793	633	612	584	483
Turkmenistan	45	90	91	155	73	100
Asia Pacific	488	648	694	678	636	432
Australia	53	151	165	150	154	121
China	96	200	250	285	228	120
India	51	32	48	78	47	53
Indonesia	86	58	57	38	50	33
Rest of Asia Pacific	203	206	174	126	156	106
World	**3 274**	**4 149**	**4 372**	**4 355**	**3 878**	**2 660**

Note: See Annex C for definitions.

Supply trends to 2030

Figure 8.5 ▷ Change in natural gas production by scenario, 2021-2030



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There are sharp reductions in Russian gas production in all scenarios, while the Middle East leads supply growth. North America sees the largest variation between scenarios.

Note: C & S America = Central and South America.

In the STEPS, the **Middle East** is the largest near-term source of supply growth (Table 8.3). New supplies are underpinned by the North Field expansion in Qatar, where volumes are primarily earmarked for export, as well as a 60 bcm rise in non-associated gas production that meets domestic demand growth in Iran, Saudi Arabia and the United Arab Emirates. In the APS, natural gas production is underpinned by resilient domestic demand growth and by increased LNG trade.

In the **United States**, total gas production rises in the STEPS from 970 bcm in 2021 to just over 1 050 bcm by 2030; this growth rate of 1% per year is much lower than the 5% seen in the previous decade. Around 120 bcm of additional supply comes from unconventional dry gas production led by the Marcellus and Utica plays, and associated gas in the Permian Basin adds an additional 30 bcm. These additional supplies more than offset declines in conventional gas output. Around 55 bcm, or over half of net production growth, is exported in the form of LNG. In the APS, even as gas production falls 7% below 2021 levels due to declining domestic demand, LNG exports increase by 45 bcm from today, almost as much as in the STEPS. In **Canada**, unconventional gas production increases by more than 50 bcm between 2021 to 2030 in the STEPS, with over 40% exported as LNG. Overall, **North American** gas production sees the biggest differences between scenarios; supply increases by more than 90 bcm to 2030 in the STEPS, but contracts by 340 bcm in the NZE Scenario (Figure 8.5).

In **Russia**, gas production falls in all scenarios. In the STEPS, it is 155 bcm per year lower in 2030 than it was in 2021. In the APS it is 210 bcm lower, taking production back to 590 bcm per year, a level last seen in 2002. The upstream projects designed to serve Nord Stream II – Kharasavey and the Bovanenkovo expansion – struggle in the near term to find alternative outlets. The Tambey field expansion to underpin new LNG projects is unlikely to ramp up to its original capacity. The flaring of associated gas has recently increased, and there is a short-term risk in all scenarios of large-scale flaring or venting to ease system pipeline pressures.

Russia's efforts to diversify its export markets have mixed success. Deliveries to China in the STEPS rise from 10 bcm in 2021 to 50 bcm by 2030. This is largely achieved through the ramping up of the Power of Siberia pipeline, which delivers about 38 bcm per year and is supplied by the Chayandinskoye and Kovyktinskoye fields in Eastern Siberia. Russia and China agreed early in 2022 to a new pipeline routing up to 10 bcm of production from Sakhalin into northeast China. Overall, however, Russia's increased pipeline natural gas deliveries to China cover less than half of the drop in exports to Europe by 2030. In some of the more mature fields in Western Siberia which currently serve Europe, such as Urengoy and Yamburg, production is gradually shut in. Reduced gas extraction reduces field productivity and the pipeline pressures needed to support natural gas flows over long distances. In the APS and NZE Scenario, lower levels of demand for natural gas intensify these difficulties.

Europe's efforts to secure supplies to displace Russian gas unlocks near-term growth in **Egypt** and in parts of **sub-Saharan Africa**, notably in the **Republic of the Congo**, where a 4.5 bcm per year LNG project is expected to start in 2023. By the mid-2020s, **Norway** expands its second-largest gas field, Ormen Lange Phase 3, which has up to 40 bcm of recoverable gas, along with smaller new fields including Tommeliten A. However, declining production from mature basins means that Norwegian gas production peaks before 2030 in each scenario.

China's most recent Five-Year Plan (2021-2025) is focussed on boosting domestic production of natural gas including shale gas, coalbed methane, tight gas and other unconventional resources. By 2030, China emerges in each scenario in the top-five largest natural gas producers, along with the United States, Russia, Iran and Qatar.

In **India**, the government recently announced a doubling of its licence area for oil and gas exploration; however, this is unlikely to contribute significant volumes in this decade. In the STEPS, gas production rises by over 15 bcm, with incremental volume mostly from the offshore Krishna Godavari basin, covering around one-third of domestic demand growth. Production growth to 2030 is similar in the APS.

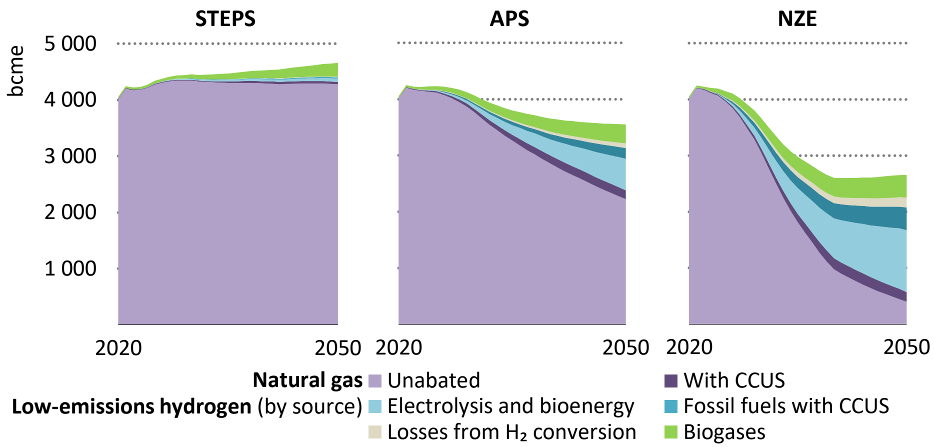
Elsewhere in Asia, gas production in **Indonesia** and **Malaysia** remains flat to 2030 in the STEPS and drop by more than 10% in the APS, with recent upstream investments largely offset by declining production from maturing fields. In **Australia**, gas production increases by 8% to 2030 in the STEPS and remains flat in the APS with incremental contributions from conventional, coalbed methane and shale gas.

In **Africa**, production rises by about 20% in the STEPS between 2021 and 2030, with most of the incremental volume coming from **Mozambique**. In the APS, gas production increases by less than 10%; there is very little growth in net trade and a more modest increase in domestic demand relative to the STEPS.

Gas production in **Central and South America** remains largely flat in the STEPS, with supply rising from **Trinidad and Tobago** (Matapal and Colibri, around 3 bcm) and **Argentina** (Vaca Muerta, 12 bcm). These are largely offset by declines elsewhere in countries such as **Bolivia**, **Venezuela** and **Peru**. In the APS, gas production falls 12% below 2021 levels by 2030.

Supply trends after 2030

Figure 8.6 ▷ Total gaseous fuel supply by scenario



Total gases increase in the STEPS, while in the APS and the NZE Scenario the drop in supply for unabated uses is partly offset by a rise in hydrogen, biogas and gas use with CCUS

Notes: H_2 = hydrogen. Includes all gases supplied to the system for transformation (to electricity, heat or hydrogen-based liquid fuels) or final consumption. The energy content of low-emissions hydrogen produced from natural gas is subtracted from natural gas use with CCUS. Losses from hydrogen conversion are for merchant production.

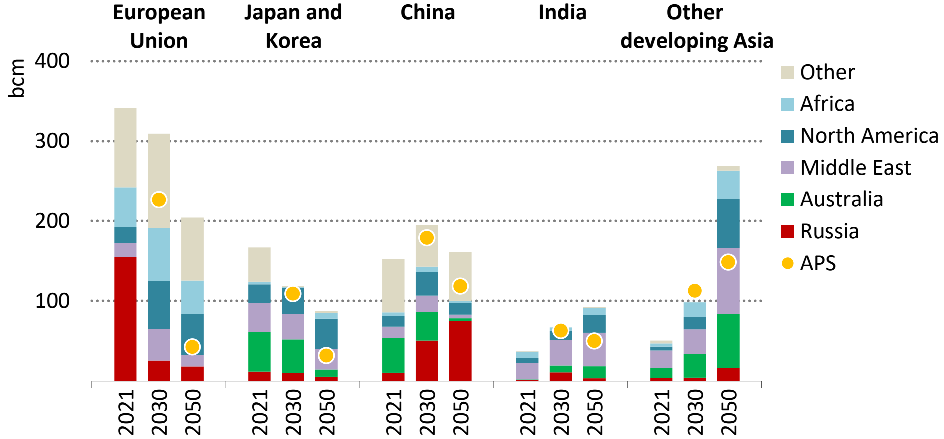
In the STEPS, natural gas production stays flat between 2030 to 2050. Shale gas production remains largely unchanged in North America, and there is some growth in the Middle East and Central and South America. New gas producers in Africa, such as Mozambique, Tanzania and Senegal, see a late surge in export-led production, underpinning 110 bcm of growth. Overall production in Russia declines by an additional 25 bcm between 2030 and 2050. Global natural gas supply in the APS declines by over 1 200 bcm between 2030 and 2050, to levels seen before the shale gas revolution. In the NZE Scenario, global gas production declines at a rate of 5% per year, and is just under 1 100 bcm by 2050.

The production of low-emissions gases ramps up in both the APS and the NZE Scenario (Figure 8.6). In the APS, low-emissions gases reach nearly 1 100 bcme by 2050, equivalent to more than 25% of global natural gas demand in 2021. Biogas rises to nearly 340 bcme by 2050 from about 35 bcme today. Over 40% of biomethane and biogas are developed in the Asia Pacific region. Low-emissions hydrogen supply reaches about 750 bcme by 2050 in the

APS and over 1 500 bcm in the NZE Scenario. Most low-emissions hydrogen is produced and used domestically, but global trade in low-emissions hydrogen-based gases begins to rise in the NZE Scenario from the mid-2020s, to reach around 240 bcme by 2050.

8.4 Gas trade

Figure 8.7 ▷ Change in natural gas net trade in selected regions in the STEPS and APS



Europe's near-term need for non-Russian gas imports leads to a rebalancing of global gas flows and to increased competition for LNG with emerging gas markets in Asia

In the STEPS, global natural gas trade increases at an annual average rate of less than 1% per year from 2021 to 2030, compared to 3% between 2010 and 2021. LNG rapidly gains market share from long-distance pipeline trade and so grows at a faster rate than overall trade, at more than 2% per year. With Russian pipeline gas to the European Union falling by nearly 90%, or 130 bcm between 2021 and 2030, competition heats up between Europe and Asia for LNG, overturning the conventional wisdom that Europe acts as a balancing market for global LNG supply (Figure 8.7).

Around 85% of the growth in global LNG supply to 2030 in the STEPS originates in the United States and the Middle East. The United States soon overtakes Russia to become the world's largest natural gas exporter. US LNG exports increase by 60% from 2021 levels to reach nearly 150 bcm by 2030, of which about 60 bcm is transported to the European Union.

In 2030, the European Union imports an additional 65 bcm of LNG in the STEPS compared to 2021, while there is a 50 bcm decline in LNG imports in Korea and Japan. Emerging market and developing economies in Asia import an additional 80 bcm of LNG, with imports mostly flat elsewhere.

Russia's share of globally traded gas falls from almost one-third in 2021 to less than 15% in the STEPS by 2030. The increase in Russian pipeline flows to China cover less than a third of the drop in deliveries to the European Union. Since China has minimal additional import requirements beyond what is currently contracted, Russia is only able to redirect around 25 bcm per year by 2040 from its Western Siberian gas fields to China through an additional pipeline. Expansion in LNG capacity in Russia is constrained by sanctions; some projects are shelved, while others see significant delays to commissioning dates. Around 10 bcm of new LNG export capacity is added in Russia by 2030, taking total export capacity to 45 bcm per year, but this falls far short of what Russia needs by that date to be on course to achieve its stated aim of 200 bcm per year of capacity by 2035.

China – currently the world's largest natural gas importer – sees imports meet 35% of demand growth between 2021 and 2030 in the STEPS. The share of pipeline gas in its total gas imports increases from 25% in 2021 to 45% in 2030 as deliveries from Russia through the Power of Siberia pipeline and the planned 10 bcm Far East pipeline are ramped up. By 2050, China accounts for nearly a quarter of all long-distance pipeline gas trade.

Around 65 bcm per year of LNG regasification capacity is under construction in China, adding to the existing capacity of 100 bcm per year. Since the start of 2021, China has also contracted for around 75 bcm per year of additional LNG over the period to 2030. All this contracting and infrastructure expansion hinges on expectations of strong demand growth, whereas in the STEPS demand moderates to around 2% per year between 2021 and 2030. With continued growth in domestic production, LNG demand grows slower than contracted supply, and so some of China's flexible LNG import contracts (around 45 bcm per year) are diverted to other markets, easing some of the global LNG supply tightness in the mid-2020s.

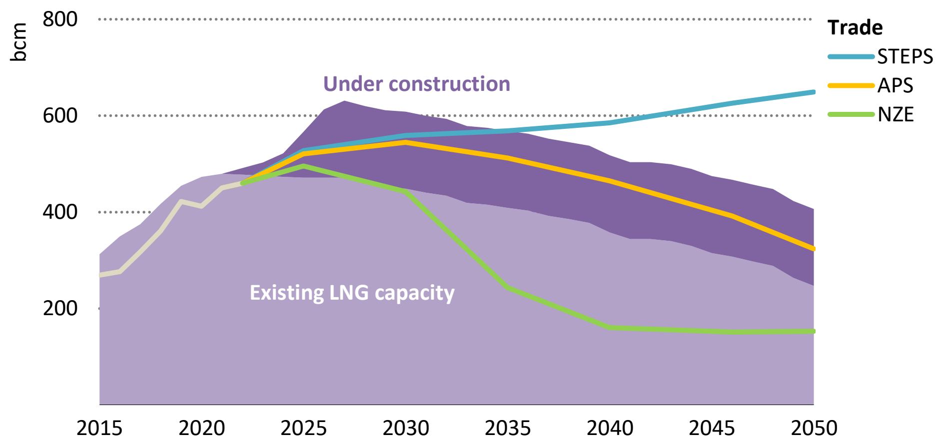
In India, gas imports double and reach nearly 70 bcm by 2030; growth moderates thereafter and imports reach 90 bcm by 2050. The remaining major gas markets in emerging market and developing economies in Asia, primarily in Southeast Asia, Pakistan and Bangladesh, grow by over 250 bcm between 2021 and 2050.

In the STEPS, an additional 240 bcm per year of LNG export capacity is needed by 2050 above what currently exists or is under construction (Figure 8.8). Inter-regional LNG trade in the STEPS expands an additional 15% from 2030 to 2050, to reach 650 bcm by 2050. East Africa is the main source of LNG supply growth, with exports rising by nearly 80 bcm between 2030 and 2050, more than offsetting declines in other parts of Africa.

In the APS, global gas trade falls slightly between 2021 and 2030, driven by faster declines in pipeline gas and slower growth in LNG demand in emerging market and developing economies in Asia. Global LNG trade peaks at around 550 bcm before 2030 and then falls to 320 bcm by 2050, about 30% below 2021 levels. Inter-regional pipeline trade declines from about 430 bcm today to less than 200 bcm by 2050, meaning overall natural gas trade is 45% lower than in 2021. In emerging natural gas markets in Asia, import volumes in the APS by 2050 are about 40% lower compared with the STEPS, as the role of gas as a transition fuel is largely limited to this decade (see section 8.8).

In the NZE Scenario, global LNG trade peaks in the mid-2020s and then falls to 2021 levels by 2030, before declining sharply to 150 bcm by 2050. In this scenario, there is no further need for additional capacity beyond what exists or is under construction.

Figure 8.8 ▷ Existing and under construction LNG capacity and total inter-regional LNG trade by scenario, 2015-2050



There is near-term growth in LNG trade in all scenarios, but sharp divergences thereafter

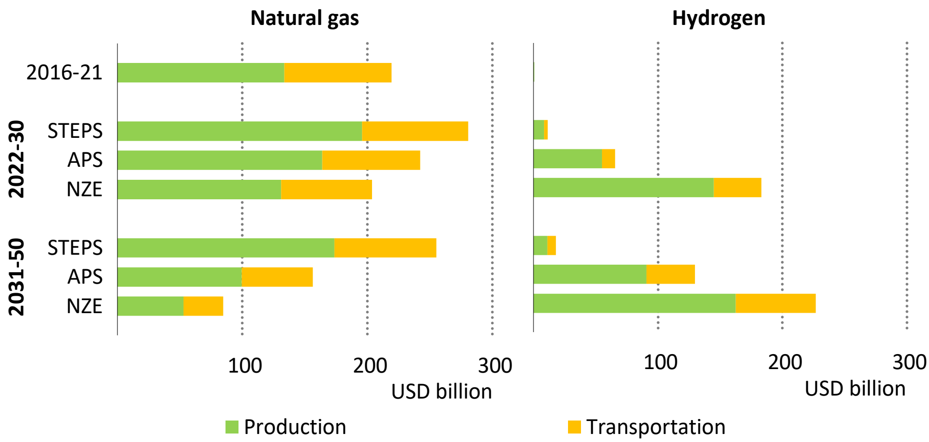
Note: LNG capacity is adjusted to reflect inter-regional trade between regions modelled in the Global Energy and Climate Model, and de-rated to 80% of nameplate capacity.

8.5 Investment

In the STEPS, around USD 300 billion in capital per year is spent on natural gas between 2022 and 2050. Around a further USD 30 billion is spent on LNG infrastructure, mainly on new liquefaction capacity. In the APS, growth in total investment spending is slower, and investment falls to half of 2021 levels by 2050. In the NZE Scenario, upstream investment in natural gas is limited to maintaining supply at existing fields and minimising the emissions intensity of production. Total spending on natural gas transport between 2022 and 2030 is similar between the STEPS and NZE Scenario, and the level of spending on transport means the average of total investment in natural gas in the NZE Scenario in 2022-30 are broadly similar to levels in 2021 (Figure 8.9).

The sharp decline in natural gas investment in the NZE Scenario after 2030 is accompanied by a parallel ramp up in investment in low-emissions hydrogen. This increases to over USD 220 billion in the NZE Scenario by 2050, which is broadly equivalent to the reduction in investment in natural gas over the same period. The majority of investment in low-emissions hydrogen supports the production of hydrogen from electrolysers (USD 150 billion on average between 2030-50, which includes investment in dedicated low-emissions electricity supply), but it also includes spending on fossil fuels equipped with CCUS (USD 20 billion a year on average). The remaining investment is in new pipelines, shipping and port infrastructure. In the NZE Scenario, around 15% of hydrogen is blended into natural gas networks by 2050, and this requires relatively minor investment in natural gas infrastructure. Hydrogen production in the NZE Scenario is relatively capital intensive compared with natural gas, requiring double the level of investment per unit of equivalent energy.

Figure 8.9 ▷ Average annual natural gas and hydrogen investment by scenario



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In the NZE Scenario, the amount invested annually for low-emissions hydrogen becomes as large as what is spent on natural gas today

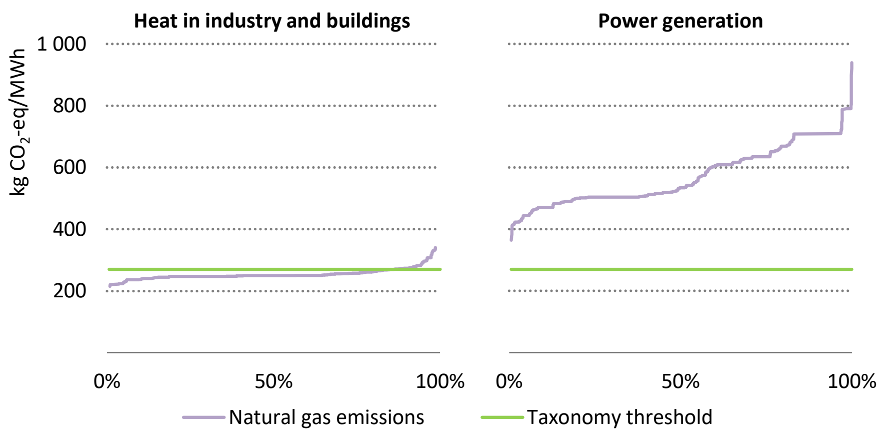
Notes: Production for hydrogen includes merchant hydrogen and onsite production from electrolysers. Transportation includes liquefaction and regasification terminals, ships, pipelines and storage. Only the costs of dedicated renewables for offsite hydrogen production are included; it excludes costs associated with the use of grid-based electricity. Some of the investment in natural gas production results in supply for natural gas-based low-emissions hydrogen production.

Box 8.2 ▷ What are the implications for natural gas of the European Union taxonomy of sustainable financial investments?

The European Union taxonomy of sustainable financial investments sets out the conditions that activities such as natural gas investment must meet in order to be considered sustainable. To meet these conditions, an activity must produce less than 270 kilogrammes of carbon-dioxide equivalent per megawatt-hour (kg CO_2-eq/MWh) of output energy, and annual direct emissions must not exceed an average of 550 kg CO_2-eq/kW of the facility's capacity over 20 years.

We assessed the life cycle emissions associated with natural gas extraction, processing, transport and consumption for both heat (in buildings and industry) and electricity generation in order to evaluate how the taxonomy thresholds would affect natural gas-related investments worldwide. This assessment takes account of the flaring and methane emissions associated with the production and transport of natural gas in 2021. An upward slope in the supply curve reflects higher emitting sources of supply.

Figure 8.10 ▷ European Union gas taxonomy thresholds compared with global life cycle emissions of natural gas, 2021



Natural gas to produce heat for buildings and industry mostly falls below the taxonomy thresholds, but unabated power plants exceed them

Note: Values on the x-axis show, in percentage terms, all the natural gas consumed worldwide for heat (1 400 bcm) and electricity (1 650 bcm) in 2021.

The taxonomy thresholds imply that most of the natural gas use to generate heat in buildings and industry can still technically qualify as a sustainable activity, as long as methane leaks and other upstream emissions are minimised. However, the use of natural gas to generate electricity involves efficiency losses that increase its combustion emissions intensity, meaning unabated gas-fired power plants would exceed the threshold by a significant margin. There are provisions in the taxonomy for unabated plants to be designated sustainable as long as the total emissions do not exceed 550 kg CO_2/kW of installed capacity each year over 20 years. In practice, this would mean flexible gas generators, with an average combustion intensity of 500 kg CO_2/MWh, could operate at a load factor of around 10% on average per year before exceeding these norms. Many power producers and the financial sector might consider such restrictions to be too significant a barrier to investment.

Key themes

8.6 Outlook for natural gas in the European Union after Russia's invasion of Ukraine

Curtailments of supply after Russia's invasion of Ukraine have left the natural gas sector in the European Union in disarray. Deliveries from Russia to the European Union fell by nearly 40% in the first-half of 2022, with Russia terminating supply contracts for multiple EU countries due to buyer refusal to accept a unilateral change in the payment system. Exports to former subsidiaries of Gazprom in Germany have ceased, and large importers such as Germany and Italy are planning a phase out of Russian gas over the course of the 2020s. With its RePowerEU Plan, the European Union is setting in motion a process to dismantle a structural dependence on energy imports from Russia built over several decades. During the winter ahead, the amount of Russian gas supplied to Europe may well be dictated by Russia's own political ends rather than by European policies, raising the risk of possible supply shortfalls and rationing. In this section, however, we look beyond immediate events to explore the longer term challenges and uncertainties for the European Union as it seeks to reduce the role of natural gas in the energy mix while diversifying its supplies.

The role of natural gas, and the level of dependence on Russian gas in particular, vary considerably across the European Union (Table 8.4). Around 40% of the European Union's total residential space and water heating demand and 30% of its cooking fuel demand is currently met by natural gas. Gas also powers 20% of total electricity generation and meets 25% of its industrial energy demand, playing an outsized role in sectors such as chemicals, textiles and food production. Options to substitute for natural gas are a crucial determinant of the near-term ability of the European Union to adjust to potential supply shortages. Natural gas use is embodied in goods and services derived from multiple industries, meaning the effects of a cessation of supply could affect various industrial and services sector value chains. This makes it very difficult to assess substitutability in a straightforward way.

In the APS, the European Union targets in the Fit for 55 package are fully met, and in some cases exceeded. The acceleration of key measures, such as rapid deployment of renewables in the power sector and energy efficiency, means that greenhouse gas (GHG) emissions reductions targets are met and that EU imports of Russian natural gas end well before 2030 – the key objective of the REPowerEU Plan (Figure 8.11).

Natural gas demand in the European Union declines by 180 bcm from 2021 to 2030 in the APS, an average fall of 6% per year. Gas use in the power sector over this period drops at a faster pace than coal use did in the European Union from 2010 to 2020. There is a parallel ramp up of renewables, especially wind and solar capacity, which increase by 600 gigawatts (GW) to 2030, while coal declines by 100 GW. Building retrofits nearly triple from the current rate of less than 1% per year and 40 million heat pumps are deployed (equivalent to installations in nearly one-third of the EU building stock). Together these actions help reduce the use of gas in buildings by 45% from 2021 to 2030, or roughly double the pace of the reduction in oil use in the EU residential heating sector in the 1980s. Natural gas demand in industry falls around 4 bcm per year, faster than the decline seen in 2020 immediately after the onset of the Covid-19 pandemic. Most of this is in energy-intensive industry such as steel and chemicals, offset by higher rates of electrification.

Table 8.4 ▷ Share of Russian gas in total natural gas demand and share of gas in sectoral demand by European Union member states and the United Kingdom, 2021

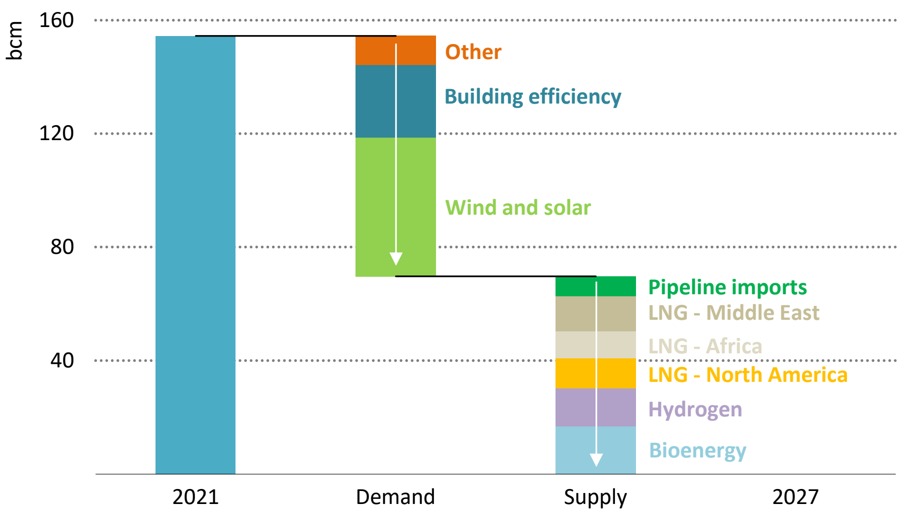
Market size	Country	Russian share	Share of gas in sectoral demand		
			Power	Industry	Buildings
>20 bcm	Germany*	46%	20%	31%	38%
	United Kingdom	3%	43%	32%	55%
	Italy*	41%	51%	31%	50%
	France*	20%	9%	31%	29%
	Netherlands**	36%	58%	30%	59%
	Spain	11%	31%	38%	22%
10-20 bcm	Poland**	46%	9%	28%	19%
	Belgium	7%	30%	28%	41%
	Romania	6%	28%	37%	34%
5-10 bcm	Hungary	78%	37%	30%	50%
	Austria*	74%	21%	34%	20%
	Czech Republic*	67%	13%	24%	30%
	Portugal	10%	40%	23%	12%
<5 bcm	Slovak Republic*	76%	20%	28%	40%
	Ireland	0%	52%	42%	22%
	Denmark**	60%	11%	30%	13%
	Greece	39%	29%	23%	9%
	Bulgaria**	100%	15%	34%	5%
	Croatia	0%	32%	51%	22%
	Finland**	68%	8%	6%	1%
	Lithuania**	50%	17%	59%	11%
	Latvia*	100%	48%	11%	13%
	Sweden	14%	1%	5%	1%
	Slovenia	12%	7%	34%	9%
	Luxembourg	25%	27%	44%	36%
	Estonia**	46%	9%	21%	9%

* Denotes a partial cut. ** Denotes a full cut.

Notes: Asterisks denote countries that stopped receiving natural gas from Russia in 2022. Table is ordered from highest to lowest natural gas demand.

Source: Share of Russia in total natural gas demand calculated using trade data from ACER (2022); Cedigaz (2022); Eurostat (2022).

Figure 8.11 ▷ Drivers of reduced natural gas supply from Russia to the European Union in the APS



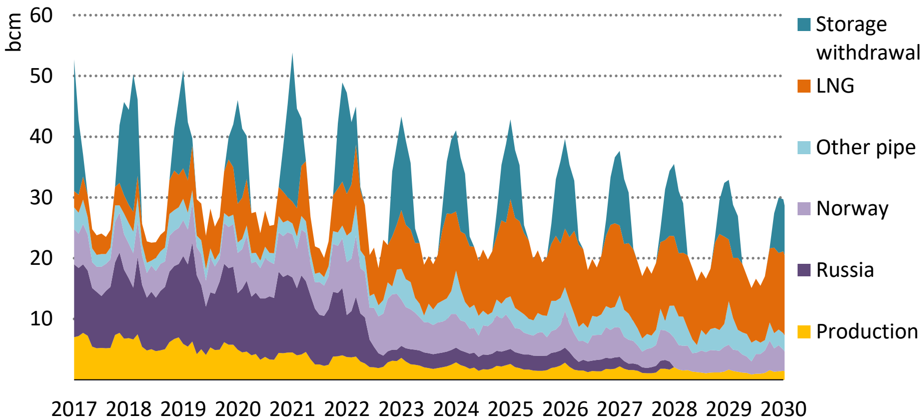
A mix of supply- and demand-side measures are required for the European Union to reduce reliance on Russian gas to zero before 2030

Note: Other includes reductions in industrial natural gas demand and gas-to-coal switching.

On the supply side, deliveries from Russia gradually fall to zero before 2030 in the APS. In parallel, European gas buyers maximise LNG shipments to existing facilities while also developing new facilities for LNG imports (announced plans total an extra 120 bcm per year of new capacity, of which around 40 bcm per year are floating storage and regasification units). LNG imports average 140 bcm per year over the 2022-27 period, meeting almost 60% of the EU non-Russian import requirements. Around 40 bcm per year of LNG on average is imported from the United States. Gas imports from Norway drop to around 60 bcm per year. There are some additional pipeline supplies from Algeria and Azerbaijan.

Part of the EU supplies in summertime are used to build up storage capacity. In the APS, the volumes required by the EU gas storage injection and withdrawal cycle reduce as seasonal variations in demand diminish and as LNG meets a higher share of demand: a net of 40 bcm of storage is withdrawn during the winter in 2030 in the APS compared to an average net withdrawal of 65 bcm between 2016 and 2021 (Figure 8.12). However, the amount of gas stored and ultimately withdrawn in 2030 is similar as a share of remaining gas demand as in 2021, meaning that storage still plays a vital role in security of supply. And unexpected events could still cause problems. For example, colder than expected winters or failure to deliver the targeted reduction in natural gas demand in buildings would increase the seasonality of demand: in the absence of adequate storage, this would increase reliance on LNG, which would be likely to push up prices.

Figure 8.12 ▷ European Union monthly natural gas supply balance in the APS



Russian gas is gradually phased out in favour of LNG. The seasonality of EU gas demand falls, but gas storage remains a crucial asset for security of supply

Notes: Values match EU annual natural gas demand in the APS. Gas volumes used to fill storage are netted off and included in storage withdrawal.

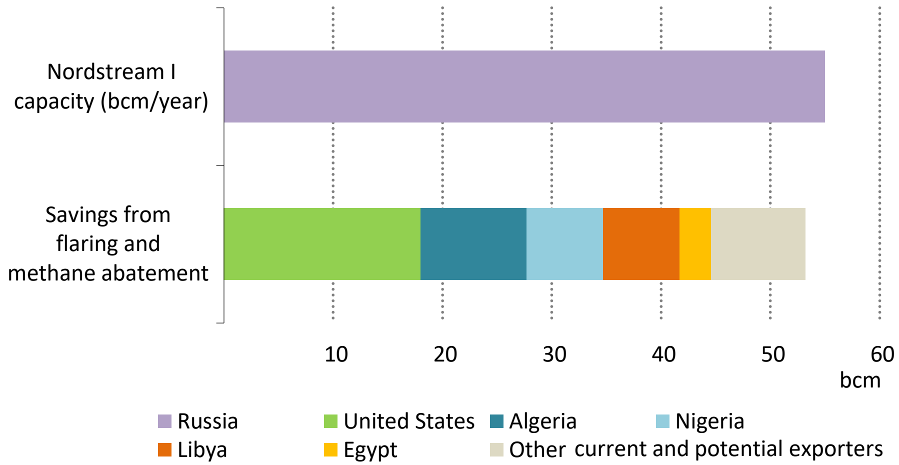
S P O T L I G H T

Cutting flaring and methane leaks can provide a double dividend for environment and energy security

Over 260 bcm of natural gas was flared, vented or lost to leaks in 2021. Of this, we estimate that nearly 210 bcm could be made available to gas markets by a global effort to eliminate non-emergency flaring and reduce methane emissions from oil and gas operations (IEA, 2022a). This would bring a double dividend: relief for very tight gas markets along with reduced GHG emissions. As the flaring intensity of oil imported by the European Union is five-and-a-half-times larger than that produced in the region (Capterio, 2021), the European Union has a clear incentive to act. Reducing imports from Russia will lower this intensity as Russia flares more gas than any other country, with an estimated total of more than 20 bcm in 2021 (Zhizhin et al., 2021).

If countries that are current or potential exporters of natural gas to the European Union were to implement flaring and methane reduction measures, the gas saved would mean that they could increase gas exports by more than 53 bcm using existing and planned infrastructure. This is equivalent to about one-third of Russian gas exports to the European Union in 2021 or the full use of the Nord Stream 1 pipeline annual capacity (Figure 8.13). Rapid action to deploy all available flaring and methane abatement technologies over the next decade would have the same effect on the global temperature rise by mid-century as immediately eliminating the GHG emissions from all of the world's cars, trucks, buses and two/three-wheelers.

Figure 8.13 ▷ Potential for flaring and methane abatement to satisfy EU gas import demand compared with the capacity of Nord Stream I



Flaring, venting and leaks are wasting gas that could be exported to the European Union at a level equivalent to the full capacity of the Nord Stream I pipeline

Some of the largest flaring reduction opportunities are in North Africa: Algeria and Egypt lost about 12 bcm of natural gas from their upstream assets in 2021 as a result of flaring and related combustion inefficiency losses. According to satellite imaging analysis carried out by analytics firm Capterio, close to 80% of flaring in Algeria and Egypt occurs within 20 kilometres (km) of existing gas pipelines with ready access to an existing export pipeline or LNG terminal (Davis et al. 2022). Most flares operate continuously and many are candidates for cost-effective abatement options.

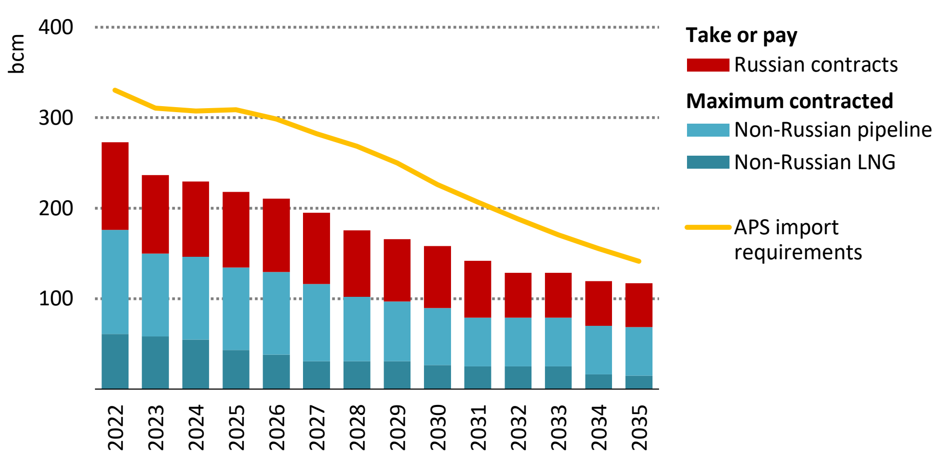
The logistical and economic challenges involved in capturing large quantities of flared gas include multiple point sources, varying levels of potential natural gas capture and complicated ownership structures across the supply chain. In North Africa there are several recent examples of flare capture projects that have reduced emissions, contributed to emissions reduction targets and created value. Kuwait Energy and United Oil and Gas built a dedicated gas pipeline in less than one year in Egypt to move up to 0.05 bcm of natural gas per year to an existing gas processing facility some 20 km away rather than flaring it. In another example, Apache and Shell (and partners including BAPETCO) recently installed gas-fired plants to power operations that previously flared gas: this reduced flaring by 0.04 bcm year while also cutting diesel consumption by up to 3 million litres per month.

A rising number of countries have set targets to cut flaring and methane emissions. Achievement of the targets will rely on governments establishing flaring and methane reduction plans underpinned by robust and transparent data. Governments could improve the investment climate by amending existing commercial contracts to incentivise operators to take action, e.g. by granting them ownership of the gas. For its part, the European Union could encourage supplier action by providing preferential funding for flaring abatement and related infrastructure to help overcome the logistical and economic hurdles common to these emissions reduction opportunities, or contracting for the saved gas.

Contracting dilemmas

Demand for imported natural gas in the European Union is projected to fall from 370 bcm per year in 2021 to 230 bcm per year by 2030 before declining to 140 bcm per year in 2035 and then 40 bcm per year by 2050 in the APS. Russian deliveries are assumed to fall at a rapid pace, irrespective of the constraints of the take-or-pay supply contracts that remain in force. On that basis, a maximum of 170 bcm per year of additional natural gas is required to 2030 above the existing firm non-Russian gas contracts; this requirement falls to 70 bcm per year by 2035 (Figure 8.14).

Figure 8.14 ▷ European Union natural gas contract balance compared with import requirements in the APS, 2022-2035



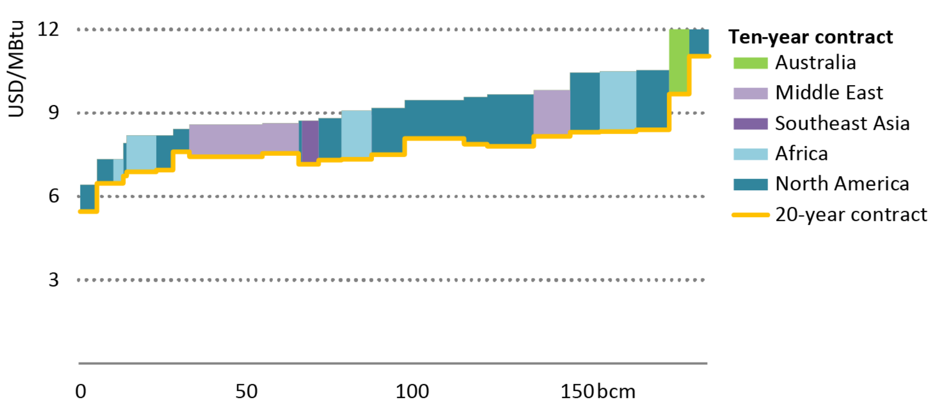
Assuming demand falls in line with the APS, gas buyers in the European Union need anywhere from 70-170 bcm of additional supply to 2030, depending on Russian imports

The dilemma for EU gas buyers is whether to contract for new capacity or rely on the spot market to fill the gap. In principle, the EU supply gap to a large extent can be filled by attracting LNG cargoes from the spot market, through paying a premium that diverts them from other markets. Around 50% of current global LNG trade, or 250 bcm, can be considered contractually flexible, and therefore open to competition to determine its end destination. The rest is governed by fixed point-to-point delivery arrangements. This proportion increases slightly over the coming years, as existing contracts expire and around 55% of the 200 bcm per year of LNG export capacity coming online between 2022 and 2026 is also flexible. However, a high level of exposure to short-term markets may put European gas buyers at the mercy of volatile global LNG supply dynamics, especially in the near term. Flexible volumes may also be converted to firm, long-term contracts by other buyers seeking assured supply.

Another solution is to sponsor new LNG export projects, thereby securing firm off-take. However, this requires long-term commitment, as capital-intensive LNG projects require long lead times to construct, a minimum take-or-pay volume commitment lasting around 20 years, and an operational lifetime of at least 30 years. Many gas buyers in the European Union meanwhile would be looking to phase out gas demand well before 2050.

To illustrate a potential way of resolving this difficulty, we conducted an assessment of 200 bcm worth of recently commissioned and under construction LNG projects around the world to calculate the gas price required if they were to recoup investment costs with 10-year contracts rather than 20-year contracts. The weighted average break-even price of gas over a 20-year contract lifetime is around USD 7.50/MBtu, with an average rate of return of nearly 20%. At the lower end of the cost scale are projects like the North Field expansion in Qatar, which enjoys low cost gas and associated liquids supplies that improve project economics. At the upper end of the scale are greenfield projects such as LNG Canada, which requires additional infrastructure to connect upstream gas fields to the liquefaction terminal.

Figure 8.15 ▷ Contract prices required to cover break-even costs of LNG supply for recently approved projects



Shortening the contract length for LNG supplies to Europe to improve alignment with net zero emissions targets would mean significantly higher delivered costs

Shortening the contract tenure to ten years would increase the break-even gas price needed to fully recoup investment costs for recently approved projects by around 20% on average (Figure 8.15). This illustrates the magnitude of contract price increases that could be required for the next crop of LNG export projects: if the additional uncontracted LNG requirements of EU members in the APS over the 2022-30 period were to be filled by new projects financed under ten-year contracts instead of twenty-year contracts, the additional cost to natural gas importers in the European Union would be around USD 140 billion.

An alternative approach would be for buyers in the European Union to contract flexible volumes for 20 years, for example from the United States, to ensure projects are permitted and to aim to sell the gas they do not need in later years to Asia. This is plausible in the STEPS, where LNG demand continues to increase to 2050, but global LNG demand peaks before 2030 in both the APS and NZE Scenario. Indeed, the rapid fall in LNG after 2030 in the NZE Scenario implies no need for additional capacity beyond what is existing or under construction; any new LNG projects approved after 2022 are at risk of not recovering their invested capital in the NZE Scenario.

Assessing the investment costs of transitioning away from Russian gas

The RePowerEU Plan sets out the investments required to reduce the European Union reliance on Russian energy imports. Many of the measures build on the Fit for 55 package, which also contains ambitious investment targets.

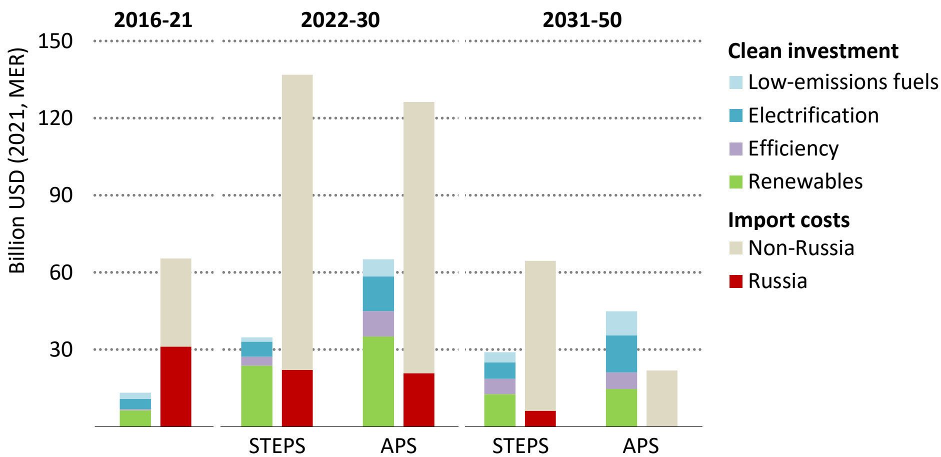
8

In the APS, investment in clean energy in the European Union averages around USD 360 billion per year between 2022 and 2030, an 80% increase on average levels over the past five years. Through a detailed sectoral decomposition of spending, we have assessed the contribution of clean energy investment to reduce natural gas demand (as distinct from reducing demand for oil or coal, or meeting new demand for energy arising from population or economic growth).

Our calculations indicate that around one-fifth of total investment in clean energy in the European Union yields a reduction in natural gas demand in the APS. The main investment categories that contribute to this reduction are building retrofits, electrification of energy services that would otherwise use natural gas (mainly through wide scale purchasing of heat pumps for use in buildings), and measures that lead to the replacement of gas with renewables in the power sector or boost investment in low-emissions fuels such as biomethane and hydrogen.

The combined cost of these measures is USD 65 billion per year on average over the 2022-30 period, around double the sums spent in the STEPS. However, the additional investments to transition away from natural gas in the APS result in much lower import costs in the long term, which are nearly USD 45 billion lower per year than in the STEPS from 2031 to 2050 (Figure 8.16). Moreover, a large portion of the transition costs go toward domestic jobs and service industries. Russian gas export earnings to the European Union over the 2016-21 period of around USD 30 billion per year are reduced to zero before 2030 in the APS; Russia fails to recover most of the income lost to reduced gas supply to Europe.

Figure 8.16 ▻ Average annual investment in clean energy to transition from natural gas in the European Union and gas import costs, 2016-50



In the APS, USD 65 billion of investment per year is required to cut natural gas demand in the European Union by 180 bcm by 2030, a sum offset over time by lower gas import costs

Note: MER = market exchange rate.

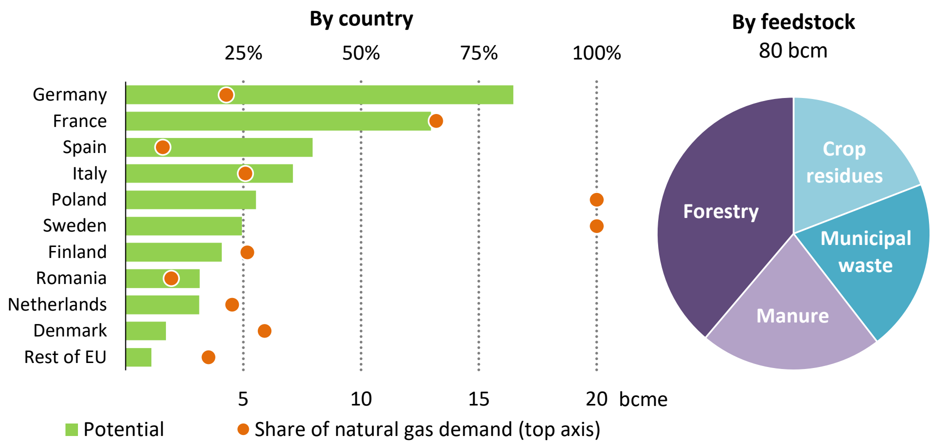
Scaling up biomethane

The European Union is supporting the scaling-up of biomethane, where there is significant potential across the region (Figure 8.17). Around 3 bcm of biomethane and 9 bcme of biogas is currently produced (most of the latter is directly consumed in local production of electricity and heat). The growth in biomethane production envisioned in the RePowerEU Plan implies a 35% average annual growth rate from 2022-30 compared to 20% in 2015-21.

IEA analysis suggests that 35 bcm of biomethane could be produced in the European Union for less than USD 20/MBtu. This is below the average price seen since July 2021, but well above the average of the past decade. However, it does not include injection costs into pipelines, or compression and liquefaction costs. Factors that could accelerate cost reduction and production growth include streamlined permitting procedures, factory-style fabrication of standardised biodigesters and related equipment, pooling of feedstocks, dedicated biogas financing facilities, and policy measures such as quotas, feed-in tariffs and contracts for difference.

Biomethane can also yield a significant quantity of digestate, a by-product which can be used as a biofertiliser. Digestate yields vary depending on the volatile solids content and methane potential of different feedstocks; 35 bcm of biomethane production could yield significant quantities of nitrogen biofertiliser, reducing mineral fertiliser use. In addition, it could avoid methane emissions if the digestate is responsibly handled and stored. There is also potential to use the relatively pure stream of CO_2 associated with the biogas upgrading process to produce synthetic methane.

Figure 8.17 ▷ Biomethane potential in the European Union by 2030 compared with share of natural gas demand in 2021



Up to 80 bcm of biomethane could be produced sustainably in the European Union by 2030; some countries have potential exceeding their current natural gas demand

Notes: EU = European Union; Rest of EU = average of the 17 member states not shown individually.

8

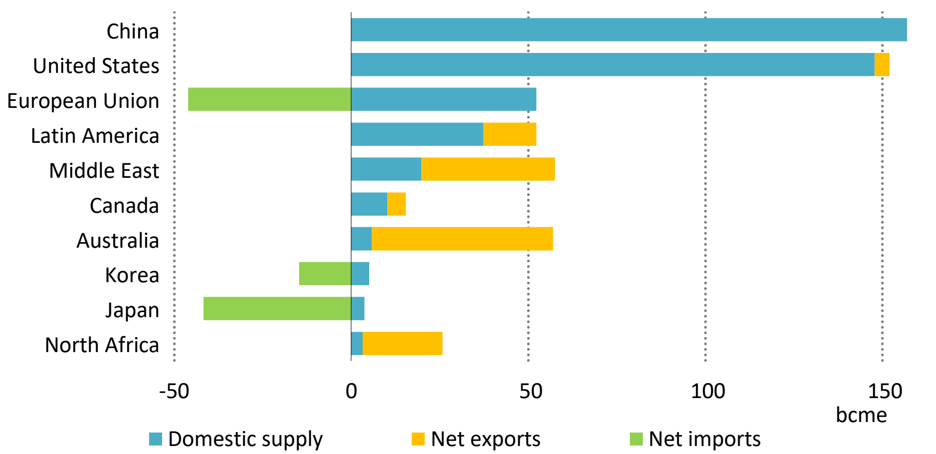
8.7 Scaling up hydrogen

Momentum behind the global low-emissions hydrogen sector has been given a major boost by Russia's invasion of Ukraine. By 2021 the sector was already converting more of its bulging project pipeline into investment decisions, and hydrogen-focussed companies were raising more money than ever before. With EU member states now aiming to reduce natural gas and oil demand by increasing low-emissions hydrogen use, and higher formal targets in the United Kingdom and elsewhere, it seems likely that major projects around the world will start construction in the near term.

Capital flows indicate where investors and companies see opportunities in the coming years. Two of the world's largest electrolysers started operations in 2022. In China, the capacity of a captive electrolyser supplying a methanol and chemical plant was expanded fivefold to 150 MW. In Spain, a solar-powered 20 MW electrolyser was commissioned at an existing fertiliser plant. Two large electrolyser projects received final investment decisions. First is a 260 MW electrolyser that aims to start supplying a refinery in China from 2023. Second is a 200 MW plant operating on wind power in the Netherlands, which is due to start in 2025, and is coupled with an existing refinery with high hydrogen demand. Overall, capital spending in 2021 on hydrogen electrolyser projects starting operation or under construction was around USD 1.5 billion, more than three-times as much as in 2020. In each project, the investment case was supported by the simplicity of the value chain.

The large pipeline of projects on which investment decisions are due to be taken in the near term depends on the scaling-up of companies across the value chain. Investors have taken note and are directing money to companies all along the hydrogen value chain. The 33 "pure play" hydrogen companies tracked by the IEA have increased their capitalisation by around USD 20 billion since mid-2020. Investors looking even further ahead allocated USD 700 million in 2021 of early stage venture capital to start-ups that are developing hydrogen technologies, which is nearly five-times the amount invested in 2020. This increase was driven by investor confidence in start-ups that offer project development services, which reinforces the perception that projects will soon be built, and in innovative technologies for hydrogen end-uses as well as for potential non-electrolysis routes to low-emissions hydrogen production, such as methane pyrolysis.

Figure 8.18 ▷ Domestic supply and trade of low-emissions hydrogen for key regions in the APS by 2050



Low-emissions hydrogen production exceeds 50 bcm of natural gas equivalent in several regions, with exports as the main driver in Australia, Middle East and North Africa

Notes: bcme = billion cubic metres of natural gas equivalent. Low-emissions hydrogen trade includes trade in hydrogen-based fuels as a means of exporting clean energy via its transformation to hydrogen. Inclusion in this figure does not imply that the traded products are all used in the form of gaseous hydrogen in importing countries. Values are given in bcme based on a conversion factor of 36 petajoules of traded energy product per bcme.

Global low-emissions hydrogen production reaches 30 Mt of hydrogen per year (Mt H_2/year) in 2030 in the APS, including hydrogen produced onsite in industry and refineries as well as that used to produce hydrogen-based liquid fuels. This is equivalent to the energy content of 100 bcm of natural gas and would represent an enormous ramp up from much less than 1 Mt of low-emissions hydrogen today. Producing and delivering this volume of hydrogen by 2030 in the APS would require cumulative investment of USD 170 billion in electrolysers and CCUS equipment, and nearly three-times this sum for new renewable electricity capacity, infrastructure and plants for conversion to hydrogen-based fuels. Installed electrolyser capacity in 2030 reaches 260 GW in the APS, fed by over 1 000 terawatt-hours (TWh) of low-emissions electricity. While much of the demand is initially concentrated in China, Europe, Japan and North America, investment becomes more evenly spread as trade between countries gets underway later this decade. By 2050, trade patterns become well established, with Australia and the Middle East as the largest exporting regions (Figure 8.18).

2030 investment challenge for hydrogen

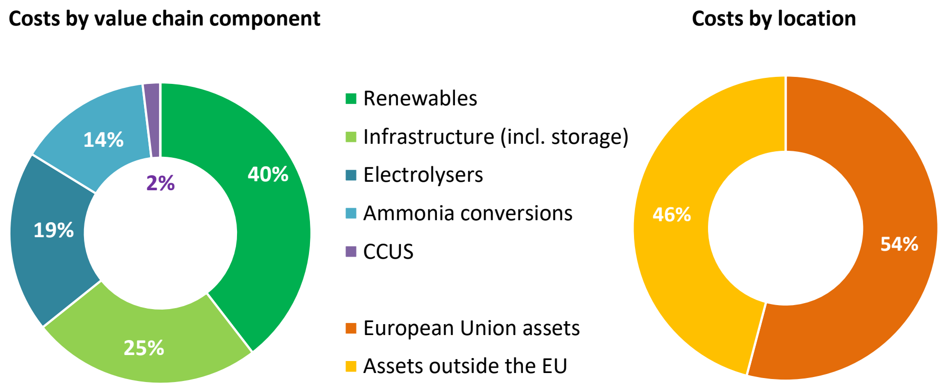
A major driver of hydrogen-related activity is the political determination of the European Union to develop and use hydrogen. In 2021, the European Commission proposed that by 2030 the industrial and transport sectors in the European Union should use approximately 11 Mt H_2/year made from the electrolysis of water by renewable electricity. In May 2022, the European Commission proposed nearly doubling this to 20 Mt H_2/year across all end-use and transformation sectors, with half of the total imported into the European Union from other countries.[2] To put this in context, EU industry currently produces and uses around 7 Mt H_2/year of hydrogen, nearly all of it from natural gas, and its transport sector uses less than 1 thousand tonnes per year. The proposal, which is calculated to displace 27 bcm of natural gas and 80 thousand barrels per day (kb/d) of oil, is too large a scale to realistically be met solely by replacing existing hydrogen sources with electrolysis. New sources of demand will also be required.

Based on a possible configuration of assets that could produce 10 Mt H_2/year within the European Union and deliver an additional 10 Mt H_2/year to the European Union in 2030, we estimate the total capital investment at USD 700-850 billion, almost half of it related to assets outside the European Union (Figure 8.19).[3] This more than doubles when the cost of capital is included. The largest single cost component would be the purchase and installation of around 440 GW of renewable electricity generation, mostly solar PV and wind, to power the electrolysis process. The purchase and installation of 290 GW of electrolysers accounts for 15% of the estimated total, less than infrastructure such as pipelines, port terminals, ships and hydrogen storage. Repurposing existing natural gas pipelines could cost less than half as much as building new ones for hydrogen, but this would have to be aligned with the phasing out of natural gas. In the APS, repurposed natural gas pipelines account for around 50% of new installed hydrogen pipeline capacity in the 2030s.

[2] These proposals are yet to be officially adopted by the European Union or translated into enabling legislation.

[3] The lower end of the range of estimates assumes that by 2030 5 Mt H_2/year could be imported by undersea pipelines, while the higher end assumes that the pipelines cannot be commissioned in this timeframe and the vast majority of imported hydrogen will be shipped in the form of ammonia, building on existing ammonia infrastructure. Shipping of liquefied hydrogen is not expected to make a significant contribution by 2030. It assumes that hydrogen will be produced from renewable electricity installations constructed for the purpose of electrolysis, which is broadly in line with proposed EU regulations but may lead to a slight overestimation of costs. Capital requirements for pipelines, hydrogen storage, new ships, ammonia production and some ammonia cracking are included.

Figure 8.19 ▷ Cost shares of a possible investment package to secure 20 Mt H_2 for the European Union from local and imported supplies by 2030



Investments to supply hydrogen to reduce oil and gas demand in the European Union are mostly needed in renewable electricity projects and half would fund non-EU assets

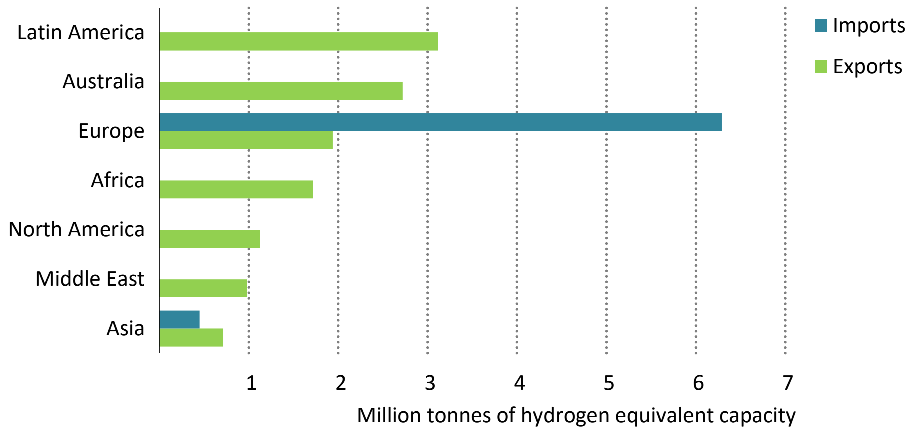
Notes: CCUS = carbon capture, storage and utilisation; EU = European Union. Ships and pipelines entering the European Union are considered as assets outside the European Union.

The European Union is not alone in pursuing hydrogen and hydrogen-based fuel imports. Japan is aiming for a 20% rate of co-firing imported ammonia at its coal-fired power plants in 2030, and this is estimated to require 0.5 Mt H_2/year. To back this up, JERA, Japan's largest electricity generator and a major gas trader, issued a tender for supply up to 0.5 Mt of low-emissions ammonia (requiring almost 0.1 Mt H_2) to Japan's largest coal-fired power plant from 2027. Korea aims to commercialise 20% ammonia co-fired power generation by 2030. Both countries are actively developing partnerships with a range of potential exporter countries and technology providers. In June 2022, BP took a 40% stake in a project that could produce 9 Mt/year of low-emissions ammonia (or 1.6 Mt H_2/year) in Australia, with Japan and Korea listed as the primary initial export targets. To be successful, the developers anticipate that they will need to raise over USD 35 billion.

Pipeline of hydrogen trading projects has swelled

If all projects under development are successful at raising funds and meeting their schedules, there would be enough global capacity to export 12 Mt H_2/year of low-emissions hydrogen or its equivalent in hydrogen-based fuels by 2030, of which 11 Mt H_2/year would come from outside the European Union (IEA, 2022b). Much of this proposed capacity would be in Chile, Argentina and Brazil, but there would also be significant amounts in Australia, Denmark, Mauritania and United States. Among Middle East and African countries, the largest proposed projects are in Egypt, Mauritania, Oman, Saudi Arabia and United Arab Emirates.

Figure 8.20 ▷ **Capacity of proposed international hydrogen trade projects targeting operation by 2030 by exporter or importer country**



If all export projects under development proceed, they could supply 12 Mt of low-emissions hydrogen equivalent by 2030, subject to the availability of import infrastructure

Notes: Projects included are those with a named location for the planned import or export facility, such as an existing port. Proposed exports within regions, such as Europe, are included.

Projects seeking to export hydrogen or hydrogen-based fuels are more numerous and more advanced than those for the corresponding import infrastructure (Figure 8.20). Of the 12 Mt H_2/year of proposed exports, projects accounting for 2 Mt H_2/year have named potential or agreed off-takers and a further 3 Mt H_2/year cite export to a specific region. However, there are currently only five ports around the world developing hydrogen import plans. These are for Amsterdam, Brünsbuttel, Rotterdam and Wilhelmshaven in Europe and Kobe in Japan.

Ammonia is emerging as the most common form for the export and import of hydrogen by sea in 2030. While around half of announced projects have not yet stated a clear preference, ammonia represents over 85% of planned capacity for those that have expressed an intention to date. Liquefied hydrogen and liquid organic hydrogen carriers are not expected to take a high share during this decade. While Europe has existing infrastructure which makes it possible to import several million tonnes of ammonia each year for chemical uses, significant additional capacity is needed if meaningful amounts of low-emissions hydrogen are to be exported to Europe as ammonia. Expanding existing facilities would be a much lower cost option for providing capacity expansion than greenfield developments. Undersea pipelines for transporting hydrogen to the European Union are also under discussion, with Germany and Norway exploring how soon such infrastructure could connect their countries.

Unlocking project investment requires global co-ordination

New contractual relationships need to be established throughout the low-emissions hydrogen value chain if the challenge of scaling up is to be met. Robust contracts that can remain in place for 10-20 years or more are essential to unlock the investment required. There are very few precedents or standards for these kinds of contracts, but they will need to be put in place and aligned to enable multiple billion dollar projects to proceed in parallel and to avoid mismatches between supply, distribution and demand.

Launching a new hydrogen value chain may need as little as three contractual relationships (two purchase agreements and one engineering, procurement and construction [EPC] contract) or as many as 20 (seven purchase agreements and 13 EPC contracts), depending on the need for new energy inputs and the intermediaries involved in trade. Most of the largest integrated projects to date have simple value chains, for example with projects being developed at fertiliser or refinery sites with existing hydrogen demand, which suggests that it may be desirable to minimise the number of contracts as far as possible.

At one end of this value chain is the manufacture of electrolysers, equipment for CO_2 capture and devices for hydrogen transport and storage. Investors in the companies and projects that will deliver the required factory output, including the supply of raw materials such as platinum for catalysts, have shown interest in the initial prospects of this business, but much more capital will be needed to achieve the 260 GW of electrolyser installations in 2030 in the APS, given that manufacturing capacity is currently around 8 GW per year. The value chain includes the installation of hydrogen production capacity and upstream contractual relationships with renewable electricity suppliers, power grid operators, electricity markets, gas suppliers, CO_2 storage companies and EPC firms. For hydrogen trade, the value chain expands to include the construction and operation of new port infrastructure, buffer storage, pipelines, ships, refuelling stations and plants to convert the hydrogen into a more readily transportable commodity (and potentially back to hydrogen). At the other end of the value chain are the off-take contracts agreed with the users of low-emissions hydrogen that guarantee revenue: all the preceding steps ultimately depend on these. Many users will also need to make significant investments in new equipment and procedures to switch from other fuels, for which they will be reliant on new manufacturing facilities for tanks, meters, burners, turbines and other hydrogen-specific apparatus.

Governments around the world have critical roles to play in facilitating co-ordinated and timely investments, and this means in particular setting clear policy frameworks that are compatible across borders. This does not mean that governments have to dictate the precise format of the traded hydrogen products, but rather that agreed standards are needed for environmental criteria, and that policies are needed to incentivise end-users to commit to long-term purchases and manage off-take risk. In both areas, international co-ordination is essential if cross-border trade is to emerge as implied by government pledges.

Standards for guaranteeing that hydrogen-based commodities meet environmental criteria have emerged as an especially important issue for project developers. Investors seek upfront certainty that output from a project will be valued by hydrogen users, but the value to users depends on whether the product meets their regulatory obligations and market incentives. Regulatory obligations could include requirements to meet a share of total hydrogen demand with low-emissions hydrogen, something that is envisaged by the draft EU Renewable Energy Directive. Market incentives could come, for example, from manufacturers that anticipate charging a premium for a car made from low-emissions steel or which have set emissions targets for financial or ethical reasons, or from government contracts or CO_2 pricing.

Table 8.5 ▷ Emissions requirements for selected hydrogen labels and programmes

Jurisdiction	Label	Publication year	Requirements	Purpose
European Union	Renewable fuel of non-biological origin	2022 (proposal not yet adopted)	70% lower life cycle GHG emissions than an equivalent fossil fuel (3.4 kg CO_2-eq/kg H_2) delivered to a customer, or 80% after 2026 if used for electricity or heat. Only electrolysis hydrogen from renewables is eligible, and must prove additionality.	Eligible fuels (including hydrogen-based fuels) can contribute to national renewables targets.
European Union	EU taxonomy-aligned hydrogen	2022	73.4% lower life cycle GHG emissions than an equivalent fossil fuel (3 kg CO_2-eq/kg H_2 life cycle emissions at the point of production, or 70% for a hydrogen-based fuel).	Guide investments into climate change mitigation.
United States	Clean hydrogen	2022	Less than 4 kg CO_2-eq/kg H_2 life cycle GHG emissions up to the point of production.	Eligibility for funding instruments, with lower emissions eligible for more support.
Victoria, Australia in partnership with Germany	Zero-carbon hydrogen	2020	Hydrogen comes solely from renewable sources.	To receive guarantees of origin from the Smart Energy Council and Hydrogen Australia.
Independent	Carbon-neutral hydrogen	2020	Zero emissions, including upstream, net of offsets. For hydrogen produced from fossil fuels, 50% or more of the CO_2 must be stored and any solid carbon permanently secured.	Accreditation under voluntary TÜV Rheinland Standard H2.21.
Independent (originally funded by the European Commission)	Low-carbon hydrogen	2017	60% lower life cycle GHG emissions than hydrogen from natural gas, excluding emissions from equipment manufacturers (4.4 kg CO_2-eq/kg H_2).	Accreditation under voluntary CertifHy system.

There is still a long way to go on the development and agreement of internationally recognised standards. Several governments and commercial entities have proposed labels for various purposes, but they are not consistent with one another (Table 8.5). Not all of the methodologies for these standards and labels take a life cycle approach to emissions accounting. Moreover, none have so far tackled the question of how to account for the potential leakage of hydrogen itself. This may emerge as an important point: there is some evidence that fugitive emissions of hydrogen and other pollutants will need to be carefully avoided if the desired climate benefits of low-emissions hydrogen or ammonia at large scale are to be realised (BEIS, 2022; Wolfram et al., 2022).

Investments that will lead to trade of low-emissions hydrogen and hydrogen-based fuels between countries this decade will rely on international recognition of standards. Regions that expect to be first-movers in importing large volumes will have some flexibility to determine standards, but dialogue with exporters will be essential: a project developer deciding whether to contract with off-takers in the European Union, Japan or Korea will be influenced by the risks related to meeting emissions criteria. Importers have the opportunity in the near term to work on ensuring compatibility between regimes.

Reliable long-term demand for low-emissions hydrogen will be the main driver of investment for scaling up. In the first decade of hydrogen sector scale up, this demand is likely to be underpinned to a significant extent by government funding support. In the longer term, the focus is likely to shift to regulatory standards and fiscal penalties. Two instruments in particular are currently being explored in Europe: carbon contracts for difference (CCfD) and so-called double auctions. In the Netherlands, the first CCfD for an electrolyser project was awarded in 2021: it guarantees that the government will top up any difference between the market price and the cost of producing the low-emissions product for 15 years. In Germany, the H2Global double auction platform, funded by the government, was launched in 2021: it will offer ten-year contracts to the cheapest suppliers of hydrogen from renewable electricity and the buyers with the highest willingness to pay. As part of the REPowerEU Plan, the European Commission is exploring adopting these two types of mechanisms at the EU level.

In addition to standards and demand creation, a range of other measures will be needed to stimulate investment. These include safety regulations, infrastructure funds, permitting processes and risk management tools such as concessional debt and insurance. In all cases, reaching international agreement is likely to take several years and there may be a need for risk management provisions for final investment decisions before such agreements are reached. For example, the hydrogen provisions in the proposed revision of the EU Renewable Energy Directive, which include sectoral targets, may not materialise in full or, if agreed, may not be transposed into national law before 2025.

8.8 Is natural gas still a transition fuel in emerging market and developing economies in Asia?

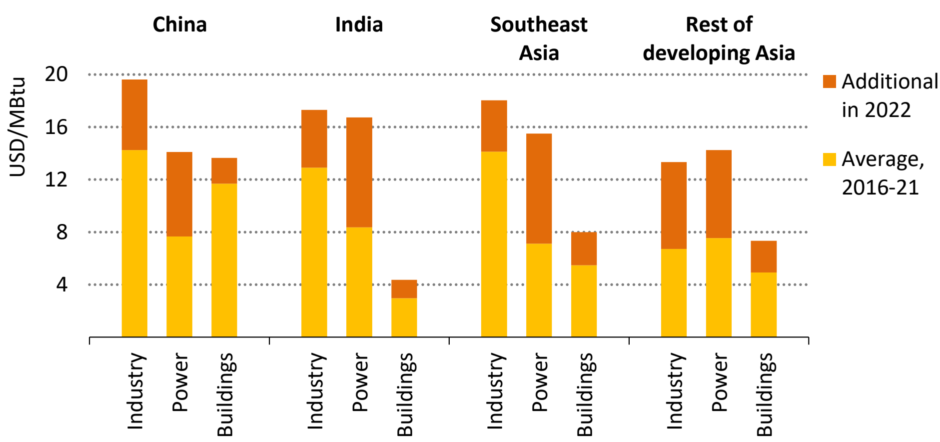
The traditional case for natural gas in emerging market and developing economies is that it is a flexible and versatile source of dispatchable energy, supporting the rapid build up of renewables while underpinning a transition away from coal. Gas can be employed in the power sector as a back-up for renewables and help to balance grids in real time. The coal, oil or biomass for process heat used by small- and medium-scale industries can also be progressively replaced by natural gas, which brings with it advantages such as improved efficiency and cleaner air, while reducing the cost of operating flexibly. Investments in transmission and distribution grids can allow gas to meet demand for cooking fuel and water heating. In more temperate parts of the developing world, natural gas can also help meet seasonal energy demand.

The strains on global natural gas supply that have been emerging since 2021 cast doubt on these propositions. The surge in LNG prices arising from high demand in Europe has pulled supply away from price-sensitive markets such as Pakistan and Bangladesh, leading to shortfalls in the power sector and industrial demand destruction in those countries. Although some markets have been somewhat shielded from volatility thanks to long-term supply contracts with fixed volume commitments and prices that are linked to oil, the price of gas for end-users in emerging markets in Asia can be expected to rise by about 55% in 2022 compared with the five-year average (Figure 8.21). There is limited fiscal headroom in emerging markets to sustain interventions that shield consumers from higher prices, such as caps on tariff increases or subsidies for bills targeted at lower income households, and so the price increases seen in 2022 have pushed up the costs of electricity as well as a wide range of industrial products and processes, stoking inflation and aggravating a cost-of-living crisis.

Increased climate ambition in some emerging market and developing countries in Asia implies that natural gas now faces existential questions about its long-term future. In this section we explore the role of natural gas in this region in the APS, a scenario which reflects recent net zero emissions pledges announced in some of the major growth markets in Asia – China, India, Malaysia, Singapore, Thailand and Viet Nam.

8

Figure 8.21 ▷ End-user prices for natural gas by sector emerging market and developing economies in Asia

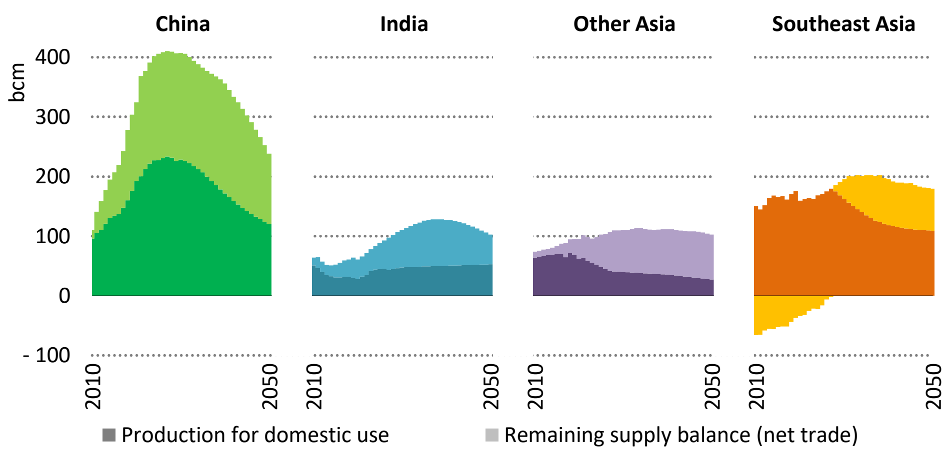


End-user prices for natural gas are estimated to increase by more than 55% in 2022, challenging the affordability of gas in price-sensitive regions

Can emerging gas markets in Asia continue to thrive on imports?

In 2010, emerging market and developing economies in Asia were, in aggregate, net gas exporters. Flat or declining production in mature gas fields in countries such as Indonesia and Malaysia, along with strong demand growth in China and India, meant gas imports rose quickly to cover 30% of total gas demand by 2021. In the APS, import dependence increases further to over 40% by 2030 (Figure 8.22).

Figure 8.22 ▷ Natural gas supply balance in emerging market and developing economies in Asia in the APS, 2010-2050



Demand growth in emerging market and developing economies in Asia requires a large increase in gas imports and associated investment in LNG terminals and domestic gas networks

This increasing reliance on natural gas imports – especially LNG – has recently been challenged by high prices. There is around 200 bcm per year of existing LNG import capacity in the region (of which 45% is in China). A further 120 bcm per year is under construction. To meet the requirements of the APS, a further 85 bcm per year of import capacity is required by 2030. To date, however, potential new entrants to the LNG market, such as the Philippines and Viet Nam, have yet to secure long-term contracts for supply that could underpin the construction of LNG regasification terminals. Utilities in the region have low credit ratings and the limited ability of off-takers to absorb higher prices brings with it significant commodity price risk, particularly against the background of a stronger US dollar. Countries such as Indonesia, Myanmar and Viet Nam are attempting to contract floating storage and regasification units, which are cheaper and quicker to build than land-based terminals and can be flexibly redirected to areas in need of short-term gas supply. However, Europe's call on these units to meet near-term LNG supply has tightened supply chains and increased competition.

How resilient is natural gas demand?

It is possible to look past the current market turbulence and make a case that natural gas demand in emerging and developing economies in Asia might turn out to be quite resilient, at least for the next decade. In the APS, natural gas satisfies nearly 20% of total energy demand growth in these economies between 2021 and 2030 – a higher percentage than in the previous decade. Although coal is widely viewed as a cheaper and more readily available alternative to natural gas in several parts of Asia, its own supply dynamics are challenged by a lack of upstream investment and constraints on access to finance. Prices have also moved higher: thermal coal import prices averaged around USD 60/tonne in 2020, but doubled in 2021 and then rose again to an average of around USD 200/tonne in the first-half of 2022.

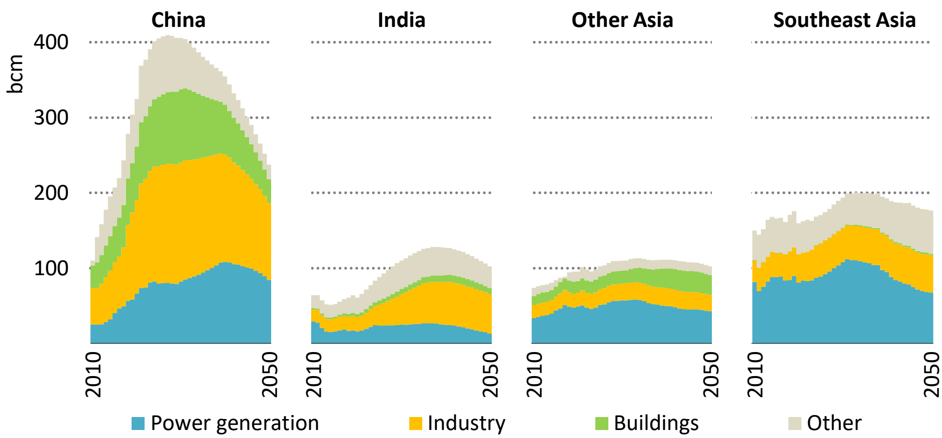
The extent to which consumers feel the effects of natural gas price increases also varies widely between countries and sectors. Cheaper domestic gas is sometimes allocated to specific consumer groups, as in India, or regulated at a price that is capped at a maximum level regardless of changes in wholesale prices, as in Indonesia. Through tariff decisions and different tax regimes, the price charged for natural gas can fall below the cost of import or production, keeping demand resilient in certain segments, as in parts of India's city gas distribution sector.

Despite gas-fired power plants being more exposed to changes in wholesale gas prices, they remain a relatively cheap thermal plant type to build and are able to operate flexibly. In 2021, final investment decisions for new gas-fired capacity reached 20 GW, 15% above the five-year average, and growth remained strong into 2022. Although the prospects for coal-to-gas switching have been adversely affected by higher gas prices, it would be technically possible, for example, for one-third of coal-fired power output in Southeast Asia to be substituted by existing gas-fired power capacity (which totals around 100 GW and currently operates at a 45% annual load factor). Doing this would avoid around 120 Mt CO_2 emissions, equivalent to 22% of emissions from coal-fired power plants in Southeast Asia (IEA, 2022c).

In the APS, around 90 GW of new natural gas-fired power generation capacity comes online in emerging market and developing economies in Asia between 2021 and 2030, an increase of over 20%. Natural gas-fired generation increases at a slightly slower pace than generation capacity, reaching 1 200 TWh by 2030, or 25% more than in 2021. This reflects increasing use of natural gas capacity as a flexible tool to balance electricity grids rather than as a baseload source of power supply (see Chapter 4, section 4.5). Using natural gas in this way requires flexible contracting arrangements for LNG supplies and additional investment in gas storage. In China, the 15 bcm of storage capacity equates to less than 5% of annual gas consumption, despite growing seasonality of demand (although there are ambitious plans to increase storage capacity to 50-60 bcm by 2025). Large-scale gas storage facilities are virtually non-existent in most other parts of Asia.

An increasing population and strong economic growth sustain the increase in natural gas consumption in emerging market and developing economies in Asia over the next decade, notably in industry, despite the near-term risks brought about by the recent supply squeeze. As prices come down from the mid-2020s, these markets see a big increase in natural gas use by 2030 as a result of coal-to-gas switching, and this helps countries with net zero emissions targets to rapidly transition away from coal. With a clouded outlook for the use of natural gas in transport (Box 8.1), industry remains the anchor for demand growth and the focal point for large-scale infrastructure investment in LNG import capacity, storage and onshore transmission and distribution grids. In the APS, gas demand in industry in emerging gas markets in Asia, not including China, is over 60% higher in 2050 than in 2021.

Figure 8.23 ▷ Natural gas demand in emerging market and developing economies in Asia in the APS

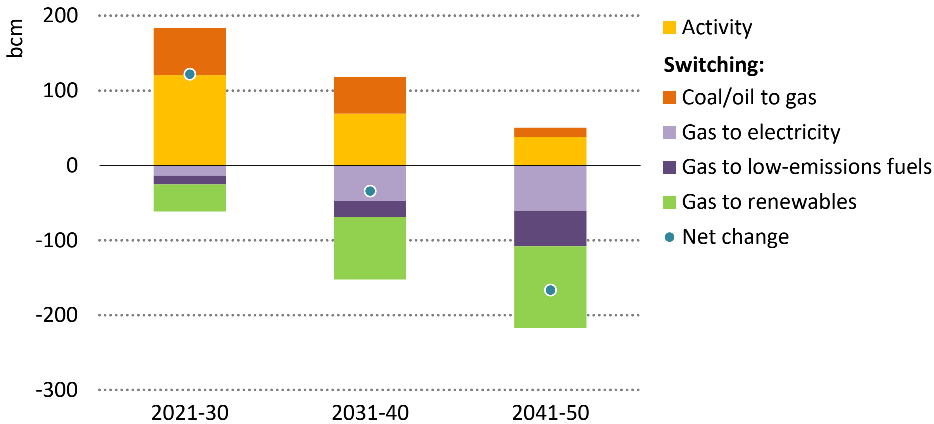


In the APS, natural gas demand peaks before 2040 in emerging market and developing economies in Asia

Ultimately, however, the prospects for natural gas in emerging market and developing economies in Asia have a limited duration. Although the trajectory varies, demand peaks in all emerging gas markets in Asia before 2040 in the APS (Figure 8.23). The share of natural gas in total power generation remains flat in the years ahead, but then falls to less than 5% by 2050 as other sources of power system flexibility drop in price and step in to replace gas. The levelised cost of electricity (LCOE) of battery storage combined with utility-scale solar – a benchmark of the competitiveness of renewables against dispatchable thermal capacity – drops by around 50% between 2021 and 2050, falling below the LCOE of a new combined-cycle gas turbine.

After 2030, natural gas demand growth slows in the APS for a number of reasons (Figure 8.24). Renewables meet all of the growth in power generation between 2030 and 2050, while electricity and the direct use of renewables meet all of the growth in buildings sector energy demand. With the exception of northern China, growth markets for gas in Asia do not have significant need for seasonal heating in buildings, and electricity and solar-based heating offers a cost-competitive alternative to the use of gas in households for cooking and hot water. Between 2030 to 2050 in industry, the growth of electricity and low-emissions fuels such as hydrogen helps to push the share of natural gas in total demand to below 9%.

Figure 8.24 ▷ Drivers of change in natural gas demand in emerging market and developing economies in Asia in the APS



Population and economic growth increase natural gas demand for a while, but renewables, low-emissions fuels and electrification diminish gas demand in the long term

Box 8.3 ▷ Is the golden age of natural gas over?

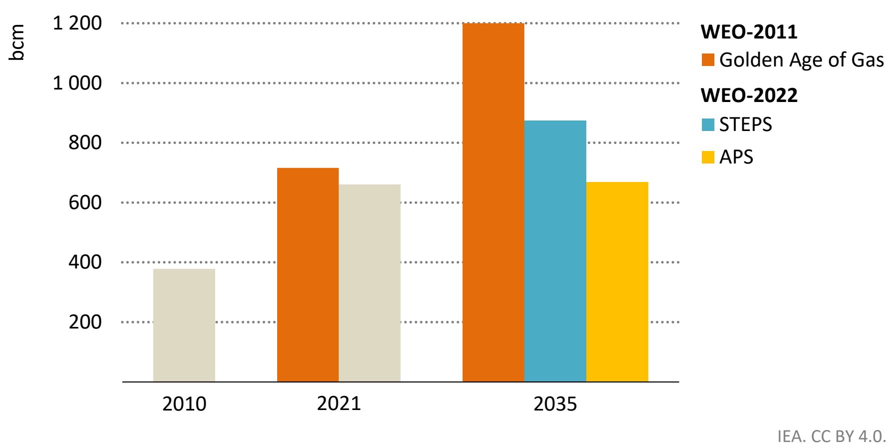
The IEA released a special report in 2011, *Are We Entering a Golden Age of Gas?*, which explored the potential for a golden age of natural gas based on supportive assumptions about the availability and price of natural gas and about demand-side policies that could support its use in the emerging world (IEA, 2011). More than a decade later, the growth in global natural gas consumption to 2021 turns out to have been very much in line with the projections made in that report. In developing Asia, natural gas demand from 2010-21 ended up being 8% higher than projected in the report. However, current longer term projections indicate a diminished role for natural gas overall and particularly in developing Asia.

The key pillars for growth in the Golden Age scenario were the competitiveness of natural gas as large volumes of shale gas were developed in the United States, strong economic growth across Asia, and supportive policies which valued the advantages that natural gas had compared with alternative fuels such as coal, oil or traditional biomass, notably in terms of lower emissions and cleaner air.

The competitiveness of natural gas, however, has come under pressure, and competition from low cost renewables such as solar PV and wind has now narrowed the space for growth in natural gas. There are also reasons to think that the age of supportive policies for natural gas may be drawing to a close. Near-term supply scarcity and energy security concerns have not only driven up natural gas prices but have also sparked long-term gas affordability concerns, and net zero emissions pledges have focussed minds on an eventual phase out of unabated natural gas.

The outlook for natural gas in emerging market and developing economies in Asia by 2035 is about 310 bcm lower in the STEPS this year than it was in the Golden Age of Gas Scenario in 2011 (Figure 8.25). In the APS, it is lower by 420 bcm. This change in the outlook to 2035 is not confined to developing Asian markets. For example, the projection of combined European Union and United Kingdom natural gas demand by 2035 in the APS is 45% lower than it was in the Golden Age of Gas report in 2011, reflecting current market concerns, increased climate ambitions and revised assumptions about economic growth.

Figure 8.25 ▷ Natural gas demand in emerging market and developing economies in Asia by *WEO-2022* scenario and outlook of the Golden Age of Gas Scenario in 2011



The contribution of natural gas to meet energy demand in developing Asia from now to 2035 appears less significant than projected a decade ago

While some may cheer the clouded outlook for natural gas, it remains an important part of the energy system in developing Asia. There is also a risk that declining prospects for gas may mean that emerging market and developing economies in Asia hold on to their coal-fired power generation for longer, resulting in unfavourable emissions outcomes (unless there is a historic acceleration in investment in CCUS). This has happened before. In energy-hungry India and Southeast Asia, for example, a challenging environment for domestic gas production between 2010 and 2021 meant natural gas became less competitive with coal. The result was around 30 bcm of natural gas demand lost to gas-to-coal switching, leading to a 50 Mt CO_2 increase in emissions which would have been avoided if natural gas had been used instead.

Outlook for solid fuels

Phase down postponed?

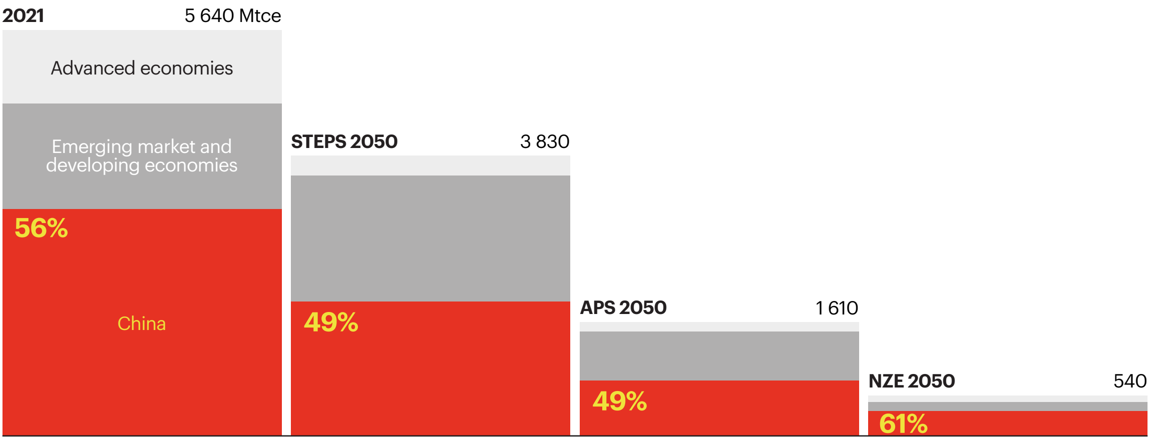
SUMMARY

- Global coal demand rebounded strongly in 2021 to 5 640 million tonnes of coal equivalent (Mtce) as economies recovered from the pandemic and coal-fired power generation reached a historic high in 2021. Both China and India have boosted investment in domestic coal production, but global production struggled to keep pace with demand increases, causing coal prices to surge. Russia – the world's third-largest coal exporter – and its invasion of Ukraine complicated coal market dynamics and brought additional pressure on prices.
- The outlook for coal is heavily dependent on the strength of the world's resolve to address climate change. In the Stated Policies Scenario (STEPS), coal demand declines gradually. In the Announced Pledges Scenario (APS), it declines about 20% below current levels by 2030, and 70% by 2050; coal demand peaks in China in the early 2020s and in India in the late 2020s. In the Net Zero Emissions by 2050 (NZE) Scenario, demand falls 45% by 2030 and 90% by 2050.
- There is very limited use of carbon capture, utilisation and storage (CCUS) with coal in the STEPS. Around 500 Mtce of coal consumed in 2050 is equipped with CCUS in both the APS and NZE Scenario, corresponding to around 30% of coal demand in the APS and more than 80% in the NZE Scenario in 2050. Unabated coal use drops by 99% between 2021 and 2050 in the NZE Scenario.
- Following the European Union ban on Russian imports, a short-lived increase in coal consumption in Europe is supplied from a variety of sources including South Africa and Colombia. The Asia Pacific region accounted for more than three-quarters of global coal imports in 2021 and this share is set to rise. Despite efforts to increase domestic production, India becomes the world's largest coal importer in the STEPS in the mid-2020s, while, by far, China remains the largest producer and consumer. In the APS, coal trade falls by 60% to 2050; in the NZE Scenario, it falls by 90%.
- Nearly 25 exajoules (EJ) of biomass (equivalent to 830 Mtce) was used for traditional cooking and heating in 2021, mainly in developing economies in Africa and Asia. This falls by 20% to 2030 in the STEPS, which still leaves around 2 billion people without access to clean cooking. In the APS, the traditional use of biomass falls by more than 60% to 2030. In the NZE Scenario, universal access to clean cooking is achieved by 2030 and the traditional use of biomass is fully phased out.
- Around 35 EJ of modern solid bioenergy was consumed in 2021, mainly for heat, power generation, and conversion into liquid and gaseous biofuels. This increases by 2030 in each scenario, rising by 30% in the STEPS, by 50% in the APS, and by just over 60% in the NZE Scenario.

Future coal use depends heavily on efforts to address climate change

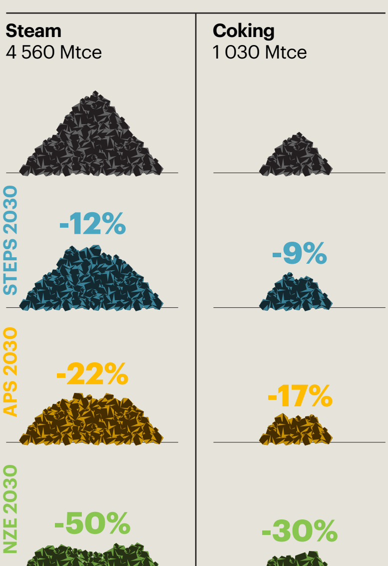
Coal demand declines in all scenarios, with a faster phase-down in advanced economies than in emerging market and developing economies.

China remains by far the most influential market for coal throughout the outlook.



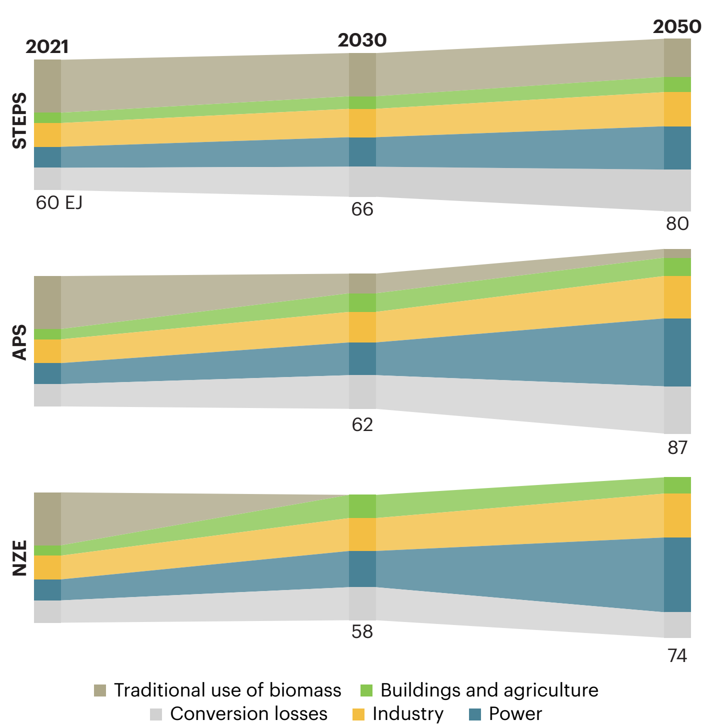
Steam coal declines further and faster than coking coal

Steam coal is mainly used for heat and electricity where it is increasingly replaced by renewables. Coking coal is mainly used in steel making where there are fewer readily available alternatives.



Traditional use of biomass gives way to modern solid bioenergy

Traditional use of biomass falls as people gain access to clean cooking, while modern bioenergy grows, mainly in the power sector and for biofuel production. In the NZE Scenario, bioenergy resources are responsibly managed and do not compete with other land uses.



Introduction

Recent developments have dealt a blow to the idea that global coal demand might soon subside. The drop in coal demand in 2020 was more than offset by a strong rebound in 2021, taking it very close to its all-time high. In advanced economies, where coal use had been declining, demand increased by nearly 10%. In emerging market and developing economies, which account for just over 80% of global coal use today, demand rose by 5%.

Coal production in 2021 struggled to keep pace with one of the largest ever annual increases in demand. Markets have been further upended by Russia's invasion of Ukraine. Russia was responsible for around half of the coal imports in the European Union in 2021, but that trading relationship ended with the EU ban on Russian coal imports. Meanwhile there have been limited short-term fuel switching opportunities to ease demand pressures. The overall result is that global coal prices reached historic highs in the first-half of 2022.

Coal-fired power generation reached a historic high in 2021, with China, India and Southeast Asia all setting new records. So far in 2022, record high natural gas prices have led to gas-to-coal switching in a number of markets, including in the European Union, and a number of coal power plants have increased utilisation or been granted lifetime extensions.

Global coal supply increased by over 5% in 2021, even though production was hampered for a number of producers by supply chain disruptions, Covid-19 containment measures and adverse weather conditions. The largest increase was in China, where production rose by around 160 million tonnes of coal equivalent (Mtce) (a 6% increase), followed by the United States with 65 Mtce (18%) and India with 50 Mtce (13%). China and India are looking to increase investment in domestic supply, but difficulties securing financing and insurance are increasingly restricting investment in new coal mines in other countries.

Solid bioenergy accounts for 10% of global energy supply today. Just over 40%, around 25 exajoules (EJ), is traditional biomass for cooking and heating, which is used by around 2.4 billion people worldwide that do not have access to clean cooking facilities. The remainder, around 35 EJ, is modern solid bioenergy, which is mainly used to generate electricity, provide heat for industry and buildings, and as feedstock for biofuels.

The outlook for coal and other solid fuels depends on government policies and different assumptions about how these will develop. This yields very wide variations in the outlook for solid fuel demand. Coal consumption falls in each of our scenarios; it declines by around 10% to 2030 in the Stated Policies Scenario (STEPS), by 20% in the Announced Pledges Scenario (APS), and by 45% in the Net Zero Emissions by 2050 (NZE) Scenario.

The chapter highlights the key findings of our updated projections. Much more detail is included in a forthcoming *World Energy Outlook* Special Report, *Coal in Net Zero Transitions: Strategies for rapid, secure and people-centred change* to be released in November 2022. Against the backdrop of current strong coal consumption and a reappraisal of energy security concerns, the report examines how policy makers and other stakeholders can implement and finance a reduction in coal emissions without compromising electricity security or economic growth, while taking into account the social consequences of change.

Scenarios

9.1 Overview

Table 9.1 ▷ Global coal demand, production and trade, and solid bioenergy use by scenario (Mtce)

			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
World coal demand	**5 220**	**5 644**	**5 149**	**3 828**	**4 539**	**1 613**	**3 024**	**539**
Power	3 108	3 642	3 174	2 086	2 852	938	1 685	306
Industry	1 690	1 629	1 684	1 520	1 426	640	1 159	206
Other sectors	423	373	291	222	261	36	180	28
Share of demand with CCUS	*0%*	*0%*	*0%*	*1%*	*1%*	*31%*	*3%*	*89%*
Advanced economies	1 585	1 024	526	297	375	127	267	84
Emerging market and developing economies	3 636	4 620	4 623	3 532	4 164	1 486	2 762	455
World coal production	**5 235**	**5 825**	**5 149**	**3 829**	**4 539**	**1 613**	**3 024**	**539**
Steam coal	4 069	4 560	4 026	2 954	3 538	1 177	2 271	407
Coking coal	866	1 030	936	736	855	381	716	120
Peat and lignite	300	235	187	139	146	56	38	12
Advanced economies	1 512	1 124	729	590	522	186	362	99
Emerging market and developing economies	3 723	4 702	4 420	3 239	4 017	1 427	2 662	443
World coal trade	**948**	**1 135**	**999**	**958**	**859**	**470**	**539**	**137**
Trade as share of production	*18%*	*19%*	*19%*	*25%*	*19%*	*29%*	*18%*	*25%*
Coastal China steam coal price	**142**	**155**	**81**	**67**	**66**	**56**	**52**	**44**
Solid bioenergy (EJ)	**49**	**60**	**66**	**80**	**62**	**87**	**58**	**74**
Traditional use of biomass	25	24	20	18	9	6	-	-
Modern bioenergy and losses	24	36	46	62	53	81	58	74

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Coastal China steam coal price reported in USD (2021)/tonne adjusted to 6 000 kcal/kg. See Annex C for definitions. Solid bioenergy losses are conversion losses for solid, liquid and gaseous biofuels production.

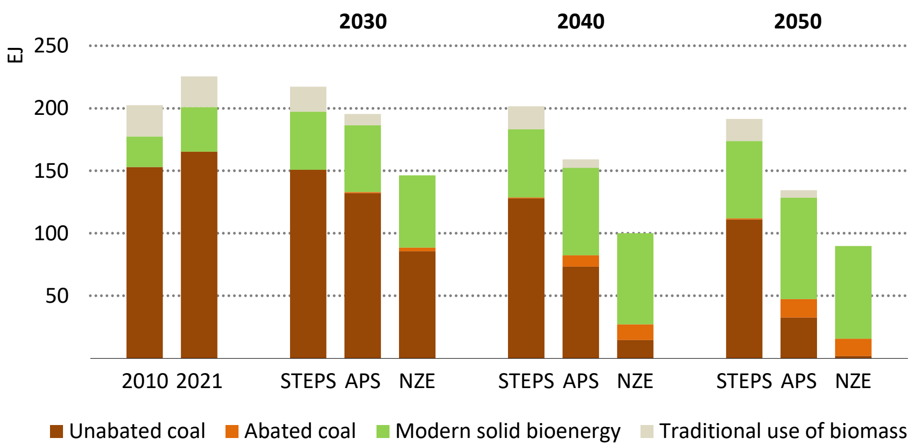
Global coal demand is set to rise slightly in 2022 as countries look to meet rising energy demand while struggling with lower economic growth. The speed of the coal decline in subsequent years depends on the stringency with which countries pursue climate and environmental targets.

In the **STEPS**, global coal demand falls by around 10% from 2021 to 2030, with a near 50% decline in advanced economies and a slight increase in emerging market and developing economies (Figure 9.1). Steam coal production falls by more than 10% to 2030 (Table 9.1); declines in coking coal are smaller, mainly because of increases in steel production in India.[1]

[1] Steam coal is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry; coking coal is mainly for steel making as a chemical reductant and a source of heat.

The European Union halts coal imports from Russia and replaces them with imports from a variety of sources including South Africa and Colombia. This change in the source of imports takes place amid a backdrop of about a 50% cut in total coal imports by the European Union in the period to 2030. By 2030, more than 80% of global coal trade takes place in the Pacific Basin (up from about 75% in 2021). The traditional use of biomass falls by 20% to 2030 as a result of efforts to move to cleaner cooking fuels, but nearly 2 billion people worldwide still rely on it for cooking and heating in 2030. The use of modern solid bioenergy increases by 30% to 2030. Between 2030 and 2050, the use of coal in industry falls by less than 10%, but its use in the power sector drops by 35% as older coal-fired power plants are retired and new renewables capacity is preferred in many cases to new coal-fired power plants.

Figure 9.1 ▷ Coal and solid bioenergy demand by scenario



Coal demand falls and modern solid bioenergy increases in all scenarios, but the pace and scale of change differ dramatically

Note: EJ = exajoule; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

In the **APS**, global coal demand falls by 20% to 2030 and by 70% to 2050. Demand in advanced economies declines by 65% to 2030 as coal use in the power and industry sectors falls rapidly. Coal demand peaks in China in the early 2020s and in India in the late 2020s. The traditional use of biomass falls by more than 60% to 2030, mainly as a result of reductions in China, India, Kenya and Nigeria. The use of modern solid bioenergy increases by 50% to 2030 and by 130% to 2050, with large increases in the power and industry sectors, and in biofuels conversion.

In the **NZE Scenario**, global coal demand falls by 45% to 2030, with a 75% decline in advanced economies and a 40% decline in emerging market and developing economies. Some coal-fired power plants are retrofitted with carbon capture, utilisation and storage (CCUS) or fire coal with low-emissions fuels, such as bioenergy or ammonia, to cut emissions and reduce the need to retire existing plants before the end of their lifetimes. Unabated coal use drops by 99% between 2021 and 2050, and in 2050 just under 90% of remaining coal power generation comes from plants equipped with CCUS. Universal access to clean cooking is achieved in 2030, and this brings to an end to the traditional use of biomass. Modern bioenergy demand increases at a similar rate to the APS, but a higher share is used in the power sector and less is transformed into biofuels.

9.2 Coal demand

Table 9.2 ▷ Coal demand by region and scenario (Mtce)

			STEPS			APS		
	2010	2021	2030	2040	2050	2030	2040	2050
North America	768	389	107	50	42	80	37	30
United States	716	363	91	32	26	64	24	17
Central and South America	37	46	40	52	60	28	25	20
Brazil	21	25	23	27	29	16	14	12
Europe	539	369	229	176	167	157	99	72
European Union	360	238	125	69	56	79	35	20
Africa	156	152	148	132	131	119	59	30
South Africa	144	129	113	87	78	95	34	6
Middle East	5	5	8	11	12	7	8	9
Eurasia	203	222	172	158	160	162	131	121
Russia	151	166	114	104	102	113	100	95
Asia Pacific	3 513	4 460	4 444	3 816	3 258	3 986	2 449	1 332
China	2 565	3 157	2 974	2 342	1 866	2 691	1 603	789
India	399	614	773	738	671	704	420	243
Indonesia	45	102	136	164	160	124	90	41
Japan	165	143	103	87	62	97	58	35
Rest of Southeast Asia	76	166	201	243	263	171	138	110
World	**5 220**	**5 644**	**5 149**	**4 394**	**3 828**	**4 539**	**2 808**	**1 613**

Note: See Annex C for definitions.

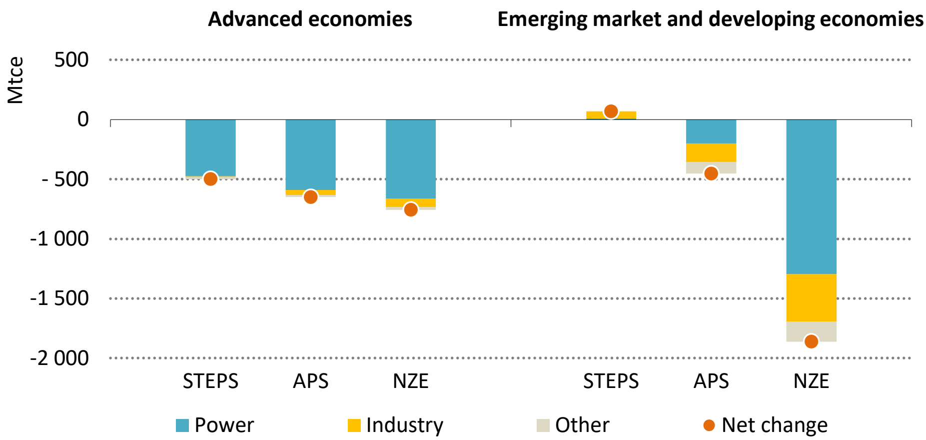
China is the world's largest coal consuming country today. It accounts for about 55% of global coal consumption (Table 9.2). Coal demand in China increased by an average of 100 Mtce each year between 2000 and 2020 as it rapidly expanded its power and industry sectors. This was equivalent to adding the current coal consumption of Indonesia every year. Coal demand in China rose again by around 2% in 2020, despite the impacts of the Covid-19 pandemic, and by a further 4% in 2021. India is the world's second-largest coal consumer today. It accounts for just over 10% of global coal consumption. Coal demand in India rose rapidly between

2010 and 2019, mainly as increases in electricity demand were largely met through coal-fired power. Coal use in India dropped by 7% in 2020 due to the pandemic, but increased by 13% in 2021, therefore already surpassing 2019 levels.

Advanced economies consumed around 1 000 Mtce of coal in 2021, accounting for just under 20% of global coal demand. Three-quarters of this was used in the power sector. Demand fell by around 15% in 2020: it then increased by 10% in 2021 as economies rebound after the pandemic, but it remains below 2019 levels. In 2022, Russia's invasion of Ukraine has led a number of European countries to delay the retirement of coal-fired power plants, reconnect previously retired units to the grid, and to temporarily expand coal use to reduce natural gas consumption.

Demand trends to 2030

Figure 9.2 ▷ Change in coal demand by scenario, 2021-2030



Outlook for coal in emerging market and developing economies varies much more by scenario than in advanced economies

Notes: Mtce = million tonnes of coal equivalent. Other includes buildings, agriculture and other energy sector.

In **advanced economies**, solar PV and wind replace a large share of coal-fired power generation in the STEPS. Coal use in power generation declines by 60% between 2021 and 2030 (Figure 9.2). More than 200 Mtce of coal is consumed in industry today in advanced economies, and this remains broadly constant through to 2030.

In the APS, demand for coal in the power sector in advanced economies falls by 80% to 2030 as more renewables are deployed, mostly solar PV and wind. Coal-fired generation capacity drops from 520 gigawatts (GW) in 2021 to 210 GW in 2030, and coal plants in 2030 are mainly used to provide flexibility: their average utilisation drops from 50% to 30%. Around 25 GW of coal-fired capacity is retrofitted and repurposed to co-fire ammonia and bioenergy by

2030. Coal use in industry falls by 20% to 2030, in part reflecting an increase in the production of near zero emissions primary steel and near zero emissions clinker for use in cement.

In **China,** around 60% of the 3 150 Mtce of coal consumed today is in the power sector and 30% in industry. In the STEPS, there is a small increase in coal demand to the late 2020s followed by a decline to around 3 000 Mtce in 2030. Coal use in power generation and in the iron and steel sub-sectors peaks in the late 2020s as electricity generation from renewables increases and as more electric arc furnaces are deployed. These reductions are partly offset by increases in coal use in the chemicals industry and in the production of synthetic fuels. Coal use in the buildings sector, which accounts for just under 5% of total demand today, falls by 80% to 2030 in response to policies to reduce air pollution. In the APS, coal demand in China peaks in the mid-2020s and declines to 2 700 Mtce in 2030. Coal use in industry falls by 20% to 2030 (compared with a 5% reduction in the STEPS) as a result of fuel switching to natural gas, more electrification and energy efficiency improvements. There are also enhanced efforts to reduce coal use in the power sector, which falls by 10% to 2030.

In **India**, coal demand in the STEPS rises by 25% to 2030. Strong economic growth – the economy expands 90% between 2021 and 2030 – brings with it more demand for coal-fired power generation and in the use of coal to produce iron and steel and cement. Coal-fired power capacity increases from 240 GW in 2021 to 275 GW in 2030, while there is limited use of electric arc furnaces in industry. In the APS, coal demand in India increases by just under 15% between 2021 and 2030, reflecting increased deployment of renewables, improvements in energy efficiency, and the installation of gas and electricity-based equipment in industry. The increase in coal demand in the industry sector is around half of that seen in STEPS, and the increase in the power sector is about 20% less.

In **Southeast Asia**, coal demand increases by nearly 30% to 2030 in the STEPS and by just under 10% in the APS. Growth is driven by increases in electricity demand from the industry and buildings sectors.

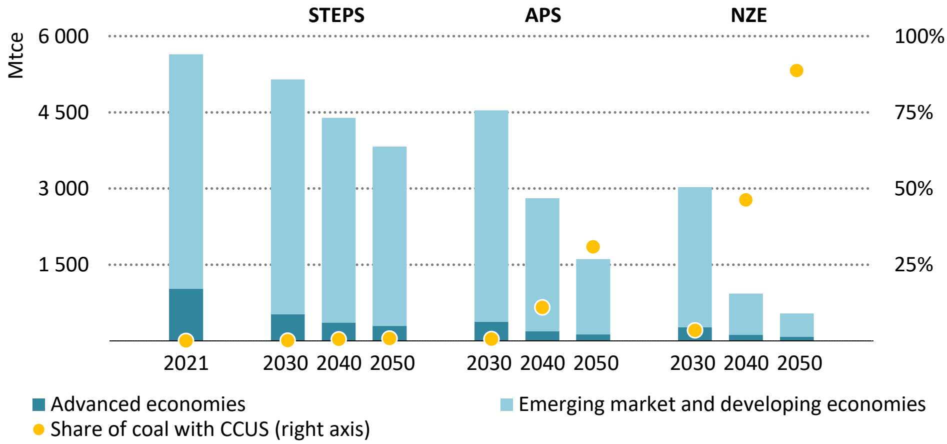
In **Africa**, coal demand remains broadly constant to 2030 in the STEPS: a decrease in demand in South Africa, led by fuel switching to less polluting alternatives, is largely offset by increases elsewhere. In the APS, much wider deployment of renewables across the continent leads to a 20% fall in total coal demand by 2030.

In **Russia,** coal demand drops by 30% to 2030 in both the STEPS and APS as natural gas and renewables replace coal use in power generation and industry.

In the **Caspian** region, coal demand remains relatively flat in the STEPS and falls by only 10% through to 2030 in the APS.

Demand trends after 2030

Figure 9.3 ▷ Global coal demand by region and scenario to 2050



Global coal demand decreases to 2050 in each scenario, but at very different speeds. Nearly 90% of coal use is equipped with CCUS by 2050 in the NZE Scenario

Notes: Mtce = million tonnes of coal equivalent; CCUS = carbon capture, utilisation and storage.

In the **STEPS**, global coal demand falls to 4 000 Mtce (a 25% drop) between 2030 and 2050 (Figure 9.3). Demand falls by 45% in advanced economies over this period and by 40% in China. Coal-fired power plant capacity in China shrinks from 1 140 GW today to 890 GW in 2050, and utilisation drops from 50% to 40%. In India, coal demand peaks in the early 2030s and then declines gradually, mainly due to rapid deployment of renewables in the power sector. However, total coal demand in India in 2050 is still around 10% higher than in 2021. Coal demand in Southeast Asia increases by 60% between 2021 and 2050, driven mainly by increases in the power, and iron and steel sectors.

In the **APS**, coal demand declines rapidly after 2030, with a 65% reduction in the power sector to 2050 and a 55% decline in industry use. Demand in China falls by more than 1 000 Mtce in the 2030s, a rate of decline that mirrors its rate of increase between 2000 and 2020. China's coal-fired power plant capacity drops to 850 GW in 2050, and its utilisation rate declines to 20% as plants are increasingly used for flexibility rather than base load generation. In India, coal demand peaks in the late 2020s and falls by 65% between 2030 and 2050. CCUS is increasingly used in a wide range of sectors and regions across the world: around 10% of coal power plants worldwide are equipped with CCUS in 2040 and almost 20% in 2050. By then, more than 120 GW of plants worldwide co-fire ammonia or bioenergy with coal.

In the **NZE Scenario**, coal demand drops to 540 Mtce in 2050, around 90% below the current level. Unabated coal use drops by 99% over this period; around half of the remaining 60 Mtce of unabated coal consumption in 2050 is used in the iron and steel industry.

9.3 Coal supply

Table 9.3 ▷ Coal production by region and scenario (Mtce)

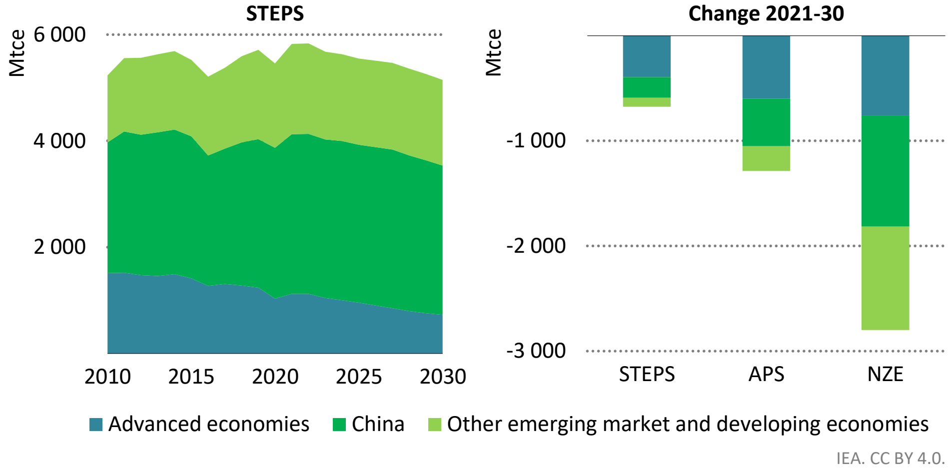
			STEPS			APS		
	2010	2021	2030	2040	2050	2030	2040	2050
North America	818	478	188	105	106	138	57	32
United States	758	433	156	79	80	115	50	29
Central and South America	79	62	41	42	41	24	10	3
Colombia	73	58	37	38	37	22	10	3
Europe	331	200	126	80	59	79	27	20
European Union	220	138	71	29	10	46	10	8
Africa	210	212	188	158	171	162	87	47
South Africa	206	199	162	114	109	138	58	19
Middle East	1	1	1	1	1	0	0	0
Eurasia	309	444	323	307	274	292	245	216
Russia	238	371	265	250	215	239	212	187
Asia Pacific	3 487	4 428	4 282	3 701	3 177	3 843	2 382	1 295
Australia	352	421	408	425	419	304	255	138
China	2 461	3 004	2 808	2 228	1 776	2 554	1 522	733
India	304	447	546	508	436	509	251	109
Indonesia	266	438	393	405	402	364	247	210
Rest of Southeast Asia	52	60	67	70	72	59	52	53
World	**5 235**	**5 826**	**5 149**	**4 395**	**3 829**	**4 539**	**2 808**	**1 613**

Notes: Mtce = million tonnes of coal equivalent. See Annex C for definitions.

Coal production in 2021 struggled to meet rising demand, especially during the first-half of the year, cutting into stock levels and pushing up prices. In China and India, coal shortages caused in part by transport bottlenecks led to power outages and factory shutdowns. Policies to ramp up domestic production and reduce coal shortages have been implemented, facilitated by the existence of large state-owned production companies. Outside China and India, most of the additional coal production in 2021 came from existing mines or reopened mines that had ceased to operate during periods of low prices: this is a reflection of the limited investment in new mines that has taken place in recent years.

Supply trends to 2030

Figure 9.4 ▷ Coal supply in the STEPS to 2030 and change by scenario



Global coal demand falls by 45% to 2030 in the NZE Scenario and this means there is no need for supply from new coal mines or mine lifetime extensions

Note: Mtce = million tonnes of coal equivalent.

China keeps coal production around the current level of 3 000 Mtce for a number of years but with coal demand falling as renewables account for an increasing share of power generation, production declines to around 2 800 Mtce in 2030 (Figure 9.4). In the APS, coal production declines more rapidly from the mid-2020s and supply in 2030 is around 15% below 2021 levels (Table 9.3).

India became the world's second-largest coal producer in 2021 (in energy terms), overtaking Australia and Indonesia, and it plans to increase domestic production by more than 100 Mtce from current levels to 2025. Coal supply increases from about 450 Mtce in 2021 to 550 Mtce in 2030 in the STEPS and just over 500 Mtce in the APS.

Indonesia sees coal production fall by 10% in the period to 2030 in the STEPS and by 20% in the APS. Indonesia currently exports close to 80% of its coal output, which is almost 100% steam coal, and exports fall significantly in the years to 2030 in both the STEPS and APS.

In the **United States**, declining domestic demand for coal and limited opportunities to tap into export markets means production in 2030 is around 65% lower than in 2021 in the STEPS, and around 75% lower in the APS.

In **Australia,** coal production plateaus between 2021 and 2030 in the STEPS, with a slight fall in domestic demand being partially offset by an increase in exports. In the APS, its coal production falls over this period by about 25%. Coking coal production remains steady, and Australia exports about 190 Mtce coking coal each year through to 2030. Steam coal production falls by about 40% over the same period as demand declines quickly in key importing countries such as Japan and Korea.

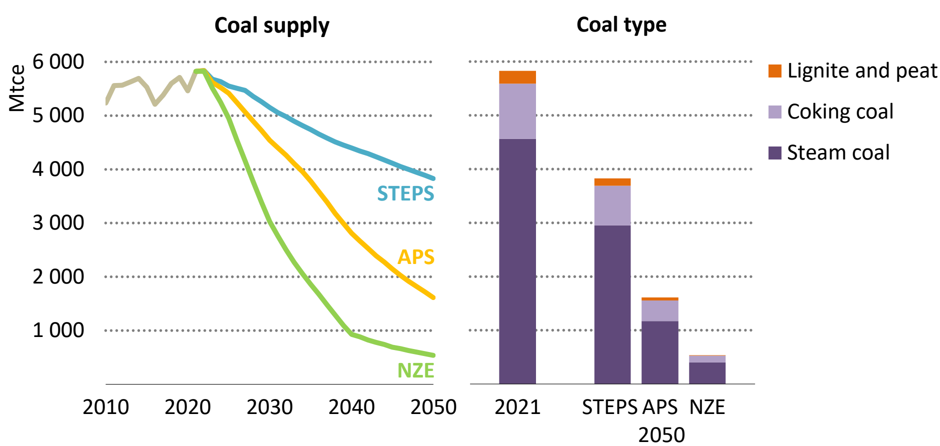
Europe is looking to replace Russian imports, but there are limited opportunities to boost indigenous coal production in ways that are consistent with long-term emissions reduction goals. Supply declines broadly in line with decreasing demand, falling by around 40% to 2030 in the STEPS and by over 55% in the APS.

Colombia saw coal production rebound in 2021 as existing operations ramped up and as mines that had closed during the Covid-19 pandemic were reopened. More than 80% of its production is steam coal for exports, with Europe as its main market. As countries in Europe transition from coal-fired generation, coal production in Colombia to 2030 falls by about 35% in the STEPS, and by 60% in the APS.

In the **NZE Scenario**, there is no need for any new coal mines or mine lifetime extensions. Steam coal production falls by 50% to 2030 as coal is rapidly eliminated from the power sector in all countries. Coking coal production falls by about 30% to 2030, a smaller decline than for steam coal since the steel industry has fewer readily available alternatives.

Supply trends after 2030

Figure 9.5 ▷ Coal supply by scenario, 2010-2050



Coal production falls by about 30% between 2021 and 2050 in the STEPS, 70% in the APS and 90% in the NZE Scenario; coking coal production declines much less than steam coal

Note: Mtce = million tonnes of coal equivalent.

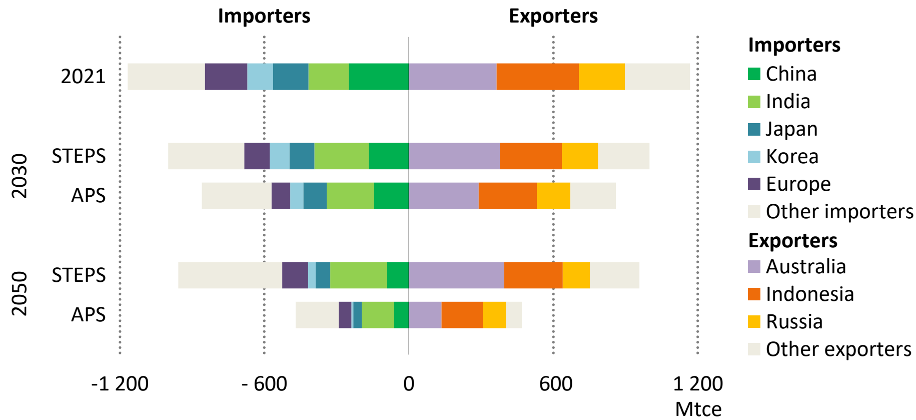
In the **STEPS**, global coal supply falls by about 25% from 2030 to 2050 (Figure 9.5). China cuts its production by around 35%, and India and advanced economies by almost 20%. Production in Indonesia is broadly constant between 2030 and 2050.

In the **APS**, global coal supply declines by 65% between 2030 and 2050. Steam coal falls by 2 400 Mtce (70% reduction) as a result of efforts to reduce emissions from the power sector, while coking coal falls by 470 Mtce (55% reduction) reflecting fuel switching and energy efficiency improvements. Production in China falls by 1 800 Mtce (70% reduction): this accounts for close to two-thirds of the global decline in supply. Production in India falls by 400 Mtce (80% reduction). The leading exporters, Australia and Indonesia, see production fall by around 55% and 40% respectively between 2030 and 2050.

In the **NZE Scenario**, global coal production declines by 80% between 2030 and 2050 to around 10% of the level in 2021, with production in 2050 down to around 410 Mtce of steam coal and 120 Mtce of coking coal.

9.4 Coal trade

Figure 9.6 ▷ Top coal importers and exporters by scenario, 2021, 2030 and 2050



Falling demand in advanced economies and China reduces coal trade in the APS by 25% to 2030 and by 60% to 2050 from 2021 levels

Note: Mtce = million tonnes of coal equivalent.

The Asia Pacific region is the main driver of international coal trade, accounting for more than three-quarters of global coal imports in 2021 (Figure 9.6). China was the largest importer in 2021 (around 250 Mtce), followed by India (around 165 Mtce). Australia and Indonesia are the two main coal exporters, together accounting for 60% of coal exports in 2021. Australia alone provided more than half of all coking coal exports. Russia is the third-largest coal exporter. It provided around half of the coal imports to the European Union in 2021 (about 20% of total EU coal demand). However, its invasion of Ukraine led the European Union to introduce a ban from August 2022 on all forms of coal imports from Russia.

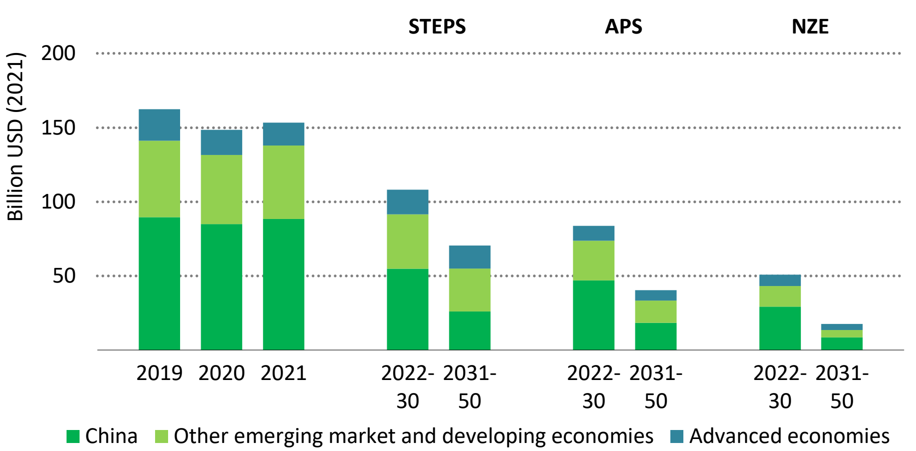
In the **STEPS**, there is a short-term increase in imports to the European Union from South Africa, United States and Colombia to replace imports from Russia. However, the amount of coal imported by the European Union drops by around 50% between 2021 and 2030, and exports from South Africa and Colombia fall by over 30% over this period. India becomes the world's largest importer in the mid-2020s: its imports rise by 35% to 2030 while China's decrease by 35%. In 2050, India imports 40% more coal than in 2021, most of which is coking coal. This changes the dynamics of exporting economies: Australian exports, which are mainly coking coal, increase by 10% to 2050, while Indonesia, mainly a steam coal exporter, sees exports fall by 30%.

In the **APS**, global coal trade falls by 25% to 2030 and by 60% to 2050. There is 470 Mtce of coal imported in 2050, mainly by countries with large distances between domestic production and consumption hubs and where differences in coal quality require domestic production to be supplemented with imports. Imports of coking coal in India increase by 40% to 2030 as it expands steel production. Indonesian exports drop by 30% to 2030 as the market for steam coal shrinks. Australia fares better, with coal exports falling by less than 20% to 2030, although its exports fall by about 50% between 2030 and 2050 as the use of clean energy technologies increases.

In the **NZE Scenario**, global coal trade declines by 90% between 2021 and 2050 as clean energy technologies progressively and speedily displace coal across the energy system.

9.5 Coal investment

Figure 9.7 ▷ Average annual investment in coal supply and coal-fired electricity generation by scenario



Investment in coal falls in all scenarios this decade: investment to 2030 is 30% lower than recent years in the STEPS, 50% lower in the APS, and two-thirds lower in the NZE Scenario

Investment in coal supply and coal-fired power generation worldwide has fallen by more than 20% since 2015. Most investment in recent years has been in China and India, together accounting for about 70% of global investment in coal-fired power plants and supply in 2021. Investment in coal supply is set to rise in the immediate future in response to energy security concerns triggered by Russia's invasion of Ukraine, recent rebound in economic activity, and rising industrial output in emerging market and developing economies.

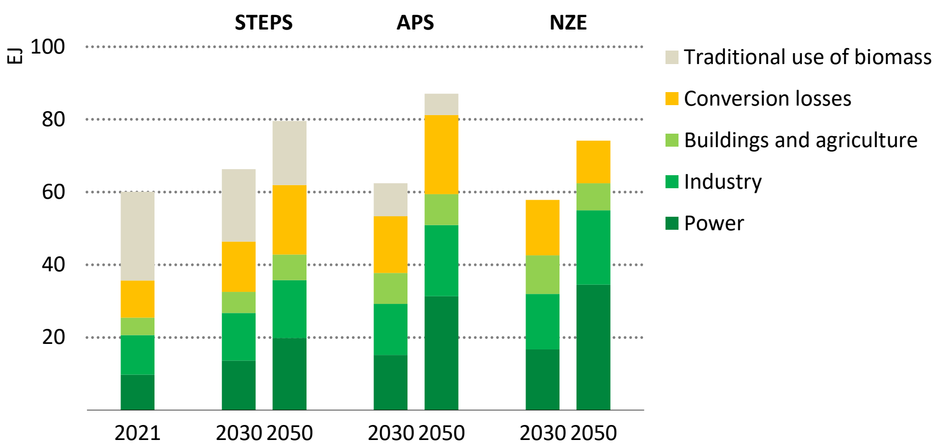
In the **STEPS**, bans by some countries on financing new coal-fired power plants and supply projects abroad together with coal phase-out policies cause average annual investment to 2030 to fall by 30% from recent levels with continued declines thereafter (Figure 9.7).

In the **APS**, there is a larger drop in spending, especially in advanced economies. By 2030, there is virtually no coal investment in the European Union, and advanced economies in Asia significantly reduce investments in coal. There is a big increase in investment in CCUS, which by 2030 accounts for half of the total coal-related investment in power generation.

In the **NZE Scenario**, there is no need for new coal mines or mine lifetime extensions, and no new coal-fired power plants are approved. Average annual investment in coal to 2030 is two-thirds lower than in recent years, and the remaining coal-related investment is focussed on maintaining production at existing mines as they wind down and on reducing their emissions intensity as much as possible, for example through reducing coal mine methane emissions.

9.6 Solid bioenergy

Figure 9.8 ▷ Solid bioenergy demand by scenario



Modern solid bioenergy plays a key role in meeting net zero emissions pledges; traditional use of biomass decreases substantially in the APS and is eliminated in the NZE Scenario

Notes: EJ = exajoule. Conversion losses occur during the production of solid, liquid and gaseous biofuels.

Worldwide, around 60 EJ (2 000 Mtce) of solid bioenergy was used in 2021 (Figure 9.8). The inefficient traditional use of biomass for cooking and heating in developing countries accounted for around 25 EJ, mainly in Africa (50% of the total) and Asia (45%).[2] The traditional use of biomass is the main cause of the 3.6 million premature deaths caused by household air pollution every year, is a source of greenhouse gas (GHG) emissions, and is a major barrier to women being able to pursue education and participate in the workforce (see Chapter 5).

Around 25 EJ of modern solid bioenergy was used in 2021 for power generation and in end-use sectors: 40% of this provided heat for industry, 40% was consumed in the power sector (generating 670 terawatt-hours of electricity and 1 EJ of commercial heat), and 20% was used in the buildings and agriculture sectors. The remaining 10 EJ of solid bioenergy was lost during conversion to solid, liquid and gaseous biofuels.

In the **STEPS**, there is limited progress on universal access to clean cooking and the traditional use of biomass falls by only 20% to 2030. In 2050, there is still nearly 20 EJ of the traditional use of biomass globally, 75% of which is used in Africa. Modern solid bioenergy use in power generation and final consumption increases by 30% to 2030, with large increases in China and Europe for use in power generation.

In the **APS**, commitments made by governments on clean cooking targets are achieved on time and in full. The traditional use of biomass falls by 60% from 2021 levels to 2030 and by around 75% to 2050. The remaining 6 EJ of traditional biomass in 2050 is consumed mainly in countries in Africa. Modern solid bioenergy use in power generation and final consumption increases by 50% to 2030 and more than doubles to 2050. Around 1.1 gigatonnes (Gt) CO_2 per year is captured through the use of bioenergy with carbon capture, utilisation and storage (BECCS) by 2050.[3] In total, modern bioenergy avoids around 1 Gt CO_2 by 2030 and 4.5 Gt CO_2 by 2050 through the displacement of fossil fuels and use of BECCS.

In the **NZE Scenario**, the traditional use of biomass is phased out worldwide by 2030 (Box 9.1). Overall modern solid bioenergy levels are broadly similar to those in the APS and 1.3 Gt CO_2 per year is captured through BECCS in 2050. Modern solid bioenergy avoids 1.8 Gt CO_2 emissions by 2030 and 5 Gt CO_2 emissions by 2050 through the displacement of fossil fuels and BECCS, and is thus responsible for just over 10% of total emissions reductions in the NZE Scenario.

[2] The traditional use of biomass is the combustion of solid biomass in basic stoves that are inefficient and polluting. This includes the use of wood, wood waste, charcoal, agricultural residues and other bio-sourced fuels such as animal dung. Modern solid bioenergy is the use of solid bioenergy in improved cook stoves and modern technologies with higher combustion efficiencies, often using processed biomass such as pellets.

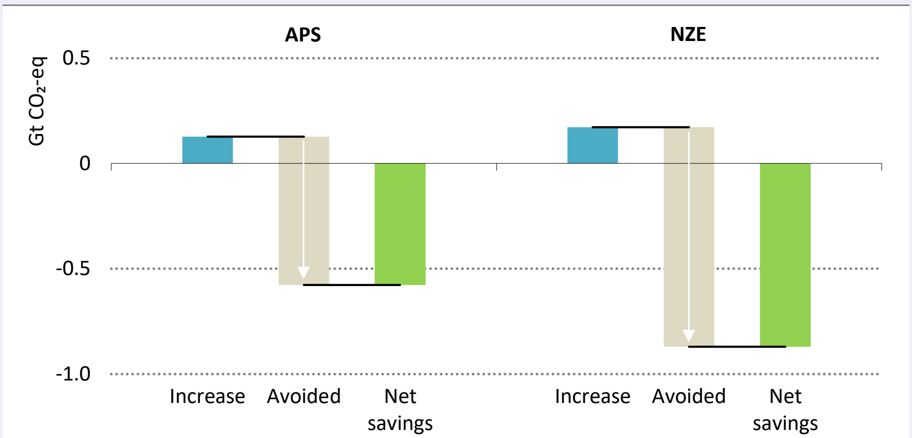
[3] BECCS leads to net negative emissions when the bioenergy is sustainably sourced and the carbon emissions resulting from its use are captured and stored on a permanent basis.

Box 9.1 ▷ What would achieving universal energy access mean for GHG emissions?

In the NZE Scenario, around 40% of people that gain access to clean cooking in the period to 2030 do so through the use of liquefied petroleum gas (LPG), 35% through improved biomass cook stoves and 15% via electricity. Increased use of LPG and electricity brings about an overall increase in fossil fuel use and CO_2 emissions. However, the traditional use of biomass currently results in methane and nitrous oxide emissions and shifting to alternative fuels avoids these emissions. Achieving universal access to clean cooking in the NZE Scenario results in an overall 870 Mt CO_2-eq reduction of GHG emissions in 2030 (Figure 9.9).

These reductions could be even larger. Some of the solid biomass used for cooking or converted into charcoal in developing countries is currently harvested unsustainably, leading to deforestation and related CO_2 emissions. The traditional use of biomass is also a major source of black carbon emissions, a short-lived aerosol with high global warming potential.

Figure 9.9 ▷ Net GHG emissions savings from clean cooking access in the APS and NZE Scenario by 2030



Achieving clean cooking targets in the APS reduces GHG emissions by 580 Mt CO_2-eq in 2030, while universal access in the NZE Scenario reduces emissions by 870 Mt CO_2-eq

Notes: Gt CO_2-eq = gigatonnes of carbon-dioxide equivalent. Methane is assumed to be equivalent to 30 tonnes CO_2 and nitrous oxide equivalent to 273 tonnes CO_2. Black carbon emissions and avoided CO_2 emissions from the combustion of unsustainably harvested biomass are not included.

In addition to the 75 EJ of modern solid bioenergy used in 2050 in the NZE Scenario, a further 25 EJ of modern bioenergy is used in the form of biogas or liquid biofuels. More than half of total bioenergy supply in 2050 in the NZE Scenario is from sources that do not require dedicated land use (Box 9.2). Total bioenergy supply of 100 EJ is at the bottom-end of the range of estimates (100-170 EJ) of global sustainable bioenergy potential in 2050, and is much lower than the level of bioenergy use in comparable 1.5 °C scenarios assessed in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, which have a median of 240 EJ of bioenergy use in 2050 (IPCC, 2021).

The NZE Scenario does not rely on offsets from outside the energy sector to achieve net zero emissions in 2050. But commensurate action on reducing emissions from agriculture, forestry and other land uses (AFOLU) would help limit climate change and provide other benefits. Such action could include measures to: halt deforestation; improve forest management practices; institute farming practices that increase soil carbon levels; and support afforestation. A number of companies and countries have recently expressed interest in such "nature-based solutions" to offset emissions from their operations. The use of offsets can be a cost-effective mechanism to reduce emissions from parts of value chains where direct emissions reductions are challenging, provided that schemes to generate emissions credits result in permanent, additional and verified emissions reductions. However, there is likely to be a limited supply of emissions credits consistent with net zero emissions globally.

Box 9.2 ▷ Where does bioenergy come from in the NZE Scenario?

There are a number of sustainability concerns linked to the use of land for bioenergy production. In the NZE Scenario, bioenergy resources are responsibly managed and do not compete with other land uses. Of the 100 EJ of total modern bioenergy supply in 2050 in the NZE Scenario, just over half is from sustainable waste streams that do not require any specific land use. This includes agriculture residues, forest and wood residues and other organic waste streams. The remaining 45 EJ of modern bioenergy demand requires land to be dedicated to bioenergy supply.

To avoid conflicts between food production and affordability, there is a general shift in the NZE Scenario away from conventional bioenergy sources towards advanced bioenergy (see Chapter 7). The focus is on the production of bioenergy from dedicated short rotation woody crops grown on cropland, pasture land and marginal lands that are not suited to food crops.[4] In the NZE Scenario, there is no net increase in cropland use for bioenergy, and no bioenergy crops are grown on existing forested land.

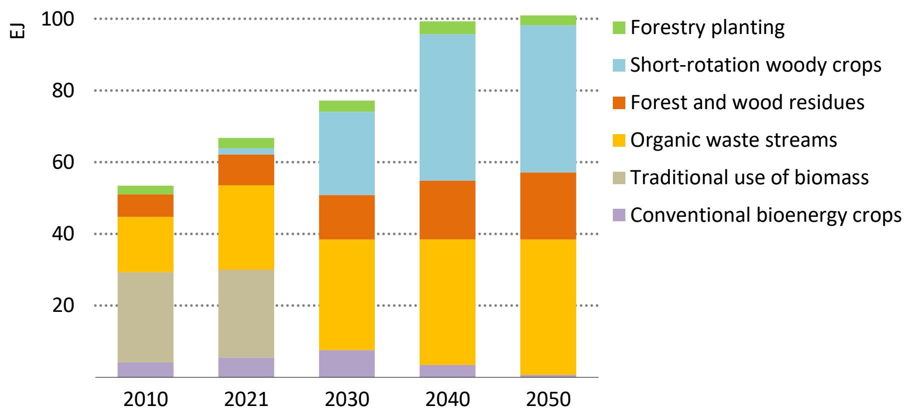
Short rotation woody crops provide just over 40 EJ of bioenergy supply in 2050 in the NZE Scenario (Figure 9.10). These can produce twice as much bioenergy per hectare as many conventional bioenergy crops and can lead to additional CO_2 removal from the atmosphere. Bioenergy supply from conventional crops falls from around 6 EJ today to less than 1 EJ in 2050 in the NZE Scenario.

[4] Cropland here refers to agricultural land used for food, animal feed and bioenergy production but excludes short-rotation woody crops not established on existing agricultural cropland.

The remaining modern bioenergy comes from sustainably managed forestry plantations and tree planting integrated with agricultural production via agroforestry systems. These do not conflict with food production or biodiversity. Such plantations can reduce CO_2 emissions in the atmosphere, produce biomass in a sustainable way and increase agriculture and forestry incomes.

Based on land area modelling using the GLOBIOM model (Havlík et al., 2014), the area of land estimated to be available is much larger than the area of land used to produce bioenergy in the NZE Scenario. This is even after taking into account sustainability considerations such as the need to protect biodiversity and to meet the UN Sustainable Development Goal 15 on biodiversity and land use. Nevertheless, it is critical to ensure that bioenergy feedstocks are certified and that there are strict controls in place to avoid land-use conflicts.

Figure 9.10 ▷ Bioenergy supply in the NZE Scenario



There is no increase in cropland use for bioenergy in the NZE Scenario and no bioenergy crops are developed on existing forested land

Note: EJ = exajoule.

9

ANNEXES

Box A.1 ▹ *World Energy Outlook* links

WEO homepage

General information	iea.org/weo
***WEO-2022* information**	iea.li/weo22

WEO-2022 datasets

Data in Annex A is available to download free in electronic format at:
iea.li/weo2022-freedata

An extended dataset, including the data behind figures, tables and the *WEO-2022* slide deck is available to purchase at:
iea.li/weo2022-extendeddata

Modelling

Documentation and methodology / Investment costs
iea.li/model

Recent analysis

An Energy Sector Roadmap to Net Zero Emissions in Indonesia	iea.li/indonesia
World Energy Employment	iea.li/employment
Nuclear Power and Secure Energy Transitions	iea.li/nuclear-power
World Energy Investment 2022	iea.li/wei22
Africa Energy Outlook 2022	iea.li/africa-outlook22
Southeast Asia Energy Outlook 2022	iea.li/se-asia22
Sustainable Recovery Tracker	iea.li/recoverytracker
Playing my part	iea.li/my-part
A 10-Point Plan to Cut Oil Use	iea.li/oil-use
A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas	iea.li/gas-reliance
Global Methane Tracker 2022	iea.li/methane-tracker22
The Role of Critical Minerals	iea.li/minerals
Net Zero by 2050	iea.li/netzero

Databases

Policy Databases	iea.li/policies-database
Sustainable Development Goal 7	iea.li/SDG
Energy subsidies: Tracking the impact of fossil-fuel subsidies	iea.li/subsidies

Tables for scenario projections

General note to the tables

This annex includes global historical and projected data by scenario for the following four datasets:

- A.1: Energy supply.
- A.2: Total final consumption.
- A.3: Electricity sector: gross electricity generation and electrical capacity.
- A.4: CO_2 emissions: carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes.

Each dataset is given for the following scenarios: (a) Stated Policies Scenario (STEPS) [Tables A.1a. to A.4a]; (b) Announced Pledges Scenario (APS) [Tables A.1b. to A.4b]; and (c) Net Zero Emissions by 2050 (NZE) Scenario [Tables A.1c. to A.4c].

This annex also includes regional historical and projected data for STEPS and APS for the following datasets:

- Tables A.5 – A.6: Total energy supply, renewables energy supply in exajoules (EJ).
- Tables A.7 – A.10: Oil production, oil demand, world liquids demand, and, refining capacity and runs in million barrels per day (mb/d).
- Tables A.11 – A.12: Natural gas production, natural gas demand in billion cubic metres (bcm).
- Tables A.13 – A.14: Coal production, coal demand in million tonnes of coal equivalent (Mtce).
- Tables A.15 – A.21: Electricity generation by total and by source (renewables, solar photovoltaics [PV], wind, nuclear, natural gas, coal) in terawatt-hours (TWh).
- Tables A.22 – A.25: Total final consumption and consumption by sector (industry, transport and buildings) in exajoules (EJ).
- Tables A.26 – A.27: Hydrogen demand (PJ) and the hydrogen balance in million tonnes of hydrogen equivalent (Mt H_2 equivalent).[1]
- Tables A.28 – A.30: Total CO_2 emissions, electricity and heat sectors CO_2 emissions, final consumption in million tonnes of CO_2 emissions (Mt CO_2).

Tables A.5 to A.30 cover: World, North America, United States, Central and South America, Brazil, Europe, European Union, Africa, Middle East, Eurasia, Russia, Asia Pacific, China, India, Japan and Southeast Asia.

The definitions for regions, fuels and sectors are in Annex C.

[1] The hydrogen balance table also includes the NZE Scenario.

Common abbreviations used in the tables include: CAAGR = compound average annual growth rate; CCUS = carbon capture, utilisation and storage. Combustion of fossil fuels in facilities without CCUS is classified as "unabated".

Both in the text of this report and in these annex tables, rounding may lead to minor differences between totals and the sum of their individual components. Growth rates are calculated on a compound average annual basis and are marked "n.a." when the base year is zero or the value exceeds 200%. Nil values are marked "-".

Please see Box A.1 for details on where to download the *World Energy Outlook (WEO)* tables in Excel format. In addition, Box A.1 lists the links relating to the main *WEO* website, documentation and methodology of the Global Energy and Climate (GEC) Model, investment costs, policy databases and recent *WEO* special reports.

Data sources

The Global Energy and Climate (GEC) Model is a very data-intensive model covering the whole global energy system. Detailed references on databases and publications used in the modelling and analysis may be found in Annex E.

The formal base year for this year's projections is 2020, as this is the last year for which a complete picture of energy demand and production is in place. However, we have used more recent data wherever available, and we include our 2021 estimates for energy production and demand in this annex (Tables A.1 to A.3). Estimates for the year 2021 are based on updates of the *Global Energy Review* reports which are derived from a number of sources, including the latest monthly data submissions to the IEA Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA *Market Report Series* that cover coal, oil, natural gas, renewables and power. Investment estimates include the year 2021, based on the IEA *World Energy Investment 2022* report.

Historical data for gross power generation capacity (Tables A.2 and A.3) are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2022 version) and the International Atomic Energy Agency PRIS database.

Definitional note: Energy supply and transformation tables

Total energy supply (TES) is equivalent to electricity and heat generation plus the *other energy sector*, excluding electricity, heat and hydrogen, plus total final consumption (TFC), excluding electricity, heat and hydrogen. TES does not include ambient heat from heat pumps or electricity trade. Solar in TES includes solar PV generation, concentrating solar power and final consumption of solar thermal. *Other renewables* in TES include geothermal and marine (tide and wave) energy for electricity and heat generation. *Biofuels conversion losses* are the conversion losses to produce biofuels (mainly from modern solid bioenergy) used in the energy sector. *Low-emissions hydrogen production* is merchant low-emissions hydrogen production (excluding onsite production at industrial facilities and refineries), with inputs referring to total fuel inputs and outputs to produced hydrogen. While not itemised separately, non-renewable waste and other sources are included in TES.

Definitional note: Fossil fuel production and demand tables

Oil production and demand is expressed in million barrels per day (mb/d). Tight oil includes tight crude oil and condensate production except for the United States, which includes tight crude oil only (US tight condensate volumes are included in natural gas liquids). Processing gains cover volume increases that occur during crude oil refining. Biofuels and their inclusion in liquids demand is expressed in energy-equivalent volumes of gasoline and diesel. Natural gas production and demand is expressed in billion cubic metres (bcm). Coal production and demand is expressed in million tonnes of coal equivalent (Mtce). Differences between historical production and demand volumes for oil, gas and coal are due to changes in stocks. Bunkers include both international marine and aviation fuels. Refining capacity at risk is defined as the difference between refinery capacity and refinery runs, with the latter including a 14% allowance for downtime. Projected shutdowns beyond those publicly announced are also counted as capacity at risk.

Definitional note: Electricity tables

Electricity generation expressed in terawatt-hours (TWh) and installed electrical capacity data expressed in gigawatts (GW) are both provided on a gross basis (i.e. includes own use by the generator). Projected gross electrical capacity is the sum of existing capacity and additions, less retirements. While not itemised separately, other sources are included in total electricity generation. Installed capacity for hydrogen and ammonia refers to full conversion only, not including co-firing with natural gas or coal.

Definitional note: Energy demand tables

Sectors comprising **total final consumption** (TFC) include industry (energy use and feedstock), transport, buildings (residential, services and non-specified other) and other (agriculture and other non-energy use). Energy demand from international marine and aviation bunkers are included in global transport totals.

Definitional note: Hydrogen tables

Total hydrogen demand includes merchant (or offsite) hydrogen demand and hydrogen demand in industry and refineries covered by onsite production. It also includes hydrogen used in the production of hydrogen-based fuels (ammonia, synthetic hydrocarbon fuels). The hydrogen balance table A.27 is expressed in hydrogen-equivalent terms, which means for hydrogen-based fuels the hydrogen input to produce these fuels is reported. Hydrogen demand in end-use sectors includes total final consumption of hydrogen and hydrogen-based fuels as well as hydrogen demand in industry covered by onsite production within industrial facilities.

Definitional note: CO_2 emissions tables

Total CO_2 includes carbon dioxide emissions: from the combustion of fossil fuels and non-renewable wastes, from industrial and fuel transformation processes (process emissions); and CO_2 emissions from flaring and CO_2 removal. CO_2 removal includes: captured and stored emissions from the combustion of bioenergy and renewable wastes; from biofuels production; and from direct air capture (DAC).

The first two entries are often reported as bioenergy with carbon capture and storage (BECCS). Note that some of the CO_2 captured from biofuels production and direct air capture is used to produce synthetic fuels, which is not included as CO_2 removal.

Total CO_2 captured includes the carbon dioxide captured from CCUS facilities (such as electricity generation or industry) and atmospheric CO_2 captured through direct air capture, but excludes that captured and used for urea production.

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Table A.1a: World energy supply

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total energy supply	**542**	**592**	**624**	**673**	**708**	**740**	**100**	**100**	**100**	**0.8**	**0.6**
Renewables	45	69	74	116	169	215	12	17	29	5.2	3.8
Solar	1	5	5	18	36	52	1	3	7	14	8.1
Wind	1	6	7	17	29	38	1	2	5	11	6.2
Hydro	12	16	16	18	21	25	2	3	3	1.8	1.6
Modern solid bioenergy	24	33	36	46	54	62	6	7	8	3.0	1.9
Modern liquid bioenergy	2	4	4	7	9	11	1	1	1	5.2	3.2
Modern gaseous bioenergy	1	1	1	3	5	9	0	0	1	8.1	7.0
Other renewables	3	4	5	8	14	19	1	1	3	6.4	4.9
Traditional use of biomass	25	24	24	20	19	18	4	3	2	-2.3	-1.1
Nuclear	30	29	30	37	43	46	5	5	6	2.1	1.5
Unabated natural gas	115	139	146	150	147	147	23	22	20	0.3	0.0
Natural gas with CCUS	0	0	0	1	2	3	0	0	0	8.1	6.5
Oil	173	172	183	197	198	197	29	29	27	0.8	0.2
of which non-energy use	25	29	31	37	41	42	5	6	6	2.1	1.0
Unabated coal	153	157	165	151	128	111	26	22	15	-1.0	-1.4
Coal with CCUS	-	0	0	0	1	1	0	0	0	33	17
Electricity and heat sectors	**200**	**228**	**242**	**261**	**287**	**312**	**100**	**100**	**100**	**0.9**	**0.9**
Renewables	21	37	40	71	113	149	17	27	48	6.6	4.6
Solar PV	0	3	4	14	30	44	1	6	14	17	9.0
Wind	1	6	7	17	29	38	3	6	12	11	6.2
Hydro	12	16	16	18	21	25	6	7	8	1.8	1.6
Bioenergy	5	9	10	15	19	23	4	6	7	4.1	2.8
Other renewables	2	4	4	7	13	19	2	3	6	7.3	5.8
Hydrogen	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Ammonia	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Nuclear	30	29	30	37	43	46	13	14	15	2.1	1.5
Unabated natural gas	47	55	57	55	51	50	24	21	16	-0.3	-0.4
Natural gas with CCUS	-	-	-	-	0	1	-	-	0	n.a.	n.a.
Oil	11	7	8	5	4	3	3	2	1	-4.7	-2.7
Unabated coal	91	99	107	93	74	60	44	36	19	-1.5	-1.9
Coal with CCUS	-	0	0	0	1	1	0	0	0	25	17
Other energy sector	**51**	**59**	**61**	**68**	**72**	**77**	**100**	**100**	**100**	**1.2**	**0.8**
Biofuels conversion losses	-	5	6	8	10	12	100	100	100	4.4	2.5
Low-emissions hydrogen											
Production inputs	-	0	0	1	2	3	100	100	100	64	23
Production outputs	-	0	0	1	1	2	100	100	100	68	24
For hydrogen-based fuels	-	-	-	0	0	0	-	6	17	n.a.	n.a.
For other energy sector	-	-	-	0	1	1	-	59	28	n.a.	n.a.

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Table A.2a: World final consumption

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total final consumption	**383**	**417**	**439**	**485**	**518**	**544**	**100**	**100**	**100**	**1.1**	**0.7**
Electricity	64	82	87	107	130	151	20	22	28	2.3	1.9
Liquid fuels	154	159	170	189	194	196	39	39	36	1.2	0.5
Biofuels	2	4	4	7	9	11	1	1	2	5.2	3.2
Ammonia	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Synthetic oil	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Oil	151	155	166	183	185	185	38	38	34	1.1	0.4
Gaseous fuels	58	68	72	79	84	88	17	16	16	0.9	0.7
Biomethane	0	0	0	1	2	4	0	0	1	13	11
Hydrogen	-	0	0	0	1	1	0	0	0	48	21
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57	68	72	77	81	81	16	16	15	0.8	0.4
Solid fuels	95	92	94	91	89	87	21	19	16	-0.3	-0.3
Solid bioenergy	38	39	40	39	40	41	9	8	7	-0.4	0.0
Coal	56	52	53	52	49	46	12	11	8	-0.2	-0.5
Heat	12	13	13	14	14	14	3	3	3	0.5	0.2
Other	1	2	3	4	6	8	1	1	1	5.1	3.7
Industry	**143**	**160**	**167**	**189**	**202**	**209**	**100**	**100**	**100**	**1.4**	**0.8**
Electricity	27	34	37	43	49	54	22	23	26	1.9	1.4
Liquid fuels	29	32	33	40	44	44	20	21	21	2.1	0.9
Oil	29	32	33	40	43	44	20	21	21	2.1	0.9
Gaseous fuels	24	30	31	35	39	42	18	19	20	1.6	1.1
Biomethane	0	0	0	0	1	2	0	0	1	16	13
Hydrogen	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Unabated natural gas	24	29	31	35	38	39	18	18	19	1.5	0.8
Natural gas with CCUS	0	0	0	0	0	0	0	0	0	17	11
Solid fuels	58	58	59	63	63	61	36	33	29	0.7	0.1
Solid bioenergy	8	10	11	13	15	16	7	7	8	2.0	1.3
Unabated coal	50	47	48	49	47	45	29	26	21	0.4	-0.2
Coal with CCUS	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Heat	5	6	7	7	7	7	4	4	4	0.9	0.4
Other	0	0	0	0	0	0	0	0	0	13	7.6
Iron and steel	31	35	36	38	38	38	22	20	18	0.6	0.1
Chemicals	37	46	48	58	63	65	29	30	31	2.0	1.0
Cement	10	12	12	13	13	12	7	7	6	0.5	-0.0

Table A.2a: World final consumption (continued)

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Transport	102	105	113	130	139	147	100	100	100	1.5	0.9
Electricity	1	1	2	4	9	13	1	3	9	11	7.5
Liquid fuels	97	99	107	120	123	126	94	92	86	1.3	0.6
Biofuels	2	4	4	6	9	10	4	5	7	5.0	3.1
Oil	95	95	103	113	114	116	90	87	79	1.1	0.4
Gaseous fuels	4	5	5	6	7	8	5	4	5	1.3	1.4
Biomethane	0	0	0	0	0	1	0	0	1	11	8.7
Hydrogen	-	0	0	0	0	1	0	0	1	40	21
Natural gas	4	5	5	6	6	6	5	4	4	0.9	0.5
Road	76	81	87	94	98	100	77	73	68	0.9	0.5
Passenger cars	39	42	45	47	47	46	40	36	31	0.4	0.1
Heavy-duty trucks	21	25	26	31	36	39	23	24	27	1.9	1.4
Aviation	11	8	10	18	21	25	9	14	17	6.7	3.2
Shipping	10	10	11	12	14	16	10	9	11	1.2	1.4
Buildings	117	128	132	136	147	158	100	100	100	0.3	0.6
Electricity	35	43	45	55	68	79	34	41	50	2.2	1.9
Liquid fuels	13	13	14	12	10	9	10	9	6	-1.6	-1.5
Biofuels	0	0	0	0	0	0	0	0	0	3.9	2.3
Oil	13	13	14	12	10	9	10	9	6	-1.6	-1.5
Gaseous fuels	27	30	31	32	32	32	24	23	20	0.1	0.1
Biomethane	0	0	0	0	1	1	0	0	1	12	10
Hydrogen	-	-	-	0	0	0	-	0	0	n.a.	n.a.
Natural gas	26	29	31	31	30	30	23	23	19	0.0	-0.1
Solid fuels	35	33	33	27	25	24	25	20	15	-2.2	-1.0
Modern biomass	4	4	4	5	6	6	3	4	4	2.3	1.3
Traditional use of biomass	25	24	24	20	19	18	18	15	11	-2.3	-1.1
Coal	6	4	4	2	1	0	3	1	0	-10	-8.6
Heat	6	7	7	7	7	7	5	5	4	0.2	0.1
Other	1	2	3	4	6	7	2	3	5	4.8	3.6
Residential	83	91	94	92	98	106	71	67	67	-0.2	0.4
Services	33	37	39	44	49	52	29	33	33	1.5	1.0
Other	22	24	26	29	30	29	100	100	100	0.9	0.4

Table A.3a: World electricity sector

	Stated Policies Scenario (TWh)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total generation	**21 539**	**26 708**	**28 334**	**34 834**	**42 642**	**49 845**	**100**	**100**	**100**	**2.3**	**2.0**
Renewables	4 234	7 539	8 060	15 073	24 442	32 452	28	43	65	7.2	4.9
Solar PV	32	824	1 003	4 011	8 356	12 118	4	12	24	17	9.0
Wind	342	1 597	1 870	4 604	8 107	10 691	7	13	21	11	6.2
Hydro	3 449	4 343	4 327	5 078	5 890	6 809	15	15	14	1.8	1.6
Bioenergy	341	666	746	1 145	1 540	1 951	3	3	4	4.9	3.4
of which BECCS	-	-	-	4	5	5	-	0	0	n.a.	n.a.
CSP	2	14	15	45	166	329	0	0	1	13	11
Geothermal	68	95	97	183	335	458	0	1	1	7.2	5.5
Marine	1	1	1	8	47	96	0	0	0	24	17
Nuclear	2 756	2 673	2 776	3 351	3 897	4 260	10	10	9	2.1	1.5
Hydrogen and ammonia	-	-	-	9	32	44	-	0	0	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	5	112	133	0	0	0	21	19
Coal with CCUS	-	1	1	5	51	61	0	0	0	21	16
Natural gas with CCUS	-	-	-	-	61	72	-	-	0	n.a.	n.a.
Unabated fossil fuels	14 494	16 435	17 436	16 324	14 074	12 862	62	47	26	-0.7	-1.0
Coal	8 670	9 439	10 201	9 044	7 211	5 892	36	26	12	-1.3	-1.9
Natural gas	4 855	6 333	6 552	6 848	6 501	6 658	23	20	13	0.5	0.1
Oil	969	664	682	432	362	312	2	1	1	-5.0	-2.7

	Stated Policies Scenario (GW)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total capacity	**5 198**	**7 849**	**8 185**	**11 954**	**16 468**	**19 792**	**100**	**100**	**100**	**4.3**	**3.1**
Renewables	1 343	2 989	3 278	6 707	10 666	13 653	40	56	69	8.3	5.0
Solar PV	39	741	892	3 020	5 573	7 464	11	25	38	15	7.6
Wind	181	737	832	1 830	2 853	3 564	10	15	18	9.2	5.1
Hydro	1 027	1 329	1 358	1 563	1 795	2 027	17	13	10	1.6	1.4
Bioenergy	83	160	173	246	327	406	2	2	2	4.0	3.0
of which BECCS	-	-	-	1	1	1	-	0	0	n.a.	n.a.
CSP	1	6	7	17	49	90	0	0	0	10	9.2
Geothermal	11	15	16	28	50	66	0	0	0	7.0	5.1
Marine	0	1	1	4	19	37	0	0	0	18	14
Nuclear	403	415	413	471	545	590	5	4	3	1.5	1.2
Hydrogen and ammonia	-	-	-	3	13	13	-	0	0	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	1	26	33	0	0	0	28	21
Coal with CCUS	-	0	0	1	10	13	0	0	0	28	18
Natural gas with CCUS	-	-	-	-	16	20	-	-	0	n.a.	n.a.
Unabated fossil fuels	3 448	4 421	4 462	4 495	4 441	4 196	55	38	21	0.1	-0.2
Coal	1 621	2 161	2 184	2 129	1 936	1 583	27	18	8	-0.3	-1.1
Natural gas	1 389	1 830	1 850	2 074	2 268	2 422	23	17	12	1.3	0.9
Oil	438	430	427	292	237	192	5	2	1	-4.1	-2.7
Battery storage	1	18	27	270	768	1 296	0	2	7	29	14

Table A.4a: World CO_2 emissions

	Stated Policies Scenario (Mt CO_2)						CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2030	2050
Total CO_2*	**32 893**	**34 779**	**36 639**	**36 211**	**33 861**	**31 979**	**-0.1**	**-0.5**
Combustion activities (+)	**30 643**	**31 904**	**33 680**	**33 135**	**30 800**	**28 946**	**-0.2**	**-0.5**
Coal	13 855	14 335	15 106	13 695	11 553	9 863	-1.1	-1.5
Oil	10 576	10 194	10 850	11 412	11 248	11 094	0.6	0.1
Natural gas	6 067	7 162	7 520	7 774	7 675	7 629	0.4	0.0
Bioenergy and waste	146	213	204	254	324	360	2.5	2.0
Industry removals (-)	**-**	**1**	**2**	**9**	**28**	**59**	**20**	**13**
Biofuels production	-	1	1	1	1	1	0.0	0.0
Direct air capture	-	-	1	8	27	58	27	15
Electricity and heat sectors	**12 474**	**13 502**	**14 378**	**12 759**	**10 676**	**9 308**	**-1.3**	**-1.5**
Coal	8 946	9 750	10 507	9 128	7 282	5 938	-1.6	-1.9
Oil	828	557	574	372	309	260	-4.7	-2.7
Natural gas	2 623	3 095	3 195	3 105	2 863	2 842	-0.3	-0.4
Bioenergy and waste	78	99	101	154	223	267	4.8	3.4
Other energy sector**	**1 438**	**1 487**	**1 522**	**1 698**	**1 695**	**1 659**	**1.2**	**0.3**
Final consumption**	**18 720**	**19 522**	**20 468**	**21 627**	**21 501**	**21 056**	**0.6**	**0.1**
Coal	4 707	4 474	4 499	4 458	4 170	3 830	-0.1	-0.6
Oil	9 117	9 080	9 704	10 456	10 388	10 331	0.8	0.2
Natural gas	2 859	3 321	3 561	3 800	3 929	3 904	0.7	0.3
Bioenergy and waste	67	114	102	100	101	94	-0.3	-0.3
Industry**	8 379	9 132	9 316	10 037	10 061	9 669	0.8	0.1
Iron and steel**	2 104	2 724	2 755	2 929	2 798	2 653	0.7	-0.1
Chemicals**	1 183	1 287	1 342	1 492	1 492	1 429	1.2	0.2
Cement**	1 928	2 458	2 526	2 648	2 699	2 585	0.5	0.1
Transport	7 011	7 113	7 670	8 472	8 571	8 700	1.1	0.4
Road	5 214	5 485	5 858	6 065	5 925	5 667	0.4	-0.1
Passenger cars	2 622	2 803	3 018	2 962	2 761	2 470	-0.2	-0.7
Heavy-duty trucks	1 468	1 688	1 791	2 070	2 274	2 435	1.6	1.1
Aviation	753	586	713	1 259	1 440	1 675	6.5	3.0
Shipping	796	796	838	905	979	1 145	0.9	1.1
Buildings	2 892	2 851	3 045	2 680	2 446	2 293	-1.4	-1.0
Residential	1 963	1 983	2 066	1 747	1 528	1 415	-1.8	-1.3
Services	929	868	979	934	919	878	-0.5	-0.4
Total CO_2 removals**	**-**	**1**	**2**	**11**	**35**	**70**	**22**	**13**
Total CO_2 captured**	**4**	**42**	**43**	**92**	**272**	**396**	**8.9**	**8.0**

**Includes emissions from industrial processes and flaring.*

***Includes emissions from industrial processes.*

Table A.1b: World energy supply

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total energy supply	542	592	624	636	626	629	100	100	100	0.2	0.0
Renewables	45	69	74	141	239	319	12	22	51	7.5	5.2
Solar	1	5	5	23	56	89	1	4	14	17	10
Wind	1	6	7	21	44	63	1	3	10	13	8.0
Hydro	12	16	16	19	23	27	2	3	4	2.1	1.9
Modern solid bioenergy	24	33	36	53	70	81	6	8	13	4.6	2.9
Modern liquid bioenergy	2	4	4	11	18	19	1	2	3	11	5.3
Modern gaseous bioenergy	1	1	1	4	8	12	0	1	2	15	8.2
Other renewables	3	4	5	10	20	28	1	2	4	9.2	6.4
Traditional use of biomass	25	24	24	9	7	6	4	1	1	-10	-4.8
Nuclear	30	29	30	39	49	56	5	6	9	2.8	2.1
Unabated natural gas	115	139	146	130	99	77	23	20	12	-1.3	-2.2
Natural gas with CCUS	0	0	0	4	10	15	0	1	2	27	13
Oil	173	172	183	179	139	108	29	28	17	-0.3	-1.8
of which non-energy use	25	29	31	36	36	35	5	6	6	1.7	0.4
Unabated coal	153	157	165	132	73	33	26	21	5	-2.5	-5.4
Coal with CCUS	-	0	0	1	9	15	0	0	2	64	29
Electricity and heat sectors	200	228	242	260	302	349	100	100	100	0.8	1.3
Renewables	21	37	40	83	160	229	17	32	66	8.5	6.2
Solar PV	0	3	4	17	42	68	1	7	19	19	11
Wind	1	6	7	21	44	63	3	8	18	13	8.0
Hydro	12	16	16	19	23	27	6	7	8	2.1	1.9
Bioenergy	5	9	10	17	28	37	4	7	11	5.8	4.5
Other renewables	2	4	4	9	22	35	2	4	10	11	8.0
Hydrogen	-	-	-	0	2	2	-	0	1	n.a.	n.a.
Ammonia	-	-	-	0	1	2	-	0	1	n.a.	n.a.
Nuclear	30	29	30	39	49	56	13	15	16	2.8	2.1
Unabated natural gas	47	55	57	49	36	28	24	19	8	-1.6	-2.4
Natural gas with CCUS	-	-	-	0	2	2	-	0	1	n.a.	n.a.
Oil	11	7	8	4	3	2	3	2	1	-6.2	-4.4
Unabated coal	91	99	107	83	43	17	44	32	5	-2.7	-6.1
Coal with CCUS	-	0	0	0	7	10	0	0	3	54	29
Other energy sector	51	59	61	69	72	78	100	100	100	1.3	0.8
Biofuels conversion losses	-	5	6	13	19	19	100	100	100	9.3	4.3
Low-emissions hydrogen											
Production inputs	-	0	0	4	15	28	100	100	100	99	32
Production outputs	-	0	0	3	11	20	100	100	100	103	33
For hydrogen-based fuels	-	-	-	1	3	8	-	23	40	n.a.	n.a.
For other energy sector	-	-	-	0	0	0	-	13	1	n.a.	n.a.

Table A.2b: World final consumption

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total final consumption	**383**	**417**	**439**	**451**	**439**	**433**	**100**	**100**	**100**	**0.3**	**-0.1**
Electricity	64	82	87	108	140	169	20	24	39	2.5	2.3
Liquid fuels	154	159	170	177	149	125	39	39	29	0.4	-1.1
Biofuels	2	4	4	11	18	19	1	2	4	11	5.3
Ammonia	-	-	-	0	1	3	-	0	1	n.a.	n.a.
Synthetic oil	-	-	-	0	1	2	-	0	0	n.a.	n.a.
Oil	151	155	166	165	129	101	38	37	23	-0.0	-1.7
Gaseous fuels	58	68	72	71	65	61	17	16	14	-0.3	-0.6
Biomethane	0	0	0	2	3	5	0	0	1	25	11
Hydrogen	-	0	0	1	5	10	0	0	2	87	30
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57	68	72	67	55	45	16	15	10	-0.8	-1.6
Solid fuels	95	92	94	76	62	53	21	17	12	-2.3	-1.9
Solid bioenergy	38	39	40	32	32	34	9	7	8	-2.6	-0.6
Coal	56	52	53	44	30	19	12	10	4	-2.1	-3.4
Heat	12	13	13	13	12	10	3	3	2	-0.1	-1.0
Other	1	2	3	6	11	15	1	1	3	9.7	5.9
Industry	**143**	**160**	**167**	**178**	**178**	**174**	**100**	**100**	**100**	**0.7**	**0.1**
Electricity	27	34	37	45	56	66	22	25	38	2.3	2.1
Liquid fuels	29	32	33	37	35	32	20	21	18	1.0	-0.2
Oil	29	32	33	36	34	30	20	20	17	0.9	-0.3
Gaseous fuels	24	30	31	33	33	30	18	18	17	0.7	-0.1
Biomethane	0	0	0	1	2	3	0	0	2	28	13
Hydrogen	-	-	-	1	2	3	-	0	2	n.a.	n.a.
Unabated natural gas	24	29	31	31	27	22	18	17	12	0.1	-1.2
Natural gas with CCUS	0	0	0	0	1	3	0	0	2	29	17
Solid fuels	58	58	59	56	47	39	36	32	22	-0.6	-1.5
Solid bioenergy	8	10	11	14	17	20	7	8	11	2.8	2.0
Unabated coal	50	47	48	42	27	15	29	23	9	-1.5	-4.0
Coal with CCUS	-	-	-	0	2	4	-	0	2	n.a.	n.a.
Heat	5	6	7	7	5	4	4	4	2	-0.0	-1.5
Other	0	0	0	1	2	3	0	1	2	42	16
Iron and steel	31	35	36	35	33	31	22	20	18	-0.3	-0.5
Chemicals	37	46	48	55	56	55	29	31	32	1.4	0.4
Cement	10	12	12	12	12	12	7	7	7	-0.2	-0.2

Table A.2b: World final consumption (continued)

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Transport	**102**	**105**	**113**	**124**	**115**	**112**	**100**	**100**	**100**	**1.0**	**-0.0**
Electricity	1	1	2	6	17	28	1	5	25	15	10
Liquid fuels	97	99	107	113	93	76	94	91	67	0.6	-1.2
Biofuels	2	4	4	10	16	17	4	8	15	11	5.0
Oil	95	95	103	102	75	54	90	83	48	-0.0	-2.2
Gaseous fuels	4	5	5	5	6	8	5	4	7	-0.3	1.6
Biomethane	0	0	0	0	0	0	0	0	0	15	6.7
Hydrogen	-	0	0	0	2	6	0	0	5	67	28
Natural gas	4	5	5	4	3	2	5	4	2	-1.7	-3.2
Road	76	81	87	90	80	73	77	73	65	0.3	-0.6
Passenger cars	39	42	45	43	35	30	40	35	27	-0.4	-1.4
Heavy-duty trucks	21	25	26	30	31	31	23	24	27	1.5	0.5
Aviation	11	8	10	18	20	24	9	14	21	6.5	3.0
Shipping	10	10	11	11	10	11	10	9	9	0.4	-0.1
Buildings	**117**	**128**	**132**	**121**	**118**	**122**	**100**	**100**	**100**	**-1.0**	**-0.3**
Electricity	35	43	45	54	63	71	34	44	58	1.9	1.5
Liquid fuels	13	13	14	11	6	5	10	9	4	-2.8	-3.7
Biofuels	0	0	0	0	0	0	0	0	0	11	5.4
Oil	13	13	14	11	6	4	10	9	4	-2.8	-3.8
Gaseous fuels	27	30	31	27	21	17	24	22	14	-1.5	-2.1
Biomethane	0	0	0	1	1	2	0	1	1	28	11
Hydrogen	-	-	-	0	1	1	-	0	1	n.a.	n.a.
Natural gas	26	29	31	26	18	13	23	21	11	-2.0	-3.0
Solid fuels	35	33	33	18	14	14	25	15	11	-6.3	-3.0
Modern biomass	4	4	4	8	7	8	3	6	6	6.8	2.0
Traditional use of biomass	25	24	24	9	7	6	18	7	5	-10	-4.8
Coal	6	4	4	1	0	0	3	1	0	-12	-13
Heat	6	7	7	7	6	6	5	5	5	-0.3	-0.5
Other	1	2	3	5	8	11	2	4	9	7.8	5.0
Residential	83	91	94	80	77	80	71	66	66	-1.7	-0.5
Services	33	37	39	41	41	42	29	34	34	0.6	0.3
Other	**22**	**24**	**26**	**28**	**27**	**24**	**100**	**100**	**100**	**0.5**	**-0.3**

Table A.3b: World electricity sector

	Announced Pledges Scenario (TWh)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total generation	**21 539**	**26 708**	**28 334**	**35 878**	**48 654**	**61 268**	**100**	**100**	**100**	**2.7**	**2.7**
Renewables	4 234	7 539	8 060	17 575	33 971	48 873	28	49	80	9.0	6.4
Solar PV	32	824	1 003	4 838	11 767	18 761	4	13	31	19	11
Wind	342	1 597	1 870	5 816	12 300	17 416	7	16	28	13	8.0
Hydro	3 449	4 343	4 327	5 213	6 460	7 543	15	15	12	2.1	1.9
Bioenergy	341	666	746	1 355	2 288	3 179	3	4	5	6.9	5.1
of which BECCS	-	-	-	46	304	532	-	0	1	n.a.	n.a.
CSP	2	14	15	100	614	1 166	0	0	2	23	16
Geothermal	68	95	97	237	479	686	0	1	1	10	7.0
Marine	1	1	1	15	64	122	0	0	0	34	18
Nuclear	2 756	2 673	2 776	3 547	4 471	5 103	10	10	8	2.8	2.1
Hydrogen and ammonia	-	-	-	79	336	567	-	0	1	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	75	890	1 338	0	0	2	66	29
Coal with CCUS	-	1	1	34	642	1 013	0	0	2	51	28
Natural gas with CCUS	-	-	-	42	249	325	-	0	1	n.a.	n.a.
Unabated fossil fuels	14 494	16 435	17 436	14 539	8 935	5 332	62	41	9	-2.0	-4.0
Coal	8 670	9 439	10 201	8 076	4 219	1 580	36	23	3	-2.6	-6.2
Natural gas	4 855	6 333	6 552	6 100	4 461	3 577	23	17	6	-0.8	-2.1
Oil	969	664	682	364	254	175	2	1	0	-6.8	-4.6

	Announced Pledges Scenario (GW)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total capacity	**5 198**	**7 849**	**8 185**	**12 932**	**20 258**	**26 541**	**100**	**100**	**100**	**5.2**	**4.1**
Renewables	1 343	2 989	3 278	7 744	14 510	20 290	40	60	76	10	6.5
Solar PV	39	741	892	3 498	7 471	11 065	11	27	42	16	9.1
Wind	181	737	832	2 251	4 246	5 727	10	17	22	12	6.9
Hydro	1 027	1 329	1 358	1 609	1 988	2 325	17	12	9	1.9	1.9
Bioenergy	83	160	173	307	529	707	2	2	3	6.6	5.0
of which BECCS	-	-	-	11	57	94	-	0	0	n.a.	n.a.
CSP	1	6	7	35	177	318	0	0	1	20	14
Geothermal	11	15	16	37	72	102	0	0	0	10	6.7
Marine	0	1	1	7	26	47	0	0	0	27	15
Nuclear	403	415	413	487	622	716	5	4	3	1.9	1.9
Hydrogen and ammonia	-	-	-	30	180	228	-	0	1	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	18	192	288	0	0	1	74	31
Coal with CCUS	-	0	0	6	130	207	0	0	1	54	29
Natural gas with CCUS	-	-	-	12	62	81	-	0	0	n.a.	n.a.
Unabated fossil fuels	3 448	4 421	4 462	4 223	3 506	2 729	55	33	10	-0.6	-1.7
Coal	1 621	2 161	2 184	1 988	1 535	942	27	15	4	-1.0	-2.9
Natural gas	1 389	1 830	1 850	1 949	1 754	1 623	23	15	6	0.6	-0.5
Oil	438	430	427	286	217	164	5	2	1	-4.4	-3.3
Battery storage	1	18	27	425	1 246	2 286	0	3	9	36	17

Table A.4b: World CO_2 emissions

	Announced Pledges Scenario (Mt CO_2)						CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2030	2050
Total CO_2*	**32 893**	**34 779**	**36 639**	**31 511**	**20 539**	**12 399**	**-1.7**	**-3.7**
Combustion activities (+)	**30 643**	**31 904**	**33 680**	**28 803**	**18 554**	**11 347**	**-1.7**	**-3.7**
Coal	13 855	14 335	15 106	11 881	6 594	2 973	-2.6	-5.5
Oil	10 576	10 194	10 850	10 093	7 169	5 078	-0.8	-2.6
Natural gas	6 067	7 162	7 520	6 680	4 967	3 758	-1.3	-2.4
Bioenergy and waste	146	213	204	149	- 176	- 463	-3.4	n.a.
Industry removals (-)	**-**	**1**	**2**	**50**	**164**	**406**	**45**	**21**
Biofuels production	-	1	1	42	136	346	55	23
Direct air capture	-	-	1	8	28	60	26	15
Electricity and heat sectors	**12 474**	**13 502**	**14 378**	**11 330**	**6 389**	**3 138**	**-2.6**	**-5.1**
Coal	8 946	9 750	10 507	8 163	4 292	1 713	-2.8	-6.1
Oil	828	557	574	322	230	156	-6.2	-4.4
Natural gas	2 623	3 095	3 195	2 759	2 022	1 598	-1.6	-2.4
Bioenergy and waste	78	99	101	85	- 155	- 329	-1.9	n.a.
Other energy sector**	**1 438**	**1 487**	**1 522**	**1 334**	**730**	**191**	**-1.5**	**-6.9**
Final consumption**	**18 720**	**19 522**	**20 468**	**18 785**	**13 438**	**9 124**	**-0.9**	**-2.7**
Coal	4 707	4 474	4 499	3 621	2 239	1 239	-2.4	-4.3
Oil	9 117	9 080	9 704	9 302	6 670	4 755	-0.5	-2.4
Natural gas	2 859	3 321	3 561	3 225	2 465	1 803	-1.1	-2.3
Bioenergy and waste	67	114	102	64	- 21	- 125	-5.0	n.a.
Industry**	8 379	9 132	9 316	8 569	6 234	3 946	-0.9	-2.9
Iron and steel**	2 104	2 724	2 755	2 512	1 808	1 120	-1.0	-3.1
Chemicals**	1 183	1 287	1 342	1 315	925	548	-0.2	-3.0
Cement**	1 928	2 458	2 526	2 329	1 758	1 084	-0.9	-2.9
Transport	7 011	7 113	7 670	7 616	5 557	4 025	-0.1	-2.2
Road	5 214	5 485	5 858	5 459	3 773	2 509	-0.8	-2.9
Passenger cars	2 622	2 803	3 018	2 589	1 598	997	-1.7	-3.7
Heavy-duty trucks	1 468	1 688	1 791	1 909	1 549	1 137	0.7	-1.6
Aviation	753	586	713	1 197	1 136	1 074	5.9	1.4
Shipping	796	796	838	778	525	362	-0.8	-2.9
Buildings	2 892	2 851	3 045	2 267	1 434	1 029	-3.2	-3.7
Residential	1 963	1 983	2 066	1 559	1 002	748	-3.1	-3.4
Services	929	868	979	708	432	282	-3.5	-4.2
Total CO_2 removals**	**-**	**1**	**2**	**86**	**431**	**918**	**53**	**24**
Total CO_2 captured**	**4**	**42**	**43**	**517**	**2 428**	**4 299**	**32**	**17**

**Includes emissions from industrial processes and flaring.*

***Includes emissions from industrial processes.*

Table A.1c: World energy supply

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total energy supply	**542**	**592**	**624**	**561**	**524**	**532**	**100**	**100**	**100**	**-1.2**	**-0.5**
Renewables	45	69	74	172	307	373	12	31	70	9.9	5.8
Solar	1	5	5	34	87	124	1	6	23	23	11
Wind	1	6	7	28	67	85	1	5	16	17	9.1
Hydro	12	16	16	21	27	30	2	4	6	3.2	2.3
Modern solid bioenergy	24	33	36	58	73	74	6	10	14	5.5	2.6
Modern liquid bioenergy	2	4	4	12	14	12	1	2	2	12	3.6
Modern gaseous bioenergy	1	1	1	7	12	15	0	1	3	21	8.8
Other renewables	3	4	5	13	26	34	1	2	6	12	7.1
Traditional use of biomass	25	24	24	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30	29	30	43	59	63	5	8	12	3.8	2.6
Unabated natural gas	115	139	146	105	34	14	23	19	3	-3.6	-7.8
Natural gas with CCUS	0	0	0	8	21	27	0	1	5	38	15
Oil	173	172	183	143	76	40	29	26	7	-2.7	-5.1
of which non-energy use	25	29	31	34	32	29	5	6	5	1.1	-0.2
Unabated coal	153	157	165	86	15	2	26	15	0	-7.1	-14
Coal with CCUS	-	0	0	3	13	14	0	1	3	91	29
Electricity and heat sectors	**200**	**228**	**242**	**246**	**311**	**381**	**100**	**100**	**100**	**0.2**	**1.6**
Renewables	21	37	40	107	228	293	17	43	77	12	7.1
Solar PV	0	3	4	27	69	97	1	11	26	25	12
Wind	1	6	7	28	67	85	3	11	22	17	9.1
Hydro	12	16	16	21	27	30	6	8	8	3.2	2.3
Bioenergy	5	9	10	18	33	38	4	7	10	6.5	4.6
Other renewables	2	4	4	13	31	44	2	5	12	15	8.9
Hydrogen	-	-	-	3	7	7	-	1	2	n.a.	n.a.
Ammonia	-	-	-	1	3	3	-	0	1	n.a.	n.a.
Nuclear	30	29	30	43	59	63	13	17	17	3.8	2.6
Unabated natural gas	47	55	57	40	1	1	24	16	0	-3.8	-14
Natural gas with CCUS	-	-	-	1	3	4	-	0	1	n.a.	n.a.
Oil	11	7	8	2	0	0	3	1	0	-13	-17
Unabated coal	91	99	107	47	0	0	44	19	0	-8.6	-33
Coal with CCUS	-	0	0	2	8	9	0	1	2	89	28
Other energy sector	**51**	**59**	**61**	**65**	**72**	**75**	**100**	**100**	**100**	**0.6**	**0.7**
Biofuels conversion losses	-	5	6	14	16	13	100	100	100	10	2.7
Low-emissions hydrogen											
Production inputs	-	0	0	14	41	58	100	100	100	126	35
Production outputs	-	0	0	9	28	42	100	100	100	131	37
For hydrogen-based fuels	-	-	-	2	9	14	-	23	34	n.a.	n.a.
For other energy sector	-	-	-	0	0	0	-	5	1	n.a.	n.a.

Table A.2c: World final consumption

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total final consumption	**383**	**417**	**439**	**398**	**356**	**337**	**100**	**100**	**100**	**-1.1**	**-0.9**
Electricity	64	82	87	110	149	176	20	28	52	2.6	2.5
Liquid fuels	154	159	170	146	91	59	39	37	17	-1.7	-3.6
Biofuels	2	4	4	12	14	12	1	3	4	12	3.6
Ammonia	-	-	-	1	2	4	-	0	1	n.a.	n.a.
Synthetic oil	-	-	-	0	2	4	-	0	1	n.a.	n.a.
Oil	151	155	166	134	72	39	38	34	11	-2.4	-4.9
Gaseous fuels	58	68	72	64	53	46	17	16	14	-1.4	-1.6
Biomethane	0	0	0	5	7	7	0	1	2	40	13
Hydrogen	-	0	0	4	12	21	0	1	6	109	33
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57	68	72	54	32	16	16	14	5	-3.1	-5.1
Solid fuels	95	92	94	62	44	34	21	15	10	-4.6	-3.4
Solid bioenergy	38	39	40	26	26	28	9	6	8	-4.8	-1.2
Coal	56	52	53	35	17	6	12	9	2	-4.4	-7.1
Heat	12	13	13	10	7	5	3	3	2	-2.9	-3.2
Other	1	2	3	7	13	17	1	2	5	11	6.5
Industry	**143**	**160**	**167**	**172**	**165**	**155**	**100**	**100**	**100**	**0.3**	**-0.2**
Electricity	27	34	37	50	66	78	22	29	50	3.4	2.6
Liquid fuels	29	32	33	34	28	23	20	20	15	0.2	-1.3
Oil	29	32	33	34	27	22	20	20	14	0.1	-1.5
Gaseous fuels	24	30	31	32	28	21	18	19	14	0.5	-1.3
Biomethane	0	0	0	2	3	5	0	1	3	42	16
Hydrogen	-	-	-	2	4	5	-	1	3	n.a.	n.a.
Unabated natural gas	24	29	31	28	17	6	18	16	4	-1.1	-5.6
Natural gas with CCUS	0	0	0	1	3	5	0	1	3	47	20
Solid fuels	58	58	59	50	36	27	36	29	17	-2.0	-2.7
Solid bioenergy	8	10	11	15	19	20	7	9	13	3.7	2.2
Unabated coal	50	47	48	33	13	1	29	19	1	-3.9	-12
Coal with CCUS	-	-	-	1	4	5	-	0	3	n.a.	n.a.
Heat	5	6	7	5	3	1	4	3	1	-3.6	-5.6
Other	0	0	0	2	4	5	0	1	3	51	18
Iron and steel	31	35	36	33	31	27	22	19	17	-0.9	-1.1
Chemicals	37	46	48	53	52	49	29	31	31	1.0	0.0
Cement	10	12	12	12	11	10	7	7	7	-0.5	-0.7

Table A.2c: World final consumption (continued)

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Transport	**102**	**105**	**113**	**101**	**80**	**77**	**100**	**100**	**100**	**-1.3**	**-1.3**
Electricity	1	1	2	8	24	37	1	8	48	20	11
Liquid fuels	97	99	107	88	46	25	94	87	32	-2.1	-4.9
Biofuels	2	4	4	11	12	10	4	11	13	11	3.0
Oil	95	95	103	76	30	7	90	76	9	-3.2	-8.8
Gaseous fuels	4	5	5	5	9	15	5	5	20	-0.4	3.8
Biomethane	0	0	0	0	0	0	0	0	1	11	6.6
Hydrogen	-	0	0	1	7	14	0	1	18	91	33
Natural gas	4	5	5	3	2	0	5	3	1	-4.3	-8.2
Road	76	81	87	72	52	48	77	71	62	-2.1	-2.1
Passenger cars	39	42	45	31	19	17	40	31	22	-4.2	-3.3
Heavy-duty trucks	21	25	26	27	24	21	23	27	28	0.4	-0.7
Aviation	11	8	10	14	13	14	9	14	19	3.7	1.3
Shipping	10	10	11	11	10	10	10	11	13	0.1	-0.3
Buildings	**117**	**128**	**132**	**99**	**88**	**85**	**100**	**100**	**100**	**-3.2**	**-1.5**
Electricity	35	43	45	48	54	57	34	48	67	0.6	0.8
Liquid fuels	13	13	14	9	4	1	10	9	1	-4.3	-8.0
Biofuels	0	0	0	0	0	0	0	0	0	16	9.9
Oil	13	13	14	9	3	1	10	9	1	-4.4	-9.1
Gaseous fuels	27	30	31	21	10	5	24	21	5	-4.4	-6.4
Biomethane	0	0	0	3	3	1	0	3	2	49	11
Hydrogen	-	-	-	0	1	1	-	0	2	n.a.	n.a.
Natural gas	26	29	31	17	4	-	23	17	-	-6.5	n.a.
Solid fuels	35	33	33	11	7	7	25	11	8	-12	-5.3
Modern biomass	4	4	4	10	7	7	3	10	8	9.8	1.6
Traditional use of biomass	25	24	24	-	-	-	18	-	-	n.a.	n.a.
Coal	6	4	4	1	0	0	3	1	0	-17	-21
Heat	6	7	7	5	5	4	5	5	5	-2.2	-1.8
Other	1	2	3	5	9	11	2	5	13	7.5	5.1
Residential	83	91	94	65	57	56	71	65	66	-4.0	-1.8
Services	33	37	39	34	32	29	29	35	34	-1.3	-1.0
Other	**22**	**24**	**26**	**26**	**23**	**20**	**100**	**100**	**100**	**-0.2**	**-1.0**

Table A.3c: World electricity sector

	Net Zero Emissions by 2050 Scenario (TWh)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total generation	**21 539**	**26 708**	**28 334**	**37 723**	**57 924**	**73 231**	**100**	**100**	**100**	**3.2**	**3.3**
Renewables	4 234	7 539	8 060	23 064	49 675	64 506	28	61	88	12	7.4
Solar PV	32	824	1 003	7 552	19 239	27 006	4	20	37	25	12
Wind	342	1 597	1 870	7 840	18 555	23 486	7	21	32	17	9.1
Hydro	3 449	4 343	4 327	5 725	7 637	8 251	15	15	11	3.2	2.3
Bioenergy	341	666	746	1 442	2 610	3 280	3	4	4	7.6	5.2
of which BECCS	-	-	-	96	510	639	-	0	1	n.a.	n.a.
CSP	2	14	15	175	911	1 500	0	0	2	31	17
Geothermal	68	95	97	312	655	857	0	1	1	14	7.8
Marine	1	1	1	20	69	125	0	0	0	38	18
Nuclear	2 756	2 673	2 776	3 896	5 413	5 810	10	10	8	3.8	2.6
Hydrogen and ammonia	-	-	-	603	1 415	1 467	-	2	2	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	282	1 211	1 317	0	1	2	92	29
Coal with CCUS	-	1	1	198	765	827	0	1	1	84	27
Natural gas with CCUS	-	-	-	84	446	490	-	0	1	n.a.	n.a.
Unabated fossil fuels	14 494	16 435	17 436	9 824	168	85	62	26	0	-6.2	-17
Coal	8 670	9 439	10 201	4 666	0	0	36	12	0	-8.3	-32
Natural gas	4 855	6 333	6 552	4 977	164	82	23	13	0	-3.0	-14
Oil	969	664	682	180	4	3	2	0	0	-14	-17

	Net Zero Emissions by 2050 Scenario (GW)						Shares (%)			CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2021	2030	2050	2030	2050
Total capacity	**5 198**	**7 849**	**8 185**	**15 306**	**26 870**	**33 878**	**100**	**100**	**100**	**7.2**	**5.0**
Renewables	1 343	2 989	3 278	10 349	21 398	27 304	40	68	81	14	7.6
Solar PV	39	741	892	5 052	11 620	15 468	11	33	46	21	10
Wind	181	737	832	3 072	6 435	7 795	10	20	23	16	8.0
Hydro	1 027	1 329	1 358	1 782	2 349	2 685	17	12	8	3.1	2.4
Bioenergy	83	160	173	320	585	744	2	2	2	7.1	5.2
of which BECCS	-	-	-	22	98	119	-	0	0	n.a.	n.a.
CSP	1	6	7	64	283	437	0	0	1	28	15
Geothermal	11	15	16	50	98	126	0	0	0	14	7.5
Marine	0	1	1	9	28	49	0	0	0	30	15
Nuclear	403	415	413	535	777	871	5	3	3	2.9	2.6
Hydrogen and ammonia	-	-	-	189	640	573	-	1	2	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	62	266	335	0	0	1	100	31
Coal with CCUS	-	0	0	44	168	201	0	0	1	92	29
Natural gas with CCUS	-	-	-	18	98	134	-	0	0	n.a.	n.a.
Unabated fossil fuels	3 448	4 421	4 462	3 389	1 476	932	55	22	3	-3.0	-5.3
Coal	1 621	2 161	2 184	1 452	401	184	27	9	1	-4.4	-8.2
Natural gas	1 389	1 830	1 850	1 724	1 004	711	23	11	2	-0.8	-3.2
Oil	438	430	427	213	71	38	5	1	0	-7.5	-8.0
Battery storage	1	18	27	778	2 311	3 860	0	5	11	45	19

Table A.4c: World CO_2 emissions

	Net Zero Emissions by 2050 Scenario (Mt CO_2)						CAAGR (%) 2021 to:	
	2010	2020	2021	2030	2040	2050	2030	2050
Total CO_2*	**32 893**	**34 779**	**36 639**	**22 846**	**5 799**	**-**	**-5.1**	**n.a.**
Combustion activities (+)	**30 643**	**31 904**	**33 680**	**20 590**	**5 103**	**510**	**-5.3**	**-13**
Coal	13 855	14 335	15 106	7 578	1 140	114	-7.4	-16
Oil	10 576	10 194	10 850	7 710	3 030	722	-3.7	-8.9
Natural gas	6 067	7 162	7 520	5 282	1 391	405	-3.8	-9.6
Bioenergy and waste	146	213	204	19	- 458	- 731	-23	n.a.
Industry removals (-)	**-**	**1**	**2**	**156**	**530**	**787**	**65**	**23**
Biofuels production	-	1	1	102	308	394	71	24
Direct air capture	-	-	1	54	222	393	57	23
Electricity and heat sectors	**12 474**	**13 502**	**14 378**	**7 076**	**- 189**	**- 351**	**-7.6**	**-188**
Coal	8 946	9 750	10 507	4 653	49	27	-8.7	-19
Oil	828	557	574	167	18	2	-13	-17
Natural gas	2 623	3 095	3 195	2 264	80	42	-3.8	-14
Bioenergy and waste	78	99	101	- 9	- 335	- 421	-176	n.a.
Other energy sector**	**1 438**	**1 487**	**1 522**	**966**	**112**	**- 266**	**-4.9**	**-194**
Final consumption**	**18 720**	**19 522**	**20 468**	**14 765**	**6 092**	**1 005**	**-3.6**	**-9.9**
Coal	4 707	4 474	4 499	2 835	1 043	73	-5.0	-13
Oil	9 117	9 080	9 704	7 162	2 865	651	-3.3	-8.9
Natural gas	2 859	3 321	3 561	2 491	1 094	213	-3.9	-9.3
Bioenergy and waste	67	114	102	29	- 96	- 205	-13	n.a.
Industry**	8 379	9 132	9 316	7 168	3 246	396	-2.9	-10
Iron and steel**	2 104	2 724	2 755	2 091	965	177	-3.0	-9.0
Chemicals**	1 183	1 287	1 342	1 137	546	38	-1.8	-12
Cement**	1 928	2 458	2 526	1 910	869	76	-3.1	-11
Transport	7 011	7 113	7 670	5 687	2 258	535	-3.3	-8.8
Road	5 214	5 485	5 858	3 988	1 370	195	-4.2	-11
Passenger cars	2 622	2 803	3 018	1 691	422	45	-6.2	-13
Heavy-duty trucks	1 468	1 688	1 791	1 574	746	136	-1.4	-8.5
Aviation	753	586	713	884	511	199	2.4	-4.3
Shipping	796	796	838	673	304	107	-2.4	-6.8
Buildings	2 892	2 851	3 045	1 632	475	55	-6.7	-13
Residential	1 963	1 983	2 066	1 197	369	55	-5.9	-12
Services	929	868	979	435	106	1	-8.6	-22
Total CO_2 removals**	**-**	**1**	**2**	**234**	**1 008**	**1 526**	**70**	**26**
Total CO_2 captured**	**4**	**42**	**43**	**1 224**	**4 422**	**6 231**	**45**	**19**

**Includes emissions from industrial processes and flaring.*

***Includes emissions from industrial processes.*

Table A.5: Total energy supply (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	542.0	592.3	624.2	673.3	740.0	635.6	629.1
North America	112.5	106.7	111.4	108.8	103.3	103.8	88.0
United States	94.1	87.2	91.4	87.3	80.4	83.2	69.1
Central and South America	26.7	26.8	28.5	32.2	41.1	32.8	37.0
Brazil	12.1	13.3	14.1	16.0	19.8	16.7	17.6
Europe	89.4	77.9	82.3	76.4	70.0	72.3	59.7
European Union	64.5	55.6	59.3	53.2	45.2	49.9	38.7
Africa	28.9	35.1	36.4	44.0	64.7	37.0	53.0
Middle East	27.0	33.6	34.8	41.8	55.0	39.5	47.9
Eurasia	35.4	38.9	41.1	39.1	42.0	37.5	37.9
Russia	28.7	31.8	33.6	30.7	31.0	29.6	28.9
Asia Pacific	207.0	260.9	275.6	310.7	335.6	293.5	286.4
China	107.3	147.7	156.8	166.4	156.5	158.3	133.3
India	27.9	36.6	39.5	53.3	70.2	48.1	56.3
Japan	20.9	16.1	16.5	14.9	12.3	14.6	10.9
Southeast Asia	22.8	29.2	30.2	40.0	53.7	38.2	45.2

Table A.6: Renewables energy supply (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	44.5	68.7	73.6	116.2	214.9	141.5	319.0
North America	9.2	12.1	12.8	19.7	33.5	26.1	49.8
United States	6.8	9.3	9.9	15.8	27.9	20.8	41.6
Central and South America	7.9	9.7	10.0	13.3	20.7	16.5	27.3
Brazil	5.6	6.9	6.9	9.0	12.6	10.9	14.2
Europe	10.1	14.2	14.9	20.6	28.1	25.6	39.2
European Union	7.9	10.5	11.1	15.1	19.9	18.6	27.0
Africa	3.7	5.1	5.4	9.3	20.5	9.7	27.9
Middle East	0.1	0.2	0.3	1.0	5.2	2.0	12.2
Eurasia	1.1	1.4	1.5	1.8	3.4	2.1	5.1
Russia	0.9	1.2	1.3	1.4	2.6	1.4	2.9
Asia Pacific	12.4	25.8	28.6	50.3	102.3	58.7	152.8
China	4.7	12.4	14.0	25.8	49.7	28.6	70.9
India	2.8	5.3	5.5	9.6	23.6	10.9	34.2
Japan	0.9	1.3	1.4	2.1	3.3	2.6	5.0
Southeast Asia	2.8	5.1	5.4	8.7	16.2	10.3	25.1

Table A.7: Oil production (mb/d)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World supply	**85.5**	**91.2**	**92.6**	**102.4**	**102.1**	**93.0**	**57.2**
Processing gains	2.2	2.1	2.3	2.5	2.8	2.3	1.9
World production	**83.4**	**89.1**	**90.3**	**99.9**	**99.3**	**90.7**	**55.3**
Conventional crude oil	66.8	59.7	60.1	62.5	62.6	56.8	31.0
Tight oil	0.7	7.3	7.4	10.9	9.9	9.7	6.7
Natural gas liquids	12.7	17.9	18.2	20.9	19.3	19.2	13.9
Extra-heavy oil & bitumen	2.6	3.4	3.7	4.4	6.2	4.1	3.4
Other	0.6	0.8	0.9	1.2	1.3	0.9	0.3
Non-OPEC	50.0	58.3	58.8	64.0	56.2	58.2	31.6
OPEC	33.3	30.8	31.5	35.9	43.1	32.5	23.7
North America	14.2	23.9	24.4	28.6	24.6	25.8	14.7
Central and South America	7.4	5.9	5.9	9.0	11.4	8.3	6.5
Europe	4.4	3.8	3.6	3.1	1.3	2.7	0.6
European Union	0.7	0.5	0.5	0.4	0.3	0.3	0.1
Africa	10.2	7.0	7.4	7.0	6.1	5.8	2.9
Middle East	25.4	27.6	27.9	33.9	40.4	31.2	22.9
Eurasia	13.4	13.4	13.7	11.9	10.6	11.2	5.4
Asia Pacific	8.4	7.5	7.4	6.3	4.8	5.7	2.2
Southeast Asia	2.6	2.1	1.9	1.5	0.9	1.3	0.5

Table A.8: Oil demand (mb/d)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**87.2**	**88.9**	**94.5**	**102.4**	**102.1**	**93.0**	**57.2**
North America	22.2	20.1	21.4	20.5	16.2	18.2	6.9
United States	17.8	16.5	17.7	16.7	12.6	15.0	5.0
Central and South America	5.5	4.9	5.3	5.5	5.8	4.8	2.4
Brazil	2.3	2.2	2.4	2.4	2.4	2.0	0.9
Europe	13.9	11.9	12.4	10.9	7.1	9.2	2.7
European Union	10.6	8.9	9.2	7.7	4.5	6.5	1.7
Africa	3.3	3.6	3.8	5.0	8.5	4.9	6.1
Middle East	7.1	7.4	7.7	8.9	10.9	8.0	7.9
Eurasia	3.2	3.8	4.1	4.2	4.5	4.1	3.9
Russia	2.6	3.1	3.3	3.2	3.1	3.1	2.8
Asia Pacific	25.0	31.4	33.3	38.2	36.7	35.1	20.6
China	8.8	13.9	15.1	16.2	12.5	15.2	7.6
India	3.3	4.5	4.7	6.7	8.3	5.9	3.9
Japan	4.2	3.2	3.3	2.7	1.7	2.4	0.7
Southeast Asia	4.0	4.7	4.9	6.7	7.4	6.0	3.9
International bunkers	7.1	5.8	6.6	9.3	12.4	8.6	6.8

Table A.9: World liquids demand (mb/d)

	Historical		Stated Policies		Announced Pledges	
	2020	2021	2030	2050	2030	2050
Total liquids	**90.9**	**96.7**	**105.8**	**107.6**	**98.7**	**69.6**
Biofuels	2.0	2.2	3.4	5.3	5.5	9.2
Hydrogen based fuels	-	-	-	0.2	0.2	3.2
Total oil	88.9	94.5	102.4	102.1	93.0	57.2
CTL, GTL and additives	0.8	0.9	1.1	1.3	1.0	0.3
Direct use of crude oil	1.0	0.8	0.5	0.3	0.4	0.2
Oil products	87.1	92.8	100.8	100.5	91.6	56.7
LPG and ethane	13.3	13.6	15.6	15.8	14.4	10.4
Naphtha	6.4	6.9	7.7	9.5	7.3	7.4
Gasoline	21.9	23.6	23.2	19.3	20.6	8.2
Kerosene	4.7	5.7	9.2	11.8	8.7	7.6
Diesel	25.0	26.5	28.2	28.2	25.0	12.6
Fuel oil	5.7	5.9	5.5	6.3	4.8	2.5
Other products	10.1	10.6	11.4	9.6	10.8	8.0
Products from NGLs	11.3	11.5	13.4	11.6	12.7	8.8
Refinery products	75.8	81.3	87.4	88.9	78.9	47.9
Refinery market share	*83%*	*84%*	*83%*	*83%*	*80%*	*69%*

Note: CTL = coal-to-liquids; GTL = gas-to-liquids; LPG = liquefied petroleum gas; NGLs = natural gas liquids.

Table A.10: Refining capacity and runs (mb/d)

	Refining capacity					Refinery runs				
		STEPS		APS			STEPS		APS	
	2021	2030	2050	2030	2050	2021	2030	2050	2030	2050
North America	21.6	21.1	20.8	20.1	11.1	17.6	18.5	18.1	16.5	7.5
Europe	15.8	14.5	13.3	14.0	6.9	12.0	11.4	9.4	10.2	3.9
Asia Pacific	37.1	40.3	41.5	39.4	28.3	29.2	33.1	34.7	30.5	18.9
Japan and Korea	7.0	6.3	5.8	6.2	3.5	5.1	5.0	4.6	4.6	2.2
China	17.5	19.0	19.0	18.5	11.1	14.2	14.5	14.1	13.4	6.4
India	5.3	6.6	7.8	6.4	5.4	4.8	6.4	7.6	5.7	4.0
Southeast Asia	5.3	6.3	6.8	6.3	6.3	3.7	5.5	6.4	5.1	4.7
Middle East	9.6	11.2	12.0	11.0	9.7	7.6	9.6	10.6	8.5	6.6
Russia	6.9	6.5	6.3	6.1	4.6	5.6	4.0	3.5	3.6	2.4
Africa	3.4	4.5	4.8	4.2	4.2	1.8	3.1	3.9	2.7	2.6
Brazil	2.2	2.3	2.3	2.0	1.6	1.8	2.1	2.2	1.7	1.2
Other	4.6	4.8	4.8	4.7	4.2	2.3	2.9	3.5	2.8	2.6
World	**101.2**	**105.2**	**105.8**	**101.5**	**70.6**	**77.9**	**84.7**	**85.9**	**76.5**	**45.7**
Atlantic Basin	54.1	53.6	52.2	51.0	32.5	40.9	41.9	40.4	37.3	20.1
East of Suez	47.1	51.6	53.6	50.5	38.1	37.0	42.9	45.5	39.1	25.6

Table A.11: Natural gas production (bcm)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	3 274	3 996	4 149	4 372	4 355	3 874	2 660
Conventional gas	2 768	2 854	2 964	2 962	3 025	2 727	2 016
Tight gas	274	311	306	317	139	191	37
Shale gas	155	747	790	995	1 091	874	557
Coalbed methane	77	80	82	74	75	58	50
Other	-	4	7	24	25	24	-
North America	811	1 164	1 189	1 283	1 017	1 098	485
Central and South America	160	154	151	149	195	133	95
Europe	341	245	239	247	208	176	65
European Union	148	56	51	39	34	16	2
Africa	203	237	265	313	369	281	239
Middle East	463	646	660	853	1 030	798	690
Eurasia	807	911	998	831	857	751	654
Asia Pacific	488	639	648	694	678	636	432
Southeast Asia	216	194	195	183	129	162	109

Table A.12: Natural gas demand (bcm)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	3 329	4 027	4 213	4 372	4 357	3 874	2 661
North America	835	1 096	1 106	1 118	820	933	396
United States	678	867	871	864	575	716	252
Central and South America	147	149	161	159	179	141	96
Brazil	29	34	42	34	37	28	17
Europe	698	594	625	511	395	394	122
European Union	446	397	421	340	235	242	45
Africa	105	164	172	215	292	189	193
Middle East	391	554	567	689	833	638	582
Eurasia	578	611	662	626	635	587	532
Russia	472	501	543	498	470	470	424
Asia Pacific	576	859	920	1 043	1 173	983	731
China	110	324	368	443	442	406	238
India	64	61	66	115	170	110	102
Japan	95	104	103	64	43	57	17
Southeast Asia	150	160	162	203	272	194	177
International bunkers	-	-	-	11	30	8	8

Table A.13: Coal production (Mtce)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**5 235**	**5 459**	**5 826**	**5 149**	**3 829**	**4 539**	**1 613**
Steam coal	4 069	4 293	4 560	4 026	2 954	3 538	1 177
Coking coal	866	939	1 030	936	736	855	381
Lignite and peat	300	227	235	187	139	146	56
North America	818	409	478	188	106	138	32
Central and South America	79	53	62	41	41	24	3
Europe	331	185	200	126	59	79	20
European Union	220	125	138	71	10	46	8
Africa	210	211	212	188	171	162	47
Middle East	1	1	1	1	1	-	-
Eurasia	309	400	444	323	274	292	216
Asia Pacific	3 487	4 200	4 428	4 282	3 177	3 843	1 295
Southeast Asia	318	481	499	460	474	423	262

Table A.14: Coal demand (Mtce)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**5 220**	**5 347**	**5 644**	**5 149**	**3 828**	**4 539**	**1 613**
North America	768	342	389	107	42	80	30
United States	716	317	363	91	26	64	17
Central and South America	37	41	46	40	60	28	20
Brazil	21	20	25	23	29	16	12
Europe	539	334	369	229	167	157	72
European Union	360	206	238	125	56	79	20
Africa	156	153	152	148	131	119	30
Middle East	5	5	5	8	12	7	9
Eurasia	203	218	222	172	160	162	121
Russia	151	164	166	114	102	113	95
Asia Pacific	3 513	4 254	4 460	4 444	3 258	3 986	1 332
China	2 565	3 037	3 157	2 974	1 866	2 691	789
India	399	542	614	773	671	704	243
Japan	165	146	143	103	62	97	35
Southeast Asia	122	258	269	337	422	295	151

Table A.15: Electricity generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**21 539**	**26 708**	**28 334**	**34 834**	**49 845**	**35 878**	**61 268**
North America	5 233	5 205	5 357	5 771	7 816	6 043	9 749
United States	4 354	4 239	4 371	4 625	6 270	4 869	7 937
Central and South America	1 130	1 276	1 331	1 605	2 592	1 789	3 543
Brazil	516	621	639	762	1 174	811	1 387
Europe	4 120	3 956	4 182	4 691	5 703	5 165	7 539
European Union	2 956	2 758	2 963	3 238	3 689	3 583	5 017
Africa	687	835	869	1 204	2 337	1 330	3 704
Middle East	829	1 203	1 233	1 651	2 886	1 606	3 460
Eurasia	1 251	1 367	1 455	1 540	1 937	1 525	1 925
Russia	1 036	1 087	1 158	1 177	1 376	1 149	1 296
Asia Pacific	8 288	12 866	13 908	18 371	26 573	18 420	31 350
China	4 236	7 767	8 539	11 136	14 342	10 958	16 109
India	974	1 533	1 686	2 708	5 298	2 689	6 553
Japan	1 164	1 009	1 024	969	992	1 036	1 303
Southeast Asia	685	1 116	1 164	1 704	3 143	1 751	3 561

Table A.16: Renewables generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**4 234**	**7 539**	**8 060**	**15 073**	**32 452**	**17 575**	**48 873**
North America	860	1 334	1 385	2 668	5 858	3 361	7 895
United States	445	833	874	2 034	4 849	2 620	6 573
Central and South America	743	888	910	1 287	2 287	1 501	3 365
Brazil	437	525	509	700	1 099	761	1 329
Europe	963	1 596	1 631	2 836	4 249	3 491	6 422
European Union	660	1 069	1 112	1 971	2 854	2 470	4 318
Africa	115	184	197	440	1 429	665	3 234
Middle East	18	35	48	166	966	234	2 227
Eurasia	229	279	285	340	545	384	786
Russia	170	219	222	249	399	252	416
Asia Pacific	1 306	3 223	3 604	7 334	17 117	7 938	24 944
China	791	2 192	2 466	4 901	9 658	5 056	12 704
India	162	325	337	956	3 866	990	5 745
Japan	115	216	232	356	586	391	768
Southeast Asia	105	266	296	506	1 463	668	2 802

Table A.17: Solar PV generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**32**	**824**	**1 003**	**4 011**	**12 118**	**4 838**	**18 761**
North America	3	130	162	708	2 556	947	3 286
United States	3	116	145	668	2 350	894	2 963
Central and South America	0	25	32	189	568	290	1 104
Brazil	0	11	14	119	340	137	446
Europe	23	176	198	553	764	688	1 184
European Union	22	139	151	461	584	567	777
Africa	0	12	15	88	384	177	1 380
Middle East	0	10	12	89	522	114	1 153
Eurasia	0	4	4	14	31	16	45
Russia	0	2	2	5	12	5	14
Asia Pacific	6	467	580	2 371	7 294	2 606	10 609
China	1	261	326	1 474	3 911	1 586	5 442
India	0	61	73	424	2 163	453	3 144
Japan	4	79	91	147	203	154	205
Southeast Asia	0	19	29	106	473	131	911

Table A.18: Wind generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**342**	**1 597**	**1 870**	**4 604**	**10 691**	**5 816**	**17 416**
North America	105	397	436	1 047	2 192	1 415	3 290
United States	95	342	379	948	1 931	1 235	2 801
Central and South America	3	85	108	219	457	289	893
Brazil	2	57	73	137	259	152	305
Europe	154	513	503	1 196	2 081	1 626	3 575
European Union	140	397	396	893	1 495	1 226	2 608
Africa	2	18	22	81	295	143	724
Middle East	0	2	4	26	246	58	704
Eurasia	0	1	5	23	91	51	213
Russia	0	0	3	14	70	16	83
Asia Pacific	77	581	794	2 011	5 329	2 236	8 017
China	45	466	655	1 543	3 312	1 577	4 345
India	20	67	77	211	1 116	213	1 550
Japan	4	9	9	59	186	75	299
Southeast Asia	0	6	12	53	232	124	602

Table A.19: Nuclear generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**2 756**	**2 673**	**2 776**	**3 351**	**4 260**	**3 547**	**5 103**
North America	935	929	913	905	885	924	1 086
United States	839	823	813	807	755	826	914
Central and South America	22	25	25	30	60	34	70
Brazil	15	14	15	21	34	24	39
Europe	1 032	834	889	844	778	896	825
European Union	854	684	733	656	570	705	603
Africa	12	10	13	25	45	30	75
Middle East	0	6	14	51	96	62	138
Eurasia	173	219	219	232	293	235	306
Russia	170	216	217	230	283	232	289
Asia Pacific	582	650	702	1 264	2 103	1 367	2 603
China	74	366	408	643	1 209	718	1 494
India	26	43	42	128	337	131	358
Japan	288	39	56	190	206	219	271
Southeast Asia	0	0	0	0	25	0	98

Table A.20: Natural gas generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**4 855**	**6 333**	**6 551**	**6 848**	**6 730**	**6 142**	**3 902**
North America	1 217	1 931	1 908	1 953	1 024	1 550	599
United States	1 018	1 679	1 641	1 555	620	1 231	283
Central and South America	178	229	256	222	213	214	89
Brazil	36	53	76	27	30	21	10
Europe	946	844	902	606	402	531	127
European Union	589	555	587	400	219	292	30
Africa	234	346	360	470	680	390	308
Middle East	527	873	888	1 198	1 606	1 128	988
Eurasia	603	604	682	762	897	711	697
Russia	521	469	535	589	598	554	501
Asia Pacific	1 151	1 506	1 555	1 636	1 908	1 617	1 094
China	92	256	291	345	344	316	330
India	107	66	70	115	156	107	70
Japan	332	395	386	198	74	192	69
Southeast Asia	336	350	361	529	787	503	334

Table A.21: Coal generation (TWh)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**8 670**	**9 439**	**10 202**	**9 049**	**5 952**	**8 109**	**2 594**
North America	2 106	912	1 045	213	32	139	38
United States	1 994	856	994	201	31	128	37
Central and South America	42	61	68	33	21	8	1
Brazil	11	18	27	10	8	1	0
Europe	1 068	603	678	352	233	201	113
European Union	755	383	460	168	16	78	23
Africa	259	248	244	205	115	171	22
Middle East	0	1	1	4	16	3	15
Eurasia	235	256	258	203	202	193	137
Russia	166	176	175	107	96	110	91
Asia Pacific	4 958	7 359	7 908	8 040	5 335	7 394	2 268
China	3 263	4 941	5 363	5 239	3 118	4 855	1 511
India	658	1 097	1 234	1 504	937	1 458	307
Japan	317	311	294	187	63	192	50
Southeast Asia	185	487	493	656	858	571	231

Table A.22: Total final consumption (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**383.2**	**417.5**	**439.1**	**484.5**	**543.6**	**450.8**	**432.7**
North America	76.6	73.7	77.5	78.5	75.1	73.8	57.7
United States	63.8	61.6	65.1	64.8	60.2	60.9	46.3
Central and South America	19.2	19.3	20.4	23.3	29.1	21.9	22.0
Brazil	9.1	9.5	10.0	11.1	13.4	10.5	10.4
Europe	63.1	57.2	60.0	57.4	51.6	53.4	39.7
European Union	45.9	41.3	43.5	40.5	34.0	37.6	26.1
Africa	20.9	25.3	26.2	31.8	47.4	27.4	37.0
Middle East	19.2	23.1	24.1	29.6	40.0	27.9	34.2
Eurasia	23.8	27.0	28.5	28.2	30.7	27.3	27.6
Russia	19.2	22.1	23.3	22.1	22.5	21.5	21.0
Asia Pacific	145.4	179.5	188.4	215.6	241.2	199.7	191.6
China	76.3	100.2	105.7	114.0	111.2	107.8	91.0
India	19.0	25.8	27.5	37.3	53.8	32.2	39.6
Japan	14.2	11.8	12.1	11.1	9.3	10.5	7.3
Southeast Asia	16.1	19.3	19.8	26.5	34.7	24.5	27.1

Table A.23: Industry consumption (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**143.2**	**160.4**	**166.7**	**189.4**	**208.8**	**178.1**	**173.7**
North America	17.9	18.3	18.6	20.9	22.1	20.0	18.4
United States	14.2	14.5	14.7	16.2	16.8	15.6	13.8
Central and South America	7.2	6.7	7.0	8.2	9.8	7.7	8.2
Brazil	4.0	3.8	4.0	4.5	5.1	4.2	4.3
Europe	19.6	18.4	18.9	18.9	17.7	18.1	15.5
European Union	14.3	13.4	13.9	13.7	11.7	13.1	10.3
Africa	3.9	4.0	4.2	6.1	10.3	5.9	8.7
Middle East	7.8	9.7	10.2	12.7	15.3	11.9	12.9
Eurasia	8.4	9.3	9.5	9.3	10.3	9.0	9.3
Russia	6.9	8.1	8.2	7.8	8.4	7.6	7.7
Asia Pacific	78.4	94.1	98.3	113.3	123.4	105.5	100.7
China	49.4	59.4	61.5	66.7	62.4	62.4	51.2
India	7.9	11.5	12.4	18.1	27.5	16.1	21.6
Japan	6.1	5.0	5.3	5.1	4.5	4.8	3.8
Southeast Asia	6.2	8.4	8.8	11.4	15.2	10.7	12.6

Table A.24: Transport consumption (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**101.7**	**105.0**	**113.4**	**129.8**	**147.0**	**123.7**	**112.5**
North America	29.6	26.9	29.1	28.4	24.9	26.7	18.0
United States	25.0	23.0	25.1	24.0	20.4	22.5	15.0
Central and South America	6.1	6.5	7.2	8.3	10.6	7.9	7.3
Brazil	2.9	3.4	3.6	4.0	4.6	3.8	3.4
Europe	15.6	14.4	15.3	14.5	11.7	13.6	8.4
European Union	11.7	10.6	11.1	10.0	7.5	9.4	5.5
Africa	3.7	4.7	5.0	6.3	11.3	6.3	10.1
Middle East	4.9	5.3	5.7	6.4	8.9	6.1	6.9
Eurasia	4.7	4.8	5.2	5.4	5.8	5.2	5.1
Russia	4.0	3.8	4.1	3.8	3.3	3.8	3.0
Asia Pacific	22.1	30.1	32.0	40.3	45.5	38.4	33.7
China	8.3	13.6	15.0	16.9	15.3	16.2	11.8
India	2.7	3.9	4.2	6.8	10.3	6.5	7.5
Japan	3.3	2.6	2.5	2.2	1.7	2.1	1.1
Southeast Asia	3.7	5.3	5.4	8.4	9.9	7.8	6.9

Table A.25: Buildings consumption (EJ)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**116.8**	**127.6**	**132.4**	**136.5**	**158.3**	**121.3**	**122.0**
North America	23.7	23.8	24.2	23.3	22.6	21.3	16.4
United States	20.5	20.3	20.8	19.7	18.4	18.2	13.6
Central and South America	4.4	4.8	4.9	5.4	7.1	4.9	5.2
Brazil	1.4	1.7	1.7	1.9	2.9	1.7	2.1
Europe	24.3	21.2	22.2	20.3	19.0	18.4	13.3
European Union	17.6	15.1	15.9	14.4	12.7	12.8	8.6
Africa	12.5	15.8	16.2	18.3	24.0	14.2	16.5
Middle East	5.3	6.5	6.7	8.9	14.3	8.4	13.1
Eurasia	8.4	9.9	10.5	10.2	10.8	9.8	9.8
Russia	6.2	7.4	7.8	7.4	7.2	7.1	7.0
Asia Pacific	38.2	45.5	47.7	50.0	60.6	44.3	47.8
China	15.6	22.2	23.7	24.4	28.8	23.6	24.2
India	7.0	8.1	8.5	9.2	12.2	6.6	7.8
Japan	4.3	3.8	3.9	3.5	3.0	3.2	2.2
Southeast Asia	5.3	4.5	4.5	5.4	8.0	4.6	6.3

Table A.26: Hydrogen demand (PJ)

	Historical		Stated Policies		Announced Pledges	
	2020	2021	2030	2050	2030	2050
World	**10 730**	**11 319**	**13 438**	**16 822**	**15 064**	**34 575**
North America	1 822	1 937	2 173	2 674	2 835	6 960
United States	1 418	1 530	1 710	2 118	2 335	6 135
Central and South America	314	344	453	758	580	1 528
Brazil	19	22	57	113	81	350
Europe	1 055	1 046	1 109	1 207	1 746	3 890
European Union	827	800	827	844	1 308	2 825
Africa	331	358	497	769	492	1 322
Middle East	1 286	1 407	1 914	2 325	1 876	2 939
Eurasia	876	869	879	942	774	861
Russia	815	802	805	859	699	759
Asia Pacific	5 047	5 358	6 409	8 107	6 717	16 348
China	2 879	3 082	3 610	3 936	3 791	7 298
India	975	1 045	1 342	2 134	1 284	3 585
Japan	210	217	244	343	349	1 119
Southeast Asia	452	468	602	848	593	1 566
International bunkers	-	-	4	41	46	728

Table A.27: Hydrogen balance (Mt H_2 equivalent)

	2021	STEPS 2030	STEPS 2050	APS 2030	APS 2050	NZE 2030	NZE 2050
Low-emission hydrogen production	1	6	24	30	225	90	452
Water electrolysis	0	4	17	21	167	58	329
Fossil fuels with CCUS	1	2	8	9	57	31	122
Bioenergy and other	0	0	0	0	1	0	2
Transformation of hydrogen	0	3	10	14	95	50	186
To power generation	-	0	1	4	19	27	60
To hydrogen-based fuels	0	0	3	6	69	18	118
In oil refining	0	2	5	3	6	2	4
To biofuels	0	1	1	1	1	3	3
Hydrogen demand for end-use sectors	0	3	15	16	131	40	266
Low-emissions hydrogen-based fuels	0	0	3	3	55	15	96
Total final consumption	0	0	1	3	39	7	68
Power generation	-	0	2	0	16	8	28
Trade	0	1	5	4	44	18	73
Trade as share of demand	0%	10%	22%	13%	19%	20%	16%

Table A.28: Total CO_2 emissions* (Mt CO_2)

	Historical 2010	Historical 2020	Historical 2021	Stated Policies 2030	Stated Policies 2050	Announced Pledges 2030	Announced Pledges 2050
World	32 893	34 779	36 639	36 211	31 979	31 511	12 399
North America	6 489	5 319	5 563	4 579	3 167	3 648	450
United States	5 469	4 382	4 610	3 583	2 180	2 861	43
Central and South America	1 149	1 095	1 187	1 199	1 315	1 002	507
Brazil	412	425	474	460	491	361	166
Europe	4 732	3 748	3 974	3 126	2 280	2 365	417
European Union	3 312	2 546	2 726	2 020	1 229	1 468	116
Africa	1 174	1 315	1 372	1 592	2 179	1 429	1 305
Middle East	1 637	1 942	2 073	2 307	2 706	2 052	1 730
Eurasia	2 159	2 200	2 309	2 107	2 097	1 968	1 649
Russia	1 694	1 731	1 811	1 561	1 414	1 476	1 221
Asia Pacific	14 433	18 227	19 109	19 839	16 266	17 690	5 300
China	8 792	11 593	12 129	11 840	7 970	10 597	2 255
India	1 686	2 229	2 472	3 275	3 325	2 934	977
Japan	1 188	1 025	1 027	755	461	660	32
Southeast Asia	1 162	1 667	1 724	2 186	2 610	1 952	1 063

*Includes emissions from industrial processes and flaring.

Table A.29: Electricity and heat sectors CO_2 emissions (Mt CO_2)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**12 474**	**13 502**	**14 378**	**12 759**	**9 308**	**11 330**	**3 138**
North America	2 596	1 730	1 841	1 000	438	695	49
United States	2 346	1 526	1 633	823	281	548	- 57
Central and South America	235	224	250	147	106	119	42
Brazil	46	56	79	27	24	13	6
Europe	1 731	1 131	1 229	744	546	509	82
European Union	1 188	732	822	432	200	259	- 7
Africa	421	454	473	455	400	388	163
Middle East	550	676	682	710	792	638	461
Eurasia	1 034	949	993	879	880	811	656
Russia	892	771	800	678	625	632	517
Asia Pacific	5 907	8 338	8 910	8 824	6 145	8 170	1 685
China	3 486	5 375	5 798	5 605	3 515	5 188	986
India	785	1 055	1 199	1 446	892	1 395	111
Japan	489	460	446	235	78	226	- 12
Southeast Asia	397	692	708	886	1 103	811	339

Table A.30: Total final consumption CO_2 emissions* (Mt CO_2)

	Historical			Stated Policies		Announced Pledges	
	2010	2020	2021	2030	2050	2030	2050
World	**18 720**	**19 522**	**20 468**	**21 627**	**21 056**	**18 785**	**9 124**
North America	3 474	3 164	3 324	3 149	2 370	2 665	556
United States	2 863	2 601	2 752	2 524	1 743	2 148	259
Central and South America	803	775	842	948	1 095	803	426
Brazil	342	342	368	397	430	322	147
Europe	2 825	2 470	2 585	2 240	1 628	1 767	320
European Union	2 010	1 716	1 795	1 496	962	1 159	116
Africa	568	690	727	963	1 610	901	1 101
Middle East	924	1 023	1 134	1 321	1 650	1 198	1 154
Eurasia	930	1 118	1 178	1 114	1 125	1 061	945
Russia	678	859	903	801	727	772	671
Asia Pacific	8 077	9 347	9 625	10 429	9 608	9 033	3 581
China	5 043	5 894	5 994	5 889	4 188	5 121	1 348
India	867	1 109	1 205	1 742	2 350	1 474	843
Japan	671	548	564	506	393	421	65
Southeast Asia	690	904	934	1 231	1 422	1 081	671

* Includes emissions from industrial processes.

Design of the scenarios

The *World Energy Outlook-2022* (*WEO-2022)* explores three main scenarios in the analyses in the chapters. These scenarios are not predictions – the IEA does not have a single view on the future of the energy system. In contrast to the 2021 edition of the *WEO*, we do not vary the assumptions about public health and economic recovery implications across the scenarios. The scenarios are:

- The **Net Zero Emissions by 2050 (NZE) Scenario** shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of the other scenarios. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular achieving universal energy access by 2030. The NZE Scenario does not rely on emissions reductions from outside the energy sector to achieve its goals, but assumes that non-energy emissions will be reduced in the same proportion as energy emissions. It is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability).
- The **Announced Pledges Scenario (APS)** takes account of all the climate commitments made by governments around the world including Nationally Determined Contributions as well as longer term net zero emissions targets, and assumes that they will be met in full and on time. The global trends in this scenario represent the cumulative extent of the world's ambition to tackle climate change as of mid-2022. The remaining difference in global emissions between the APS and the goals in the NZE Scenario shows the "ambition gap" that needs to be closed to achieve the goals agreed in the Paris Agreement in 2015.
- The **Stated Policies Scenario (STEPS)** does not take for granted that governments will reach all announced goals. Instead, it explores where the energy system might go without additional policy implementation. As with the APS, it is not designed to achieve a particular outcome. It takes a granular, sector-by-sector look at existing policies and measures and those under development. The remaining difference in global emissions between the STEPS and the APS represents the "implementation gap" that needs to be closed for countries to achieve their announced decarbonisation targets.

B.1 Population

Table B.1 ▷ Population assumptions by region

	Compound average annual growth rate			Population (million)			Urbanisation (share of population)		
	2000-21	2021-30	2021-50	2021	2030	2050	2021	2030	2050
North America	0.9%	0.6%	0.5%	502	532	580	82%	84%	89%
United States	0.8%	0.5%	0.4%	335	352	381	83%	85%	89%
C & S America	1.1%	0.7%	0.5%	523	559	601	81%	83%	88%
Brazil	1.0%	0.5%	0.2%	214	224	229	87%	89%	92%
Europe	0.3%	0.0%	-0.1%	700	701	690	76%	78%	84%
European Union	0.2%	-0.1%	-0.2%	451	448	429	75%	77%	84%
Africa	2.5%	2.3%	2.1%	1 372	1 686	2 487	44%	48%	59%
Middle East	2.1%	1.5%	1.1%	252	289	348	73%	76%	81%
Eurasia	0.4%	0.3%	0.2%	237	244	253	65%	67%	73%
Russia	-0.1%	-0.2%	-0.2%	144	142	134	75%	77%	83%
Asia Pacific	1.0%	0.6%	0.4%	4 250	4 496	4 734	50%	55%	65%
China	0.5%	0.2%	-0.1%	1 423	1 443	1 383	63%	71%	80%
India	1.3%	0.8%	0.6%	1 393	1 504	1 639	35%	40%	53%
Japan	-0.1%	-0.5%	-0.6%	125	120	105	92%	93%	95%
Southeast Asia	1.2%	0.8%	0.6%	674	726	792	51%	56%	66%
World	**1.2%**	**0.9%**	**0.7%**	**7 835**	**8 507**	**9 692**	**57%**	**60%**	**68%**

Notes: C & S America = Central and South America. See Annex C for composition of regional groupings.

Sources: UN DESA (2018, 2019); World Bank (2022a); IEA databases and analysis.

- Population is a major determinant of many of the trends in the *Outlook*. We use the medium variant of the United Nations projections as the basis for population growth in all scenarios, but this is naturally subject to a degree of uncertainty.
- The 2022 Revision of UN DESA's World Population Prospects could not be incorporated in this modelling cycle as the modelling was already advanced by its publication time.
- The rate of population growth is assumed to slow over time, but the global population nonetheless exceeds 9.6 billion by 2050 (Table B.1).
- More than half of the increase over the projection period to 2050 is in Africa and around a further third is in the Asia Pacific region.
- India adds around 250 million people to its population to become the world's most populous country, overtaking China, where the population is projected to decrease by around 40 million.
- The share of the world's population living in towns and cities has been rising steadily, a trend that is projected to continue over the period to 2050. In aggregate, this means that *all* of the 2 billion increase in global population over the period is added to cities and towns.

B.2 CO_2 prices

Table B.2 ⊳ CO_2 prices for electricity, industry and energy production in selected regions by scenario

USD (2021) per tonne of CO_2	2030	2040	2050
Stated Policies Scenario			
Canada	54	62	77
Chile, Colombia	13	21	29
China	28	43	53
European Union	90	98	113
Korea	42	67	89
Announced Pledges Scenario			
Advanced economies with net zero emissions pledges[1]	135	175	200
Emerging market and developing economies with net zero emissions pledges[2]	40	110	160
Other emerging market and developing economies	-	17	47
Net Zero Emissions by 2050 Scenario			
Advanced economies with net zero emissions pledges	140	205	250
Emerging market and developing economies with net zero emissions pledges	90	160	200
Other emerging market and developing economies	25	85	180

Note: Values are rounded.

[1] Includes all OECD countries except Mexico.

[2] Includes China, India, Indonesia, Brazil and South Africa.

- There are 68 direct carbon pricing instruments existing today, covering more than 40 countries. Global carbon pricing revenue in 2021 increased by almost 60% from 2020 levels, to around USD 84 billion (World Bank, 2022).
- Existing and planned CO_2 pricing schemes are reflected in the STEPS, covering electricity generation, industry, energy production sectors and end-use sectors, e.g. aviation, road transport and buildings, where applicable.
- In the APS, higher CO_2 prices are introduced across all regions with net zero emissions pledges. No explicit pricing is assumed in sub-Saharan Africa (excluding South Africa), the Caspian region and Other Asia regions. Instead, these regions rely on direct policy interventions to drive decarbonisation in the APS.
- In the NZE Scenario, CO_2 prices cover all regions and rise rapidly across all advanced economies as well as in emerging economies with net zero emissions pledges, including China, India, Indonesia, Brazil and South Africa. CO_2 prices are lower, but nevertheless, rising in other emerging economies such as North Africa, Middle East, Russia and Southeast Asia. CO_2 prices are lower in all other emerging market and developing economies, as it is assumed they pursue more direct policies to adapt and transform their energy systems.

- All scenarios consider the effects of other policy measures alongside CO_2 pricing, such as coal phase-out plans, efficiency standards and renewable targets (Tables B.6 - B.10). These policies interact with carbon pricing; therefore, CO_2 pricing is not the marginal cost of abatement as is often the case in other modelling approaches

B.3 Fossil fuel resources

Table B.3 ▷ Remaining technically recoverable fossil fuel resources, 2021

Oil (billion barrels)	Proven reserves	Resources	Conventional crude oil	Tight oil	NGLs	EHOB	Kerogen oil
North America	237	2424	237	217	172	798	1 000
Central and South America	291	856	253	57	49	493	3
Europe	15	112	57	19	28	3	6
Africa	125	444	304	54	84	2	-
Middle East	887	1 139	887	29	179	14	30
Eurasia	146	940	228	85	57	552	18
Asia Pacific	50	277	122	72	65	3	16
World	**1 752**	**6 192**	**2 088**	**533**	**633**	**1 865**	**1 073**

Natural gas (trillion cubic metres)	Proven reserves	Resources	Conventional gas	Tight gas	Shale gas	Coalbed methane
North America	16	148	50	10	81	7
Central and South America	8	84	28	15	41	-
Europe	5	46	18	5	18	5
Africa	19	101	51	10	40	0
Middle East	81	120	101	9	11	-
Eurasia	69	168	130	10	10	17
Asia Pacific	21	138	44	21	53	20
World	**219**	**806**	**422**	**80**	**254**	**49**

Coal (billion tonnes)	Proven reserves	Resources	Coking coal	Steam coal	Lignite
North America	257	8 389	1 031	5 840	1 519
Central and South America	14	60	3	32	25
Europe	137	982	164	415	403
Africa	15	343	45	297	0
Middle East	1	41	36	6	-
Eurasia	191	2 015	387	996	632
Asia Pacific	460	8 974	1 737	5 809	1 428
World	**1075**	**20 803**	**3 401**	**13 395**	**4 007**

Notes: NGLs = natural gas liquids; EHOB = extra-heavy oil and bitumen. The breakdown of coal resources by type is an IEA estimate. Coal world resources exclude Antarctica.

Sources: BGR (2021); BP (2022); CEDIGAZ (2022); OGJ (2022); US DOE/EIA (2013); US DOE/EIA (2015); USGS (2012a); USGS (2012b); IEA databases and analysis.

- The *World Energy Outlook* supply modelling relies on estimates of the remaining technically recoverable resource, rather than the (often more widely quoted) numbers for proven reserves. Resource estimates are subject to a considerable degree of uncertainty, as well as the distinction in the analysis between conventional and unconventional resource types.
- Overall, the remaining technical recoverable resources of fossil fuels remain similar to the *World Energy Outlook-2021*. All fuels are at a level comfortably sufficient to meet the projections of global energy demand growth to 2050 in all scenarios. Remaining technically recoverable resources of US tight oil (crude plus condensate) total more than 200 billion barrels.
- World coal resources are made up of various types of coal: around 80% is steam and coking coal and the remainder is lignite. Coal resources are more available in parts of the world without substantial natural gas and oil resources, notably in Asia.
- Overall, the gradual depletion of resources (at a pace that varies by scenario) means that operators have to develop more difficult and complex reservoirs. This tends to push up production costs over time, although this effect is offset by the assumed continuous adoption of new, more efficient production technologies and practices.

B.4 Electricity generation technology costs

Table B.4a ▷ Technology costs in selected regions in the Stated Policies Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2, O&M (USD/MWh)			LCOE (USD/MWh)			VALCOE (USD/MWh)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
United States															
Nuclear	5 000	4 800	4 500	90	90	90	30	30	30	105	100	95	105	100	95
Coal	2 100	2 100	2 100	35	15	n.a.	25	25	25	95	210	n.a.	95	210	n.a.
Gas CCGT	1 000	1 000	1 000	55	40	20	35	40	40	60	70	110	60	70	80
Solar PV	1 090	710	510	21	22	23	10	10	10	50	30	25	60	50	60
Wind onshore	1 380	1 310	1 250	42	43	44	10	10	10	35	30	30	40	40	45
Wind offshore	4 040	2 460	1 820	42	46	49	35	20	15	120	70	50	120	75	60
European Union															
Nuclear	6 600	5 100	4 500	80	80	80	35	35	35	140	120	105	140	120	105
Coal	2 000	2 000	2 000	40	20	n.a.	115	130	140	180	255	n.a.	165	215	n.a.
Gas CCGT	1 000	1 000	1 000	20	10	n.a.	100	120	130	155	270	n.a.	135	220	n.a.
Solar PV	810	530	410	14	14	14	10	10	10	50	35	30	60	80	80
Wind onshore	1 590	1 510	1 450	29	30	30	15	15	15	55	50	45	65	60	60
Wind offshore	3 040	2 000	1 500	51	56	59	15	10	10	60	40	30	60	45	40
China															
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60	65	65	60
Coal	800	800	800	60	50	35	60	60	70	75	80	95	75	70	50
Gas CCGT	560	560	560	35	25	20	95	105	115	115	130	140	100	110	105
Solar PV	630	410	300	17	18	19	10	5	5	35	20	15	45	50	60
Wind onshore	1 160	1 090	1 050	26	27	28	15	10	10	45	40	40	50	50	50
Wind offshore	2 860	1 840	1 380	33	39	43	25	15	10	100	55	40	100	60	35
India															
Nuclear	2 800	2 800	2 800	75	85	90	30	30	30	75	65	65	75	65	65
Coal	1 200	1 200	1 200	65	75	75	40	35	35	60	55	50	60	55	45
Gas CCGT	700	700	700	40	50	45	75	85	85	95	100	105	95	90	85
Solar PV	590	380	270	20	21	22	5	5	5	35	20	15	40	35	55
Wind onshore	930	880	830	26	28	30	10	10	10	45	40	35	50	45	45
Wind offshore	2 780	1 820	1 300	33	37	39	25	15	10	120	75	50	120	80	60

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; VALCOE = value-adjusted LCOE; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine. Cost components, LCOE and VALCOE figures are rounded. Lower values for VALCOE indicate improved competitiveness.

Sources: IEA analysis; IRENA Renewable Costing Alliance; (IRENA, 2022).

Table B.4b ▷ Technology costs in selected regions in the Announced Pledges Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
United States												
Nuclear	5 000	4 800	4 500	90	90	90	30	30	30	100	100	100
Coal	2 100	2 100	2 100	30	n.a.	n.a.	85	150	180	165	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	50	25	n.a.	60	85	95	85	130	n.a.
Solar PV	1 090	680	470	21	22	23	10	10	10	50	30	25
Wind onshore	1 380	1 290	1 220	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 360	1 620	42	46	49	35	20	15	120	65	45
European Union												
Nuclear	6 600	5 100	4 500	80	80	70	35	35	35	140	115	115
Coal	2 000	2 000	2 000	30	n.a.	n.a.	135	175	210	220	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	25	10	n.a.	110	130	135	160	240	n.a.
Solar PV	810	510	360	14	14	14	10	10	10	50	35	25
Wind onshore	1 590	1 490	1 410	29	30	30	15	15	15	55	50	45
Wind offshore	3 040	1 920	1 320	51	56	59	15	10	5	60	35	25
China												
Nuclear	2 800	2 800	2 500	85	80	80	25	25	25	65	65	60
Coal	800	800	800	60	50	20	65	85	150	80	105	195
Gas CCGT	560	560	560	30	25	25	95	110	130	110	130	155
Solar PV	630	400	270	17	18	19	10	5	5	35	20	15
Wind onshore	1 160	1 080	1 020	26	27	28	15	10	10	45	40	35
Wind offshore	2 860	1 780	1 200	33	39	43	25	15	10	100	55	35
India												
Nuclear	2 800	2 800	2 800	75	85	90	30	30	30	70	65	65
Coal	1 200	1 200	1 200	65	75	35	40	65	170	60	85	205
Gas CCGT	700	700	700	40	45	30	70	85	115	90	105	145
Solar PV	590	360	240	20	21	22	5	5	5	35	20	15
Wind onshore	930	870	800	26	28	30	10	10	10	45	40	35
Wind offshore	2 780	1 740	1 140	33	37	39	25	15	10	120	70	45

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; (IRENA, 2022).

Table B.4c ▷ Technology costs in selected regions in the Net Zero Emissions by 2050 Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
United States												
Nuclear	5 000	4 800	4 500	90	90	85	30	30	30	100	100	100
Coal	2 100	2 100	2 100	30	n.a.	n.a.	85	155	220	165	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	50	25	n.a.	55	80	105	80	130	n.a.
Solar PV	1 090	620	430	21	22	23	10	10	10	50	30	25
Wind onshore	1 380	1 270	1 190	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 200	1 500	42	46	49	35	20	15	120	60	40
European Union												
Nuclear	6 600	5 100	4 500	80	80	70	35	35	35	140	115	115
Coal	2 000	2 000	2 000	25	n.a.	n.a.	135	185	250	230	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	25	15	n.a.	95	115	135	145	195	n.a.
Solar PV	810	470	340	14	14	14	10	10	10	50	35	25
Wind onshore	1 590	1 470	1 380	29	30	30	15	15	15	55	50	45
Wind offshore	3 040	1 800	1 240	51	56	59	15	10	5	60	35	25
China												
Nuclear	2 800	2 800	2 500	85	80	70	25	25	25	65	65	65
Coal	800	800	800	55	n.a.	n.a.	80	120	180	100	n.a.	n.a.
Gas CCGT	560	560	560	35	25	n.a.	90	110	130	105	130	n.a.
Solar PV	630	360	250	17	18	19	10	5	5	35	20	15
Wind onshore	1 160	1 060	1 000	26	27	28	15	10	10	45	40	35
Wind offshore	2 860	1 640	1 120	33	39	43	25	15	10	100	50	35
India												
Nuclear	2 800	2 800	2 800	70	85	90	30	30	30	75	65	65
Coal	1 200	1 200	1 200	65	n.a.	n.a.	40	105	200	60	n.a.	n.a.
Gas CCGT	700	700	700	40	40	n.a.	55	80	110	75	100	n.a.
Solar PV	590	320	210	20	21	22	5	5	5	35	20	15
Wind onshore	930	840	790	26	28	30	10	10	10	45	35	35
Wind offshore	2 780	1 560	1 080	33	37	39	25	15	10	120	65	45

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; (IRENA, 2022).

- All costs are expressed in year-2021 dollars.
- Major contributors to the levelised cost of electricity (LCOE) include: overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided); cost of fuel inputs; plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, and onshore and offshore wind.
- Weighted average cost of capital (WACC) reflects analysis for utility-scale solar PV in the *World Energy Outlook-2020* (IEA, 2020), with a range of 3-6%, and for offshore wind analysis from the *Offshore Wind Outlook 2019* (IEA, 2019), with a range of 4-7%. Onshore wind was assumed to have the same WACC as utility-scale solar PV. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (7-8% based on the stage of economic development).
- The value-adjusted levelised cost of electricity (VALCOE) incorporates information on both costs and the value provided to the system. Based on the LCOE, estimates of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies.
- Fuel, CO_2 and O&M costs reflect the average over the ten years following the indicated date in the projections (and therefore vary by scenario in 2021).
- Solar PV and wind costs do not include the cost of energy storage technologies, such as utility-scale batteries.
- The capital costs for nuclear power represent the "nth-of-a-kind" costs for new reactor designs, with substantial cost reductions from the first-of-a-kind projects.

B.5 Other key technology costs

Table B.5 ▷ Capital costs for selected technologies by scenario

		Stated Policies		Announced Pledges		Net Zero Emissions by 2050	
	2021	2030	2050	2030	2050	2030	2050
Primary steel production (USD/tpa)							
Conventional	640	650	660	650	670	650	680
Innovative	n.a.	1 400	1 050	1 330	980	1 020	910
Vehicles (USD/vehicle)							
Hybrid cars	16 122	14 686	14 861	14 528	14 718	14 460	14 638
Battery electric cars	21 322	15 772	14 185	15 265	13 618	14 783	13 251
Batteries and hydrogen							
Hydrogen electrolysers (USD/kW)	1 505	575	445	390	265	315	230
Fuel cells (USD/kW)	100	60	40	50	35	45	30
Utility-scale stationary batteries (USD/kWh)	285	185	135	185	135	180	135

Notes: kW = kilowatt; tpa = tonne per annum; kWh = kilowatt-hour; n.a. = not applicable. All values are in USD (2021).

Sources: IEA analysis; James et. al. (2018); Thompson, et al. (2018); Financial Times (2020); BNEF (2021); Cole et al. (2020); Tsiropoulos et al. (2018);

- All costs represent fully installed/delivered technologies, not solely the module cost, unless otherwise noted. Installed/delivered costs include engineering, procurement and construction costs to install the module.
- Industry costs reflect production costs in the iron and steel sub-sector and differentiate between conventional and innovative production routes. Conventional routes are blast furnace-basic oxygen furnace (BF-BOF) and direct reduced iron-electric arc furnace (DRI-EAF). The innovative routes are Hisarna with carbon capture, utilisation and storage (CCUS), DRI-EAF with CCUS and hydrogen-based DRI-EAF. Costs for conventional primary steel increase over time reflecting an increasing shift towards DRI-EAF in new capacity, which is more capital intensive.
- Vehicle costs reflect production costs, not retail prices, to better reflect the cost declines in total cost of manufacturing, which move independently of final market prices for electric vehicles to customers. Historical values in 2021 have been used for the global average battery pack size. In hybrid cars, the future cost increase is driven by regional fuel economy and emissions standards.
- Electrolyser costs reflect a projected weighted average of installed electrolyser technologies (excluding China, where the modelled costs are lower), including inverters.
- Fuel cell costs are based on stack manufacturing costs only, not installed/delivered costs. The costs provided are for automotive fuel cell stacks for light-duty vehicles.
- Utility-scale stationary battery costs reflect the average installed costs of all battery systems rated to provide maximum power output for a four-hour period.

B.6 Policies

The policy actions assumed to be taken by governments are key variables in this *World Energy Outlook (WEO)* and the main reason for the differences in outcomes across the scenarios. An overview of the policies and measures that are considered in the various scenarios is included in Tables B.6 - B.10.

The policies are additive: measures listed under the Announced Pledges Scenario (APS) supplement those in the Stated Policies Scenario (STEPS). The tables begin with broad cross-cutting policy frameworks, followed by more detailed policies by sector: power, industry, buildings and transport. The tables for the STEPS list only the *new policies* enacted, implemented or revised since the publication of the *WEO-2021*. Policies already considered in previous editions of the *WEO* are not listed due to space constraints. However, we do restate major long-term policies to be clear which targets and goals are met in the STEPS and which are only met in the APS. Some regional policies have been included if they play a significant role in shaping energy at a global scale, e.g. regional carbon markets, standards in very large provinces or states. The tables do not include all policies and measures; rather they highlight the policies most prominent in shaping global energy demand today, while being derived from an exhaustive examination of announcements and plans in countries around the world. A more comprehensive list of energy-related policies by country can be viewed on the IEA Policies and Management Database (PAMS), https://www.iea.org/policies.

Table B.6 ▷ Cross-cutting policy assumptions for selected regions/countries by scenario

Region/ country	Scenario	Assumptions
United States	STEPS	• Energy provisions in the Inflation Reduction Act (2022), Consolidated Appropriations Act (2021) and Infrastructure Investment and Jobs Act (2021). • Defence Production Act supporting domestic production of heat pumps, solar equipment and batteries. • US Methane Emissions Reduction Action Plan.
	APS	• Updated NDC aiming to reduce GHG emissions by 50-52% by 2030 (from 2005 levels) and national target to reach net zero GHG emissions by 2050. • Commitment to reduce methane emissions from the oil and gas sector by 40-45% by 2025 and 2021 US Methane Emissions Reduction Action Plan.
Canada	STEPS	• Energy and emissions reduction-related provisions in the 2020 Healthy Environment and a Healthy Economy Plan; extended Investing in Canada Infrastructure Programme; and Emissions Reduction Fund. • Hydrogen Strategy and Strategic Innovation Fund.
	APS	• Commitment to reach net zero GHG emissions target by 2050. • Commitment to reduce methane emissions from the oil and gas sector by 40-45% by 2025, and further by 75% by 2030 relative to 2012. Measures in the Healthy Environment and Healthy Economy action plan.
Central and South America	STEPS	• Colombia: Energy provisions in the Ten Milestones in 2021 Plan; National Strategy for Mitigation of Short-Lived Climate Pollutants; and National Energy Plan to 2050. • Chile: 2021 National Strategy for Green Hydrogen.
	APS	• Brazil: Long-term objective of reaching climate neutrality by 2050. • Chile, Costa Rica and Colombia: Net zero emissions by 2050. • Commitment to Global Methane pledge by eight countries in the region. • Colombia: National Strategy for Mitigation of Short-Lived Climate Pollutants.
European Union	STEPS	• Energy spending provisions in the European Green Deal and national recovery plans within the EU Recovery and Resilience Facility. • Spending provisions to stimulate long-term investment in energy efficiency and clean energy implemented as part of national policy responses to the energy crisis as of August 2022. • Horizon Europe research and innovation funding programme.
	APS	• Full implementation of the decarbonisation targets in the Fit for 55 package. • 2050 Net Zero Emissions target by 2050 embedded in the 2021 European Climate Law. • EU member state-level targets for climate neutrality. • Targets in the EU Hydrogen Strategy for a Climate Neutral Europe. • Partial implementation of the targets laid out in the REPowerEU Plan, eliminating the import of Russian gas supply to the European Union well before 2030. • EU member states commitment to the Global Methane Pledge.
Other Europe	STEPS	• United Kingdom: Ten Point Plan; Build Back Greener plan; 2020 Energy White Paper; and provisions of the 2021 North Sea Transition Deal. • Norway: 2021 Green Conversion Package.
	APS	• United Kingdom: Full implementation of the target for net zero GHG emissions by 2050. Commitment to the Global Methane Pledge. • Norway, Iceland and Switzerland: Climate neutrality targets. • Norway: Climate Action Plan 2021-2030.

Table B.6 ▷ Cross-cutting policy assumptions for selected regions/countries by scenario (continued)

Region/ country	Scenario	Assumptions
Australia and New Zealand	STEPS	• Australia: Spending and policy measures from the 2020 Climate Solutions Package. • New Zealand: Energy-related measures from the Covid Response and Recovery Fund.
	APS	• Australia: Full implementation of the 2022 Climate Change Bill emissions target, including net zero emissions by 2050, and -43% by 2030 relative to 2005. • New Zealand: Full implementation of the New Zealand Zero Carbon amendment to the Climate Change Response Act setting a net zero emissions target for all GHG except biogenic methane by 2050. Commitment to the Global Methane Pledge.
China	STEPS	• Made in China 2025 transition from heavy industry to higher value-added manufacturing. • 14th Five-Year Plan: ○ Reduce CO_2 intensity of economy by 18% from 2021 to 2025. ○ Reduce energy intensity of economy by 13.5% from 2021 to 2025. ○ 20% non-fossil share of energy mix by 2025. ○ 25% non-fossil share of energy mix by 2030. • NDC: ○ Aim to peak CO_2 emissions before 2030. ○ Lower CO_2 emissions per unit of GDP by 60% from 2005 levels.
	APS	• Carbon neutrality target by 2060.
India	STEPS	• Energy-related elements of the Self-Reliant India Scheme (Atmanirbhar Bharat). • 450 GW renewables capacity by 2030 and 50% of total installed capacity to be non-fossil fuel-based energy sources by 2030. • Enhanced enforcement of energy efficiency policy under the 2022 amendments to the Energy Conservation Act. • National Hydrogen Mission.
	APS	• Updated NDC to reduce national carbon intensity by 45% by 2030 from 2005 levels, increase in non-fossil energy capacity to 500 GW by 2030, and reduce carbon emissions by 1 Gt CO_2 by 2030. • Net zero emissions by 2070.
Southeast Asia	STEPS	• Indonesia: 23% share of renewable energy in primary energy supply by 2025 and 31% by 2050. • Singapore: Green Plan 2030.
	APS	• Indonesia: Net zero emissions by 2060 or before. • Malaysia: Carbon neutrality target by 2050. • Thailand: Net zero GHG emissions target by 2065. • Viet Nam: Carbon neutrality target by 2050. • Indonesia, Malaysia, Philippines and Viet Nam: Commitment to the Global Methane Pledge.

Table B.6 ⊳ Cross-cutting policy assumptions for selected regions/countries by scenario (continued)

Region/ country	Scenario	Assumptions
Japan	STEPS	• Implementation of concrete policies (renewable energy, batteries, energy efficiency and nuclear power) announced in the 6th Strategic Energy Plan under the Basic Act on Energy Policy, aiming to realise the Plan's 2030 energy outlook. • Public spending on clean energy innovation - 2021 national budget.
	APS	• Full implementation of the 6th Strategic Energy Plan under the Basic Act on Energy Policy, including carbon neutrality target for 2050 and other policy targets beyond 2030. • Accelerated nuclear policies under discussion in the Green Transformation (GX) Implementation Council. • Commitment to the Global Methane Pledge.
Korea	STEPS	• New Energy Policy. • Korean New Deal Clean Energy Spending. • 14th Long-term Natural Gas Supply and Demand Plan (2021-2034). • Methane Reduction Plan 2018-2030.
	APS	• Carbon Neutrality and Green Growth Act for Climate Change committing to CO_2 neutrality by 2050. • Commitment to reduce methane emissions from all sectors by 30% below 2018 levels by 2030, with a 28.6% sectoral reduction target for energy.
Africa	APS	• Net zero emissions targets by 2050 in Nigeria, South Africa, Rwanda and Ghana. Nine other net zero emissions commitments from sub-Saharan African countries. • All universal access targets for electricity and clean cooking.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. NDC = Nationally Determined Contributions (Paris Agreement); CCUS = carbon capture, utilisation and storage; GHG = greenhouse gases; GW = gigawatt; Gt = gigatonnes.

Table B.7 ▷ Electricity sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• Inflation Reduction Act grants and tax credits for renewables, nuclear power and CCUS. • 100% carbon-free electricity or energy targets by 2050 in up to 21 states plus Puerto Rico and Washington DC. • 30 GW offshore wind capacity by 2030. • Updated renewable portfolio standard policies (Delaware, Illinois, Nebraska, North Carolina and Oregon).
	APS	• G7 commitment: Achieve predominantly decarbonised electricity sector by 2035.
Canada	STEPS	• Reach nearly 90% non-emitting renewables generation by 2030. • Phase out conventional coal-fired plants by 2030.
	APS	• G7 commitment: Achieve predominantly decarbonised electricity sector by 2035.
European Union	STEPS	• New coal phase out commitments in Slovenia, Estonia and Croatia. • Updated National Energy and Climate Plans, notably offshore wind targets.
	APS	• Higher targets for renewables (40% renewables share of gross final consumption by 2030) within Fit for 55 package. • G7 commitment: Achieve predominantly decarbonised electricity sector by 2035.
Other Europe	APS	• United Kingdom: Energy Security Strategy sets new ambitions for offshore wind, nuclear & hydrogen. G7 commitment: Achieve predominantly decarbonised electricity sector by 2035.
Africa	STEPS	• Partial implementation of national electrification strategies.
	APS	• South Africa: Increased renewables capacity and reduced coal-fired capacity under 2019 Integrated Resource Plan. • Full implementation of national electrification targets.
China	STEPS	• 14th Five-year Plan for Renewables targets for 3 300 TWh of renewables by 2025 (of which 1 400 TWh should be solar and wind) and that over 50% of incremental electricity consumption is met by renewables.
	APS	• Overall coal use to decline in the 15th Five-Year Plan period (2025-2030).
India	APS	• Updated NDC - 50% cumulative electric power installed capacity from non fossil fuel-based energy resources by 2030.
Japan	STEPS	• Achieve electricity generation outlook by 2030 in the 6th Strategic Energy Plan. • Restart nuclear power plants aligned with the 6th Strategic Energy Plan and the Green Transformation (GX) policy initiative.
	APS	• Accelerated nuclear expansion, including SMRs, under discussion in the Green Transformation (GX) Implementation Council. • Green Growth Strategy: 30-45 GW of offshore wind capacity in 2040. • 6th Strategic Energy Plan, with additional policies to support renewables in power generation to reach 2030 targets. • G7 commitment: Achieve predominantly decarbonised electricity sectors by 2035.
Korea	STEPS	• Increase renewables in electricity generation to over 20% and nuclear power to over 30%, and decrease coal-fired power by 2030 under the New Energy Policy Direction.
Southeast Asia	APS	• Indonesia: Renewable energy accounts for half (21 GW) of total power capacity addition under the National Electricity Supply Business Plan (RUPTL) 2019-2028. • Viet Nam: Power Development Plan 8 proposed 19-20 GW of solar, 18-19 GW of wind, 22 GW of natural gas and 37 GW of coal-fired capacity by 2030.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. ETS = emissions trading system; TWh = terawatt-hour; GW = gigawatt; SMR = small modular reactor.

Table B.8 ▷ Industry sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
All regions	APS	• UN Resolution to end plastic pollution with ban on single-use plastics. Lowers plastics demand. • Net Zero Emissions Steel Initiative. • Concrete Action for Climate.
United States	STEPS	• Inflation Reduction Act of 2022: Investments in clean manufacturing and tax credits for CCUS.
	APS	• Department of Energy Industrial Decarbonization Roadmap. • First Movers Coalition demand and production targets per sub-sector, notably 10% of aluminium and steel produced by low-emissions means by 2030.
Canada	STEPS	• Clean industry packages and provisions to promote clean industry within Building Canada's Clean Industrial Advantage.
Central and South America	STEPS	• Brazil: Energy efficiency guarantee fund.
European Union	STEPS	• EU updates to the emissions trading system reflecting extensions for free allocation and 2.2% annual reductions of emissions allowances. • EU: Innovation Fund support for renewable energy, energy-intensive industries, energy storage and CCUS. • Sweden: Government credit guarantees for green investment. • France: France 2030 - EUR 5.6 billion for industry decarbonisation.
Other Europe	STEPS	• United Kingdom: Industrial Decarbonisation Challenge. Pilot funding for low-emissions industrial clusters, and Industrial Energy Transformation Fund funding for energy efficiency.
	APS	• United Kingdom: Industrial Decarbonisation Strategy.
Australia and New Zealand	STEPS	• Australia: National Hydrogen Strategy to develop clean hydrogen.
China	STEPS	• Made in China 2025 targets for industrial energy intensity. • Reduce comprehensive energy consumption per tonne of steel by 2% by 2025. • Emissions from steel sub-sector peak before 2030.
	APS	• Expansion of the emissions trading system coverage to industry.
India	STEPS	• Perform, Achieve, Trade (PAT) Scheme to trade energy saving credits. • Make in India programme. Boost to industry sector by building 11 industrial world-class corridors. • Union Budget 2021-2022, i.e. the national budget, includes USD 26 billion to enhance the manufacturing capabilities of 14 key sub-sectors.
Japan	STEPS	• Green Innovation Fund provides funding for R&D for innovative technology.
	APS	• Technology Roadmap for Transition Finance in the cement, pulp and paper sub-sectors.

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; CCUS = carbon capture, utilisation and storage; ETS = emissions trading system; R&D = research and development.

B

Table B.9 ▷ Buildings sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• Inflation Reduction Act: Rebates for heat pumps and energy efficiency upgrades in residential and commercial buildings. • Updated minimum energy performance standards for central air conditioning and heat pumps.
	APS	• State and local implementation of energy smart building codes and zero energy building codes.
Canada	STEPS	• Implementation of updated appliance efficiency standards. • Large-scale energy-efficient retrofits as part of the Canada Infrastructure Bank growth plan. • Greener Homes Grant and interest-free loans for deep home retrofits.
	APS	• All new buildings meet zero carbon-ready building standards by 2030.
Central and South America	STEPS	• Colombia: Support for efficient lighting, efficient refrigerators and substitution of firewood use with LPG or electric cooking stoves. • Argentina: Strengthened energy efficiency building codes and mandatory efficiency labelling for new social housing.
European Union	STEPS	• EU Recovery and Resilience Facility flagship area (Renovate) for energy efficiency in buildings. • Country-level incentives for renovation and appliance upgrades, new building codes, and clean heating incentives and investment. • Bans on installing certain fossil fuel-fired boilers in new or existing buildings: Austria (2021); France (2022); Belgium (Flanders, 2022); Slovenia (2023); Germany (2026).
	APS	• EU Energy Performance of Buildings Directive objective to achieve a highly energy-efficient and decarbonised building stock by 2050. • Renovation Wave objective to double the rate of building energy retrofits by 2030.
Other Europe	STEPS	• United Kingdom: Low-Carbon Heat Support and Heat Networks Investment Project; various retrofit incentive schemes for improving buildings efficiency as part of the Plan for Jobs.
	APS	• United Kingdom: Future homes standard banning fossil fuel heating in new home construction by 2025. • United Kingdom: Ban on installing natural gas-fired boilers in all existing buildings (2035).
Africa	STEPS	• Southern African Development Community lighting standards. • Minimum energy performance standards for major residential appliances and equipment, including in: Algeria, Benin, Egypt, Ghana, Kenya, Morocco, Nigeria, Rwanda, South Africa, Tunisia.
	APS	• All targets for clean cooking met.
Australia and New Zealand	STEPS	• Australia: Funding for energy efficiency measures, including energy rating labels and state funding for energy-efficient retrofits. Energy efficiency standards for new homes upgraded to seven stars in 2023. • New Zealand: Replace all remaining coal-fired boilers in schools with electric or renewable biomass alternatives by 2025.

Table B.9 ⊳ Buildings sector policies and measures as modelled by scenario for selected regions/countries (continued)

Region/ country	Scenario	Assumptions
China	STEPS	• Standard for maximum energy consumption per square metre in buildings. • Green and High-Efficiency Cooling Action Plan. • Minimum performance standards and energy efficiency labelling for room air conditioners.
India	STEPS	• Energy Conservation and Sustainable Building Code as part of the Energy Conservation (Amendment) Bill, comprising norms or energy efficiency and conservation, minimum use of renewable energy and other green buildings requirements. • Cooling Action Plan. Standards and labelling for light commercial air conditioners, freezers and light bulbs. • Energy efficiency labelling for residential buildings for renters and homeowners.
Japan	STEPS	• Revised retail labelling system.
	APS	• New residential and services buildings meet the net zero energy home or net zero energy building standard on average by 2030.
Korea	STEPS	• Rebate for purchase of appliances entitled to energy efficiency grade 1. • Korean New Deal: Increased funding to improve the efficiency of schools, public housing, recreational and healthcare facilities.
	APS	• All new buildings meet zero carbon-ready building standards by 2030.
Southeast Asia	STEPS	• Viet Nam: Minimum performance standards and labelling for appliances and lighting in residential and commercial buildings. • Singapore: Enhancements to minimum energy performance standards for light bulbs. • Malaysia: Minimum energy performance standards and labelling for washing machines, refrigerators and air conditioners.

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; LPG = liquefied petroleum gas.

Table B.10 ▷ Transport sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
All regions	APS	• LDVs: COP26 declaration by 39 governments on all sales of new cars and vans being zero emissions globally by 2040, and by no later than 2035 in leading markets.[1] • HDVs: Global MoU on Zero Emissions Medium- and Heavy-duty Vehicles among 15 countries, targets 100% new truck and bus sales being zero emissions by 2040.[2] • International Civil Aviation Organization Carbon Offsetting and Reduction Scheme for International Aviation to offset CO_2 emissions above 2019 levels. • International Maritime Organization initial GHG emission strategy to reduce emissions from international shipping by at least 50% by 2050 compared to 2008.
United States	STEPS	• Inflation Reduction Act: Extension of federal tax credit for electric LDVs and charging infrastructure to 2032, and tax credits for biofuels including sustainable aviation fuel. • Fuel economy standards to improve 8% per year for passenger cars and light trucks for model years 2024-2025 and requirement of 10% for model year 2026 relative to 2021 levels. More stringent standards for GHG emissions for model years 2023-2026 which requires 5-10% emissions reductions per year. • In California, Advanced Clean Cars II regulation aims to achieve zero emissions passenger cars and light truck sales by 2035, as well as Advanced Clean Trucks regulation to achieve a zero emissions medium- and heavy-duty truck fleet by 2045.
	APS	• Announced executive order for a target of 50% of all new passenger cars and light-duty trucks to be zero emissions vehicles by 2030. • Sustainable Aviation Fuel Grand Challenge to scale up the production of at least 3 billion gallons per year by 2030, and by 2050 sufficient sustainable aviation fuel to meet 100% of domestic aviation demand. • Washington State target to phase out all new sales and registrations of internal combustion engine cars and vans from 2030.
Canada	STEPS	• Provinces of Quebec and British Columbia aim to phase out all new sales and registrations of internal combustion engine passenger vehicles by 2035.
	APS	• Emissions Reduction Plan to achieve 100% zero emissions light-duty vehicles sales target by 2035. • National aim to achieve 100% of medium- and heavy-duty truck sales to be emissions vehicles by 2040.
Central and South America	APS	• Colombia: All urban bus sales are to be zero emissions by 2035. • Chile: All LDV and urban bus sales are to be zero emissions by 2035, as well as long-distance trucks and intercity buses by 2045. • Costa Rica: Target of 100% of LDV sales to be zero emissions vehicles from 2050. • Ecuador: All public transport vehicles must be electric from 2025.

[1] Full list of signatories: https://zevdeclaration.org/signatories-list/

[2] Full list of signatories: https://globaldrivetozero.org/mou-nations/

Table B.10 ▷ Transport sector policies and measures as modelled by scenario for selected regions/countries (continued)

Region/ country	Scenario	Assumptions
European Union	STEPS	• National recovery and resilience plans of EU member states support green mobility, railways, electric vehicles and charging infrastructure. • Renewable Energy Directive II to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy.
	APS	• Fit for 55 package: ○ Average emissions of new cars to reduce emissions by 55% from 2030 and by 100% from 2035 relative to 2021 levels. ○ Alternative Fuels Infrastructure Regulation to accelerate the vehicle recharging infrastructure deployment. ○ ReFuelEU Aviation sets a 63% blending mandate of sustainable aviation fuels by 2050, with a sub-obligation of synthetic fuels. ○ FuelEU Maritime initiative targets the reduction of average GHG intensity of energy used on-board by ships up to 75% by 2050 relative to 2020 levels. • Revision of the Clean Vehicles Directive including minimum requirements for aggregate public procurement for zero emissions urban buses.
Other Europe	STEPS	• United Kingdom: Almost 11% ethanol blend mandate by 2032. • Norway: National Transport Plan supporting railways and the maritime sector.
	APS	• United Kingdom: Implementation of a ban in 2030 on sales of new internal combustion engine cars and vans. Hybrid vehicles to be phased out from 2035. 100% zero emissions new trucks and bus sales by 2040. Sustainable aviation fuel mandate of 10% by 2030. • Norway: Sustainable aviation fuel target of 30% by 2030. All city buses to be zero emissions by 2025. Target of 100% of new HDV sales to be zero emissions by 2030.
Australia and New Zealand	APS	• New Zealand: Transition to 100% sales of zero emissions new cars and vans by 2035. Targets zero emissions vehicles to make up 100% of urban bus sales by 2025 and 100% of stock by 2035.
Japan	STEPS	• National budget 2022 for subsidies supporting electric and FCEVs. • Fuel economy standard of LDVs to improve fuel efficiency by 32% to 2030 relative to 2016 levels.
	APS	• Green Growth Strategy and the 6th Strategic Energy Plan aiming for sales of 100% zero emissions vehicles (including hybrids) for passenger vehicles by 2035 and for light commercial vehicles by 2040.
Korea	STEPS	• Subsidy scheme to support electric vehicles. • Investment in urban and mass transit. • Partial implementation of target for zero emissions vehicles: one-third of new passenger car sales in 2030 are electric vehicle or FCEVs.
	APS	• Target to increase the number of FCEVs to 200 000 by 2025 (Green New Deal). • Full implementation of target for zero emissions vehicles: by 2030, 50% of passenger car sales to be hybrid or plug-in hybrid vehicles and 33% to be battery electric and FCEVs.

Table B.10 ▷ Transport sector policies and measures as modelled by scenario for selected regions/countries (continued)

Region/ country	Scenario	Assumptions
China	STEPS	• Meets and exceeds targets from the China Society of Automotive Engineers for new energy vehicles to reach 20% of new vehicle sales in 2025. • Corporate average fuel consumption target of 4.0 litres/100 km for 2025 and 3.2 litres/100 km for 2030. • New Energy Automobile Industry Development Plan (2021-2035). • Extension of purchase tax exemption and subsidies for new energy vehicles. • National railway investments.
	APS	• China Society of Automotive Engineers target new energy vehicle car sales reach more than half by 2035 including 1 million FCEVs.
India	STEPS	• Urban and public transit investments. • Partial implementation of 20% bioethanol blending target for gasoline and 5% biodiesel in 2030.
	APS	• Extension of FAME Phase II programme to support the target of 500 000 electric three-wheelers and 1 million electric two-wheelers. • National railways target of net zero emissions by 2030.
Southeast Asia	STEPS	• Indonesia: Introduction of the B30 programme to increase biodiesel blends to 30% with 40% mandate in 2023.
	APS	• Indonesia: Government plans to phase out conventional two-wheelers from 2025 and to have 2 million electric vehicles in passenger light-duty vehicle stock by 2030. • Thailand: Target for 100% zero emissions vehicle sales from 2035. • Malaysia: 100% of cars by 2030 to be electrified, CNG, LPG or biofuel-fuelled vehicles. • Singapore: Targets to phase out passenger internal combustion engine vehicles by 2040.
Other Asia	APS	• Pakistan: Targets for 30% of passenger light-duty vehicle sales to be electric by 2030 and 90% of truck sales to be electric vehicles by 2040. 90% of urban bus sales to be electric vehicles by 2040. 50% of electric two/three-wheeler sales by 2030.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. LDV = light-duty vehicle and includes passenger cars and light commercial vehicles. HDV = heavy-duty vehicle. MoU = memorandum of understanding; GHG = greenhouse gases; km = kilometre; FCEVs = fuel cell electric vehicle; CNG = compressed natural gas; LPG = liquefied petroleum gas.

Definitions

This annex provides general information on terminology used throughout this report including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Area	km^2	square kilometre
	Mha	million hectares
Batteries	Wh/kg	watt hours per kilogramme
Coal	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
Distance	km	kilometre
Emissions	ppm	parts per million (by volume)
	t CO_2	tonnes of carbon dioxide
	Gt CO_2-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
	g CO_2/km	grammes of carbon dioxide per kilometre
	g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	EJ	exajoule (1 joule x 10^{18})
	PJ	petajoule (1 joule x 10^{15})
	TJ	terajoule (1 joule x 10^{12})
	GJ	gigajoule (1 joule x 10^{9})
	MJ	megajoule (1 joule x 10^{6})
	boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	bcme	billion cubic metres of natural gas equivalent
	MBtu	million British thermal units
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
	Gcal	gigacalorie
Gas	bcm	billion cubic metres
	tcm	trillion cubic metres
Mass	kg	kilogramme
	t	tonne (1 tonne = 1 000 kg)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonnes (1 tonne x 10^9)

Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/t CO_2	US dollars per tonne of carbon dioxide
Oil	kb/d	thousand barrels per day
	mb/d	million barrels per day
	mboe/d	million barrels of oil equivalent per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

		Multiplier to convert to:					
		EJ	Gcal	Mtoe	MBtu	bcme	GWh
Convert from:	EJ	1	2.388×10^8	23.88	9.478×10^8	27.78	2.778×10^5
	Gcal	4.1868×10^{-9}	1	10^{-7}	3.968	1.163×10^{-7}	1.163×10^{-3}
	Mtoe	4.1868×10^{-2}	10^7	1	3.968×10^7	1.163	11 630
	MBtu	1.0551×10^{-9}	0.252	2.52×10^{-8}	1	2.932×10^{-8}	2.931×10^{-4}
	bcme	0.036	8.60×10^6	0.86	3.41×10^7	1	9 999
	GWh	3.6×10^{-6}	860	8.6×10^{-5}	3 412	1×10^{-4}	1

Note: There is no generally accepted definition of boe; typically the conversion factors used vary from 7.15 to 7.40 boe per toe. Natural gas is attributed a low heating value of 1 MJ per 44.1 kg. Conversions to and from billion cubic metres of natural gas equivalent (bcme) are given as representative multipliers but may differ from the average values obtained by converting natural gas volumes between IEA balances due to the use of country-specific energy densities. Lower heating values (LHV) are used throughout.

Currency conversions

Exchange rates *(2021 annual average)*	1 US dollar (USD) equals:
British Pound	0.73
Chinese Yuan Renminbi	6.45
Euro	0.84
Indian Rupee	73.92
Japanese Yen	109.75

Source: OECD National Accounts Statistics (database): purchasing power parities and exchange rates dataset (period-average), https://doi.org/10.1787/data-00004-en, accessed September 2022.

Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life cycle greenhouse gas emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. This definition differs from the one used for "advanced biofuels" in US legislation, which is based on a minimum 50% life cycle greenhouse gas reduction and, therefore, includes sugar cane ethanol.

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Agriculture, forestry and other land use (AFOLU) **emissions:** Includes greenhouse gas emissions from agriculture, forestry and other land use.

Ammonia (NH_3)**:** Is a compound of nitrogen and hydrogen. It can be used as a feedstock in the chemical sector, as a fuel in direct combustion processes in fuel cells, and as a hydrogen carrier. To be considered a low-emissions fuel, ammonia must be produced from hydrogen in which the electricity used to produce the hydrogen is generated from low-emissions generation sources. Produced in such a way, ammonia is considered a low-emissions hydrogen-based liquid fuel.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to a main power grid may also have a source of back-up power generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline. Capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off-grid systems that are not connected to a main power grid.

Battery storage: Energy storage technology that uses reversible chemical reactions to absorb and release electricity on demand.

Billion cubic metres of natural gas equivalent (bcme)**:** An energy unit equal to the energy content of one standard billion cubic metres of natural gas.

Biodiesel: Diesel-equivalent fuel made from the transesterification (a chemical process that converts triglycerides in oils) of vegetable oils and animal fats.

Bioenergy: Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases.

Biogas: A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Include both biogas and biomethane.

Biogasoline: Includes all liquid biofuels (advanced and conventional) used to replace gasoline.

Biojet kerosene: Kerosene substitute produced from biomass. It includes conversion routes such as hydroprocessed esters and fatty acids (HEFA) and biomass gasification with Fischer-Tropsch. It excludes synthetic kerosene produced from biogenic carbon dioxide.

Biomethane: Biomethane is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any carbon dioxide and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. It is also known as renewable natural gas.

Buildings: The buildings sector includes energy used in residential and services buildings. Services buildings include commercial and institutional buildings and other non-specified buildings. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Bunkers: Includes both international marine bunker fuels and international aviation bunker fuels.

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS): The process of capturing carbon dioxide emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore, or used as an input or feedstock in manufacturing.

Carbon dioxide (CO_2): Is a gas consisting of one part carbon and two parts oxygen. It is an important greenhouse (heat-trapping) gas.

Chemical feedstock: Energy vectors used as raw materials to produce chemical products. Examples are crude oil-based ethane or naphtha to produce ethylene in steam crackers.

Clean energy: In *power*, clean energy includes: generation from renewable sources, nuclear and fossil fuels fitted with CCUS; battery storage; and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry and transport, excluding aviation bunkers and domestic navigation. In *end-use applications*, clean energy includes: direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; CCUS in industry and direct air capture. In *fuel supply*, clean energy includes low-emissions fuels.

Clean cooking systems: Cooking solutions that release less harmful pollutants, are more efficient and environmentally sustainable than traditional cooking options that make use of solid biomass (such as a three-stone fire), coal or kerosene. This refers to improved cook stoves, biogas/biodigester systems, electric stoves, liquefied petroleum gas, natural gas or ethanol stoves.

Coal: Includes both primary coal, i.e. lignite, coking and steam coal, and derived fuels, e.g. patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas works gas, coke-oven gas, blast furnace gas and oxygen steel furnace gas. Peat is also included.

Coalbed methane (CBM)**:** Category of unconventional natural gas that refers to methane found in coal seams.

Coal-to-gas (CTG)**:** Process in which coal is first turned into syngas (a mixture of hydrogen and carbon monoxide) and then into synthetic methane.

Coal-to-liquids (CTL)**:** Transformation of coal into liquid hydrocarbons. One route involves coal gasification into syngas (a mixture of hydrogen and carbon monoxide), which is processed using Fischer-Tropsch or methanol-to-gasoline synthesis. Another route, called direct-coal liquefaction, involves reacting coal directly with hydrogen.

Coking coal: Type of coal that can be used for steel making (as a chemical reductant and a source of heat), where it produces coke capable of supporting a blast furnace charge. Coal of this quality is commonly known as metallurgical coal.

Concentrating solar power (CSP)**:** Thermal power generation technology that collects and concentrates sunlight to produce high temperature heat to generate electricity.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. Commonly referred to as first generation biofuels and include sugar cane ethanol, starch-based ethanol, fatty acid methyl ester (FAME), straight vegetable oil (SVO) and hydrotreated vegetable oil (HVO) produced from palm, rapeseed or soybean oil.

Critical minerals: A wide range of minerals and metals that are essential in clean energy technologies and other modern technologies and have supply chains that are vulnerable to disruption. Although the exact definition and criteria differ among countries, critical minerals for clean energy technologies typically include chromium, cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, platinum group metals, zinc, rare earth elements and other commodities, as listed in the Annex of the IEA special report on the *Role of Critical Minerals in Clean Energy Transitions* available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. The *World Energy Outlook* uses an additive index decomposition of the type Logarithmic Mean Divisia Index (LMDI).

Demand-side integration (DSI)**:** Consists of two types of measures: actions that influence load shape such as energy efficiency and electrification; and actions that manage load such as demand-side response measures.

Demand-side response (DSR)**:** Describes actions which can influence the load profile such as shifting the load curve in time without affecting total electricity demand, or load shedding such as interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time.

Direct air capture (DAC): Technology to capture CO_2 directly from the atmosphere using liquid solvents or solid sorbents. It is generally coupled with permanent storage of the CO_2 in deep geological formations or its use in the production of fuels, chemicals, building materials or other products. When coupled with permanent geological CO_2 storage, DAC is a carbon removal technology.

Dispatchable generation: Refers to technologies whose power output can be readily controlled, i.e. increased to maximum rated capacity or decreased to zero in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmission and distribution losses.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

End-use sectors: Include industry, transport, buildings and other, i.e., agriculture and other non-energy use.

Energy-intensive industries: Includes production and manufacturing in the branches of iron and steel, chemicals, non-metallic minerals (including cement), non-ferrous metals (including aluminium), and paper, pulp and printing.

Energy-related and industrial process CO_2 emissions: Carbon dioxide emissions from fuel combustion and from industrial processes. Note that this does not include fugitive emissions from fuels, flaring or CO_2 from transport and storage. Unless otherwise stated, CO_2 emissions in the *World Energy Outlook* refer to energy-related and industrial process CO_2 emissions.

Energy sector greenhouse gas (GHG) emissions: Energy-related and industrial process CO_2 emissions plus fugitive and vented methane (CH_4) and nitrous dioxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bioethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Currently, ethanol is made from starches and sugars, but second-generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

Fischer-Tropsch synthesis: Catalytic production process for the production of synthetic fuels, e.g. diesel, kerosene or naphtha, typically from mixtures of carbon monoxide and hydrogen (syngas). The inputs to Fischer-Tropsch synthesis can be from biomass, coal, natural gas, or hydrogen and CO_2.

Fossil fuels: Include coal, natural gas and oil.

Gaseous fuels: Include natural gas, biogases, synthetic methane and hydrogen.

Gases: See gaseous fuels.

Gas-to-liquids (GTL)**:** A process that reacts methane with oxygen or steam to produce syngas (a mixture of hydrogen and carbon monoxide) followed by Fischer-Tropsch synthesis. The process is similar to that used in coal-to-liquids.

Geothermal: Geothermal energy is heat from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use)**:** Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating, and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply)**:** Obtained from the combustion of fuels, nuclear reactors, geothermal resources or the capture of sunlight. It may be used for heating or cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation.

Heavy-duty vehicles (HDVs)**:** Includes both medium-freight trucks (3.5 to 15 tonnes) and heavy-freight trucks (>15 tonnes)

Heavy industries: Iron and steel, chemicals and cement.

Hydrogen: Hydrogen is used in the energy system as an energy carrier, as an industrial raw material, or is combined with other inputs to produce hydrogen-based fuels. Unless otherwise stated, hydrogen in this report refers to low-emissions hydrogen.

Hydrogen-based fuels: See low-emissions hydrogen-based fuels.

Hydropower: Energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, aluminium, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under other energy sector. There is an exception for fuel transformation in blast furnaces and coke ovens, which are reported within iron and steel. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

Improved cook stoves: Intermediate and advanced improved biomass cook stoves (ISO tier > 1). It excludes basic improved stoves (ISO tier 0-1).

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Includes the quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and instead included in the residential, services and agriculture category.

Investment: Investment is the capital expenditure in energy supply, infrastructure, end-use and efficiency. Fuel supply investment includes the production, transformation and transport of oil, gas, coal and low-emissions fuels. *Power sector* investment includes new construction and refurbishment of generation, electricity grids (transmission, distribution and public electric vehicle chargers), and battery storage. *Energy efficiency* investment includes efficiency improvements in buildings, industry and transport. *Other end-use* investment includes the purchase of equipment for the direct use of renewables, electric vehicles, electrification in buildings, industry and international marine transport, equipment for the use of low-emissions fuels, and CCUS in industry and direct air capture. Data and projections reflect spending over the lifetime of projects and are presented in real terms in year-2021 US dollars converted at market exchange rates unless otherwise stated. Total investment reported for a year reflects the amount spent in that year.

Levelised cost of electricity (LCOE)**:** The LCOE combines into a single metric all the cost elements directly associated with a given power technology, including construction, financing, fuel, maintenance and costs associated with a carbon price. It does not include network integration or other indirect costs. The LCOE provides a first indicator of competitiveness. For a more complete indicator, see VALCOE.

Light-duty vehicles (LDVs)**:** Include passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Light industries: Includes non-energy-intensive industries: food and tobacco, machinery, mining and quarrying, transportation equipment, textile, wood harvesting and processing and construction.

Lignite: A type of coal that is used in the power sector mostly in regions near lignite mines due to its low energy content and typically high moisture levels, which generally makes long-distance transport uneconomic. Data on lignite in the *World Energy Outlook* include peat.

Liquid biofuels: Liquid fuels derived from biomass or waste feedstock, e.g. ethanol, biodiesel and biojet fuels. They can be classified as conventional and advanced biofuels according to the combination of feedstock and technologies used to produce them and their respective maturity. Unless otherwise stated, biofuels are expressed in energy-equivalent volumes of gasoline, diesel and kerosene.

Liquid fuels: Include oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-emissions electricity: Includes renewable energy technologies, low-emissions hydrogen-based generation, low-emissions hydrogen-based fuel generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Low-emissions fuels: Include modern bioenergy, low-emissions hydrogen and low-emissions hydrogen-based fuels.

Low-emissions gases: Includes biogas, biomethane, low-emissions hydrogen and low-emissions synthetic methane.

Low-emissions hydrogen: Hydrogen that is produced from water using electricity generated by renewables or nuclear, from fossil fuels with minimal associated methane emissions and processed in facilities equipped to avoid CO_2 emissions, e.g. via CCUS with a high capture rate, or derived from bioenergy. In this report, total demand for low-emissions hydrogen is larger than total final consumption of hydrogen because it additionally includes hydrogen inputs to make low-emissions hydrogen-based fuels, biofuels production, power generation, oil refining, and hydrogen produced and consumed onsite in industry.

Low-emissions hydrogen-based fuels: Include ammonia, methanol and other synthetic hydrocarbons (gases and liquids) made from low-emissions hydrogen. Any carbon inputs, e.g. from CO_2, are not from fossil fuels or process emissions.

Low-emissions hydrogen-based liquid fuels: A subset of low-emissions hydrogen-based fuels that includes only ammonia, methanol and synthetic liquid hydrocarbons, such as synthetic kerosene.

Lower heating value: Heat liberated by the complete combustion of a unit of fuel when the water produced is assumed to remain as a vapour and the heat is not recovered.

Marine energy: Represents the mechanical energy derived from tidal movement, wave motion or ocean currents and exploited for electricity generation.

Middle distillates: Include jet fuel, diesel and heating oil.

Mini-grids: Small electric grid systems, not connected to main electricity networks, linking a number of households and/or other consumers.

Modern energy access: Includes household access to a minimum level of electricity (initially equivalent to 250 kilowatt-hours (kWh) annual demand for a rural household and 500 kWh for an urban household); household access to less harmful and more sustainable cooking and heating fuels, and improved/advanced stoves; access that enables productive economic activity; and access for public services.

Modern gaseous bioenergy: See biogases.

Modern liquid bioenergy: Includes biogasoline, biodiesel, biojet kerosene and other liquid biofuels.

Modern renewables: Include all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid bioenergy: Includes all solid bioenergy products (see solid bioenergy definition) except the traditional use of biomass. It also includes the use of solid bioenergy in intermediate and advanced improved biomass cook stoves (ISO tier > 1), requiring fuel to be cut in small pieces or often using processed biomass such as pellets.

Natural gas: Includes gas occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both non-associated gas originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil production as well as methane recovered from coal mines (colliery gas). Natural gas liquids, manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg (Standard Conditions). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Natural gas liquids (NGLs)**:** Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilisation of natural gas. NGLs are portions of natural gas recovered as liquids in separators, field facilities or gas processing plants. NGLs include, but are not limited to, ethane (when it is removed from the natural gas stream), propane, butane, pentane, natural gasoline and condensates.

Network gases: Include natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: The use of fuels as feedstocks for chemical products that are not used in energy applications. Examples of resulting products are lubricants, paraffin waxes, asphalt, bitumen, coal tars and timber preservative oils.

Non-renewable waste: Non-biogenic waste, such as plastics in municipal or industrial waste.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear power plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Mini-grids and stand-alone systems for individual households or groups of consumers not connected to a main grid.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Includes both conventional and unconventional oil production. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirits, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses in low-emissions hydrogen and hydrogen-based fuels production, bioenergy processing, gas works, petroleum refineries, coal and gas transformation and liquefaction. It also includes energy own use in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category. Fuel transformation in blast furnaces and coke ovens are not accounted for in the other energy sector category.

Other industry: A category of industry branches that includes construction, food processing, machinery, mining, textiles, transport equipment, wood processing and remaining industry.

Passenger car: A road motor vehicle, other than a moped or a motorcycle, intended to transport passengers. It includes vans designed and used primarily to transport passengers. Excluded are light commercial vehicles, motor coaches, urban buses, and mini-buses/mini-coaches.

Peat: Peat is a combustible soft, porous or compressed, fossil sedimentary deposit of plant origin with high water content (up to 90% in the raw state), easily cut, of light to dark brown colour. Milled peat is included in this category. Peat used for non-energy purposes is not included here.

Plastic collection rate: Proportion of plastics that is collected for recycling relative to the quantity of recyclable waste available.

Plastic waste: Refers to all post-consumer plastic waste with a lifespan of more than one year.

Power generation: Refers to fuel use in electricity generation plants, heat plants, and combined heat and power plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Process emissions: CO_2 emissions produced from industrial processes which chemically or physically transform materials. A notable example is cement production, in which CO_2 is emitted when calcium carbonate is transformed into lime, which in turn is used to produce clinker.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector, e.g. freight, could be considered as productive, but is treated separately.

Rare earth elements (REEs)**:** A group of seventeen chemical elements in the periodic table, specifically the fifteen lanthanides plus scandium and yttrium. REEs are key components in some clean energy technologies, including wind turbines, electric vehicle motors and electrolysers.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking.

Road transport: Includes all road vehicle types (passenger cars, two/three-wheelers, light commercial vehicles, buses and medium and heavy freight trucks).

Self-sufficiency: Corresponds to indigenous production divided by total primary energy demand.

Services: Energy used in commercial facilities, e.g. offices, shops, hotels, restaurants, and in institutional buildings, e.g. schools, hospitals, public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking and desalination.

Shale gas: Natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability of gas to flow through the rock than is the case within a conventional reservoir. Shale gas is generally produced using hydraulic fracturing.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or people on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Single-use plastics (or disposable plastics)**:** Plastic items used only one time before disposal.

Solar: Includes solar photovoltaics and concentrating solar power.

Solar home systems: Small-scale photovoltaic and battery stand-alone systems, i.e. with capacity higher than 10 watt peak (Wp) supplying electricity for single households or small businesses. They are most often used off-grid, but also where grid supply is not reliable. Access to electricity in the IEA definition considers solar home systems from 25 Wp in rural areas and 50 Wp in urban areas. It excludes smaller solar lighting systems, e.g. solar lanterns of less than 11 Wp.

Solar photovoltaics (PV)**:** Electricity produced from solar photovoltaic cells.

Solid bioenergy: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid biogenic wastes.

Solid fuels: Include coal, modern solid bioenergy, traditional use of biomass and industrial and municipal wastes.

Stand-alone systems: Small-scale autonomous electricity supply for households or small businesses. They are generally used off-grid, but also where grid supply is not reliable. Stand-alone systems include solar home systems, small wind or hydro generators, diesel or gasoline generators, etc. The difference compared with mini-grids is in scale and that stand-alone systems do not have a distribution network serving multiple costumers.

Steam coal: A type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic methane: Methane from sources other than natural gas, including coal-to-gas and low-emissions synthetic methane.

Synthetic oil: Synthetic oil produced through Fischer-Tropsch conversion or methanol synthesis. It includes oil products from CTL and GTL, and low-emissions liquid hydrogen-based fuels.

Tight oil: Oil produced from shale or other very low permeability formations, generally using hydraulic fracturing. This is also sometimes referred to as light tight oil. Tight oil includes tight crude oil and condensate production except for the United States, which includes tight crude oil only (US tight condensate volumes are included in natural gas liquids).

Total energy supply (TES)**:** Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens), transport, buildings (including residential and services) and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the United Nations Sustainable Development Goals (SDG). It incorporates total final consumption by end-use sectors, but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (indicator SDG 7.2.1), where TFEC is the denominator.

Traditional use of biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire or basic improved cook stoves (ISO tier 0-1), often with no or poorly operating chimneys. Forms of biomass used include wood, wood waste, charcoal agricultural residues and other bio-sourced fuels such as animal dung.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes all size categories of commercial vehicles: light trucks (gross vehicle weight less than 3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (>15 tonnes).

Unabated fossil fuel use: Combustion of fossil fuels in facilities without CCUS.

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

Value-adjusted levelised cost of electricity (VALCOE)**:** Incorporates information on both costs and the value provided to the system. Based on the LCOE, estimates of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies.

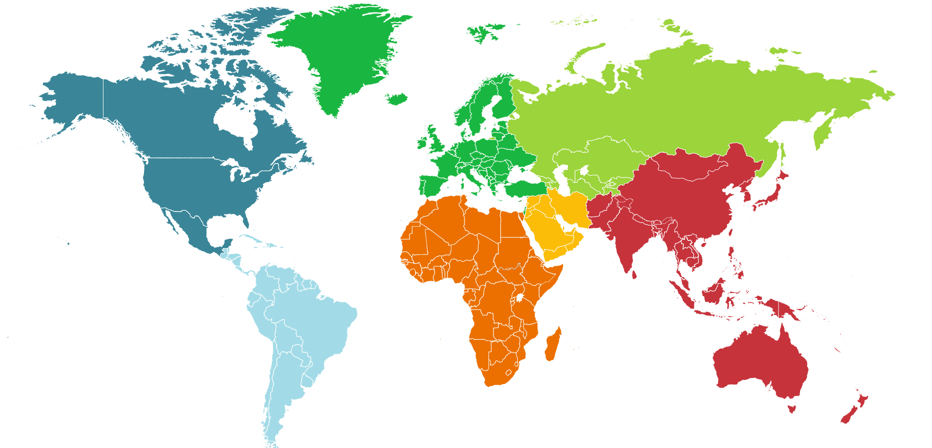
Variable renewable energy (VRE)**:** Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero carbon-ready buildings: A zero carbon-ready building is highly energy efficient and either uses renewable energy directly or an energy supply that can be fully decarbonised, such as electricity or district heat.

Zero emissions vehicles (ZEVs)**:** Vehicles that are capable of operating without tailpipe CO_2 emissions (battery electric and fuel cell vehicles).

Regional and country groupings

Figure C.1 ▷ Main country groupings



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Türkiye, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Colombia, Costa Rica, Iceland, Israel, Latvia and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Czech Republic, Colombia, Costa Rica, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom and United States.

OPEC (Organization of the Petroleum Exporting Countries)**:** Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Republic of Türkiye: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and acronyms

AC	alternating current
AFOLU	agriculture, forestry and other land use
APEC	Asia-Pacific Economic Cooperation
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy equipped with CCUS
BEV	battery electric vehicles
CAAGR	compound average annual growth rate
CAFE	corporate average fuel economy standards (United States)
CBM	coalbed methane
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CEM	Clean Energy Ministerial
CH_4	methane
CHP	combined heat and power; the term co-generation is sometimes used
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent

C

COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
CTG	coal-to-gas
CTL	coal-to-liquids
DAC	direct air capture
DACS	direct air capture and storage
DC	direct current
DER	distributed energy resources
DRI	direct reduced iron
DSI	demand-side integration
DSO	distribution system operator
DSR	demand-side response
EHOB	extra-heavy oil and bitumen
EMDE	emerging market and developing economies
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (United States)
ESG	environmental, social and governance
EU	European Union
EU ETS	European Union Emissions Trading System
EV	electric vehicle
FAO	Food and Agriculture Organization of the United Nations
FCEV	fuel cell electric vehicle
FDI	foreign direct investment
FID	Final investment decision
FiT	feed-in tariff
FOB	free on board
GEC	Global Energy and Climate (model)
GDP	gross domestic product
GHG	greenhouse gases
GTL	gas-to-liquids
HDV	heavy-duty vehicle
HEFA	hydrogenated esters and fatty acids
HFO	heavy fuel oil
HVDC	high voltage direct current
IAEA	International Atomic Energy Agency
ICE	internal combustion engine
ICT	information and communication technologies
IEA	International Energy Agency
IGCC	integrated gasification combined-cycle
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IMO	International Maritime Organization
IOC	international oil company
IPCC	Intergovernmental Panel on Climate Change

LCOE	levelised cost of electricity
LCV	light commercial vehicle
LDV	light-duty vehicle
LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LULUCF	land use, land-use change and forestry
MEPS	minimum energy performance standards
MER	market exchange rate
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (an agency within the OECD)
NGLs	natural gas liquids
NGV	natural gas vehicle
NOC	national oil company
NPV	net present value
NO_X	nitrogen oxides
N_2O	nitrous dioxide
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	plug-in hybrid electric vehicles
PLDV	passenger light-duty vehicle
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PPA	power purchase agreement
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SDG	Sustainable Development Goals (United Nations)
SME	small and medium enterprises
SMR	steam methane reformation
SO_2	sulphur dioxide
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	thermal energy storage
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
TSO	transmission system operator
UAE	United Arab Emirates
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USGS	United States Geological Survey
VALCOE	value-adjusted levelised cost of electricity
VRE	variable renewable energy
WACC	weighted average cost of capital
WEO	World Energy Outlook
WHO	World Health Organization
ZEV	zero emissions vehicle
ZCRB	zero carbon-ready building

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Inputs to the Global Energy and Climate Model

General note

This annex includes references of databases and publications used to provide input data to the IEA Global Energy and Climate (GEC) Model. The IEA's own databases of energy and economic statistics provide much of the data used in the GEC Model. These include IEA statistics on energy supply, transformation, demand at detailed levels, carbon dioxide emissions from fuel combustion and energy efficiency indicators that form the bedrock of the *World Energy Outlook* and *Energy Technology Perspectives* modelling and analyses.

Supplemental data from a wide range of external sources are also used to complement IEA data and provide additional detail. This list of databases and publications is comprehensive, but not exhaustive.

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Typeset in France by IEA - October 2022
Cover design: IEA
Photo credits: © Gettyimages

Revised version, November 2022.
Information notice found at: www.iea.org/corrections

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With the world in the midst of the first global energy crisis – triggered by Russia's invasion of Ukraine – the *World Energy Outlook 2022 (WEO)* provides indispensable analysis and insights on the implications of this profound and ongoing shock to energy systems across the globe.

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