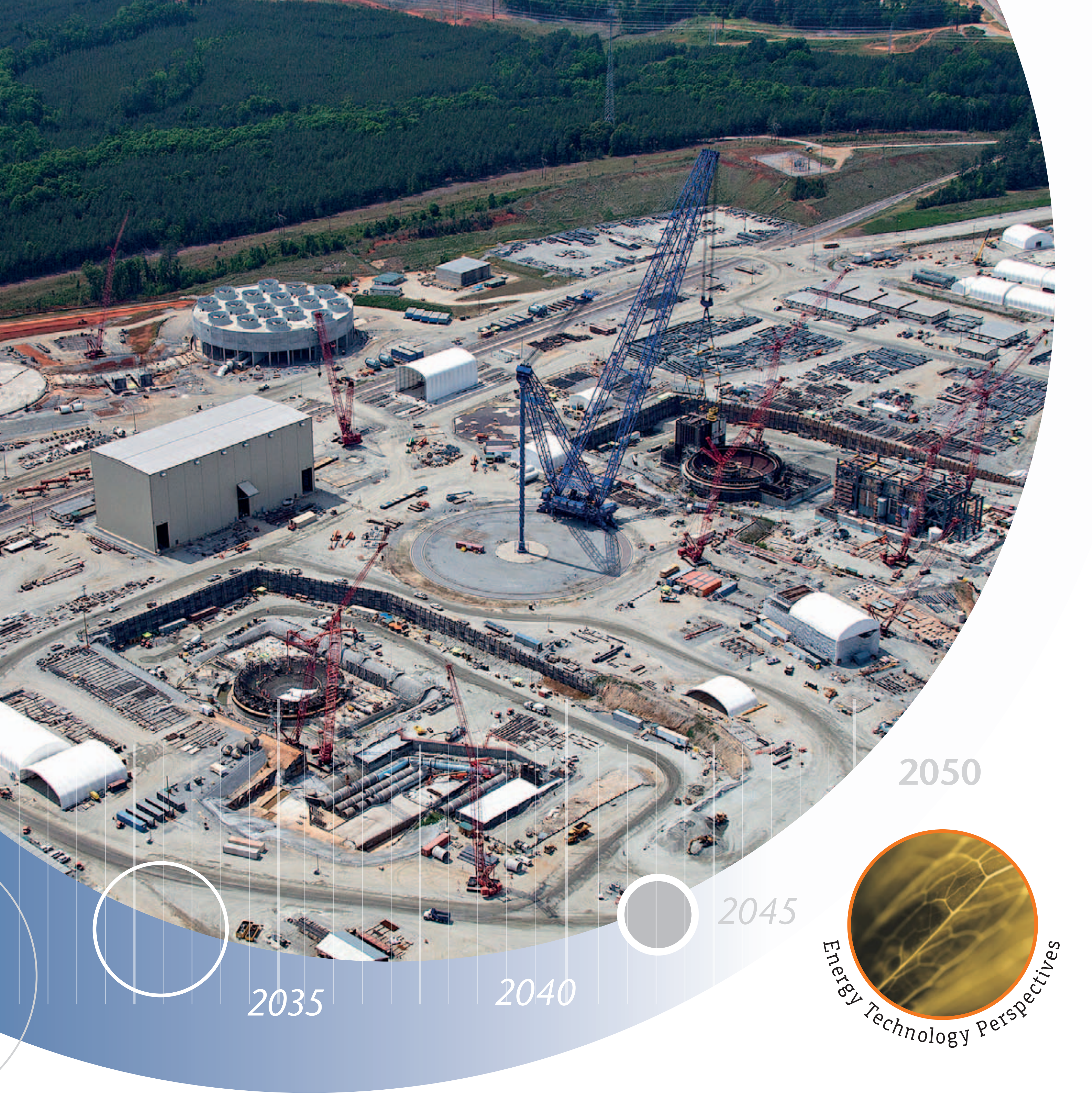

Technology Roadmap

Nuclear Energy

2015 edition

NEA Nuclear Energy Agency

International Energy Agency
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Foreword

Current trends in energy supply and use are unsustainable. Without decisive action, energy-related emissions of carbon dioxide will nearly double by 2050 and increased fossil energy demand will heighten concerns over the security of supplies. We can change our current path, but this will take an energy revolution in which low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage, nuclear power and new transport technologies will all require widespread deployment if we are to sharply reduce greenhouse gas (GHG) emissions. Every major country and sector of the economy would need to be involved. The task is urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing on the need to turn political statements and analytical work into concrete action. To spark this movement, the International Energy Agency (IEA) is leading the development of a series of *Roadmaps* for some of the most important technologies. By identifying the steps needed to accelerate the implementation of technology changes, these *Roadmaps* will enable governments, industry and financial partners to make the right choices – and in turn help societies to make the right decisions.

This *Roadmap* is an update of the 2010 *Technology Roadmap: Nuclear Energy* (IEA/NEA, 2010), and, similarly to the 2010 edition, it has been prepared jointly by the IEA and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA). The nuclear energy landscape has changed since 2010, with a number of events affecting its development: the Fukushima Daiichi accident, which heightened public concern over the safety of nuclear energy in many countries, and the subsequent safety reviews and development of new safety requirements to ensure even higher levels of safety for existing and future nuclear power plants; the shift towards Generation III reactors for nuclear new build; and the economic and financial crises that have both lowered energy demand and made financing of capital-intensive infrastructure projects more challenging, especially in liberalised electricity markets. As a follow-up to this *Roadmap*, the NEA is initiating a highly technical survey to identify the critical research and development efforts that are needed to enable countries to consider advanced nuclear energy technologies as they attempt to reduce their reliance on fossil fuels.

Each country must decide what energy mix is optimal for its national circumstances. However, the fundamental advantages provided by nuclear energy in terms of reduction of GHG emissions, competitiveness of electricity production and security of supply still apply. The number of reactors under construction is currently the highest in 25 years, with the People's Republic of China leading the way in terms of new projects. There is also renewed interest in developing more innovative designs and advanced nuclear fuel cycles to address new markets and improve the competitiveness of nuclear power plants. The *Roadmap* is based on a scenario where long-term global temperature increases are limited to just 2 degrees Celsius (°C) and outlines a scenario that highlights nuclear energy's potential contribution to this low-carbon future. This scenario is not a prediction of what will happen.

Nuclear energy can play a key role in decarbonising our electricity systems by providing a stable source of low-carbon base-load electricity. By identifying major barriers and recommendations on how they can be overcome, this *Roadmap* aims to assist governments interested in maintaining or developing nuclear energy technologies. To get us onto the right pathway, this *Roadmap* highlights several key actions to be addressed in the next decade to ensure the conditions for a safe, publicly accepted and affordable deployment of nuclear technology in countries that already have the technology as well as in newcomer countries.

This publication is produced under our authority as Executive Director of the IEA and Director-General of the NEA.

Maria van der Hoeven
Executive Director, IEA

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Director-General, NEA

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Key findings

- Nuclear power is the largest source of low-carbon electricity in OECD countries, with an 18% overall share of electricity production in 2013 and second at global levels with an 11% share. The updated vision for the 2014 Nuclear Roadmap – based on the 2 degrees Celsius (°C) scenario (2DS)[1] of *Energy Technology Perspectives: Scenarios and Strategies to 2050* (IEA, forthcoming 2015) – sees nuclear continuing to play a major role in lowering emissions from the power sector, while improving security of energy supply, supporting fuel diversity and providing large-scale electricity at stable production costs.

- In the 2D scenario, global installed capacity would need to more than double from current levels of 396 gigawatts (GW) to reach 930 GW in 2050, with nuclear power representing 17% of global electricity production. Although lower than the 2010 Roadmap vision of 1 200 GW and 25% share of generation, this increase still represents a formidable growth for the nuclear industry.

- The near-term outlook for nuclear energy has been impacted in many countries by the Fukushima Daiichi nuclear power plant accident. Although the accident caused no direct radiation-related casualties, it raised concerns over the safety of nuclear power plants and led to a drop in public acceptance, as well as to changes in energy policies in a limited number of countries. This, together with an economic crisis that has lowered demand in many countries and a financial crisis that is making financing of capital-intensive projects challenging, has led to a decrease in overall construction starts and grid connection rates over the last four years.

- However, in the medium to long term, prospects for nuclear energy remain positive. A total of 72 reactors were under construction at the beginning of 2014, the highest number in 25 years. According to the 2D scenario, China would account for the largest increase in nuclear capacity additions from 17 GW in 2014 to 250 GW in 2050 and, by 2050, would represent 27% of global nuclear capacity and nuclear power generation. Other growing nuclear energy markets include India, the Middle East and the Russian Federation. According to 2DS projections, nuclear capacity would either decline or remain flat in most OECD countries, with the exception of the Republic of Korea, Poland, Turkey and the United Kingdom.

- Nuclear safety remains the highest priority for the nuclear sector. Although the primary responsibility for nuclear safety lies with the operators, regulators have a major role to play to ensure that all operations are carried out with the highest levels of safety. Lessons learnt from the Fukushima Daiichi accident have emphasised that regulators should be strong and independent. Safety culture must be promoted at all levels in the nuclear sector (operators and industry, including the supply chain, and regulators) and especially in newcomer countries.

- Governments have a role to play in ensuring a stable, long-term investment framework that allows capital-intensive projects to be developed and provides adequate electricity prices over the long term for all low-carbon technologies. Governments should also continue to support nuclear research and development (R&D), especially in the area of nuclear safety, advanced fuel cycles, waste management and innovative designs.

- Nuclear energy is a mature low-carbon technology, which has followed a trend towards increased safety levels and power output to benefit from economies of scale. This trajectory has come with an increased cost for Generation III reactors compared with previous generations, but this should also lead to better performance and economics for standardised Nth-of-a-kind (NOAK) plants, although this has yet to be confirmed.

- Small modular reactors (SMRs) could extend the market for nuclear energy by providing power to smaller grid systems or isolated markets where larger nuclear plants are not suitable. The modular nature of these designs may also help to address financing barriers.

1 The 2°C Scenario outlines the technologies needed across all energy sectors so that CO_2 emissions in 2050 are reduced by half compared to 2009 levels, allowing for long-term global temperature increases of just 2°C. See Box 5 for more details.

Key actions for the next ten years

In order for nuclear to reach its deployment targets under the 2D scenario, annual connection rates should increase from 5 GW in 2014 to well over 20 GW during the coming decade. Such rapid growth will only be possible if the following actions are implemented over the next ten years:

- The contributions of nuclear energy – providing valuable base-load electricity, supplying important ancillary services to the grid and contributing to the security of energy supply – must be fully acknowledged. It is important, therefore, to review arrangements in the electricity market so as to ensure that they offer investment frameworks as favourable to new nuclear build as they are to other low-carbon technologies and that they allow nuclear power plants to operate effectively.

- Vendors must demonstrate the ability to build on time and to budget, and to reduce the costs of new designs. Integrating lessons learnt from recent first-of-a-kind (FOAK) experiences in project management and planning, human resource allocation, supply chain set-up, qualification and oversight, as well as reactor design, construction simplification and optimisation, will be key.

- Enhanced standardisation, harmonisation of codes, standards and regulatory requirements, and the streamlining of regulatory licensing processes are needed to reduce costs and to improve new build planning and performance. At the same time, industry must continue to improve quality assurance and control for nuclear structures, systems and components, and nuclear safety culture must be enhanced across the whole nuclear sector, spanning the supply chain, the vendors, the utilities and the regulators.

- Information exchange and experience sharing among regulators, and among operators of nuclear power plants, should be enhanced so as to improve overall safety and operational performance.

- Countries choosing to develop nuclear power for the first time must be prepared to set up the required infrastructures prior to the start of a nuclear programme. Building capacities in terms of trained, educated and competent staff for future operation and regulatory oversight is an absolute necessity and requires long-term planning.

- Actions to improve public acceptance must also be strengthened. These include implementing post-Fukushima safety upgrades in existing reactors and demonstrating that nuclear regulators are strong and independent. It will also entail improving outreach to the public by providing transparent and fact-based information on the risks and benefits of nuclear power, and on the role that it can play with respect to energy security, affordability, climate change mitigation and air quality.

- Governments that have not yet finalised their strategies for managing nuclear waste, should do so without delay. For high-level waste, deep geological disposal (DGD) is the recommended solution. If the geology and the safety case allow, and if it makes economic sense, governments should implement a DGD at national level. Alternatively, they might consider a regional solution, making use of another country's planned or operational DGD site for waste management. Long-term planning, political commitment and strong engagement with local communities are central to this strategy.

Introduction

Since the release in 2010 of *Technology Roadmap: Nuclear Energy* (IEA/NEA, 2010), a number of events have had a significant impact on the global energy sector and on the outlook for nuclear energy. They include the Fukushima Daiichi nuclear power plant (NPP) accident in March 2011, the global financial and economic crises that hit many industrialised countries during the period 2008-10 and failings in both electricity and CO_2 markets. The Fukushima Daiichi accident has had a detrimental impact on public opinion and the overall acceptance of nuclear power as a source of energy, causing a few countries to establish policies to phase-out nuclear power. The financial crisis led to the introduction of new financial regulations that have made financing of capital-intensive projects such as nuclear new build even more difficult than in the past. The economic crisis that followed reduced the demand for electricity, which, combined with strong policy support for renewables, has resulted in a situation of overcapacity in generation for many OECD countries. Furthermore, in liberalised electricity markets, the lack or inefficiency of carbon pricing and subsidised alternative technologies, as well as falling wholesale prices, are making investment in nuclear power less attractive.

In parallel, the rapid development of unconventional gas and oil has lessened the urgency of developing new energy technologies in some parts of the world. Cheap shale gas in the United States, for example, has helped to dramatically reduce power sector emissions and lower electricity costs in certain parts of the country. As a consequence, both the demand for and price of coal have dropped in the United States. This drop has resulted in an increase in exports, especially to Europe where coal consumption has increased, in part to replace lost nuclear capacity (e.g. in Germany). Despite these additional challenges, nuclear energy still remains a proven low-carbon source of base-load electricity, and many countries have reaffirmed the importance of nuclear energy within their countries' energy strategies.

To achieve the goal of limiting global temperature increases to just 2 degrees Celsius (°C) by the end of the century, a halving of global energy-related emissions by 2050 will be needed. This will require an unprecedented transition in the way energy is consumed and produced. A wide range of low-carbon energy technologies will be needed to support this transition, including a variety of renewable energy technologies, energy efficiency, advanced vehicles, carbon capture and storage and nuclear energy. Notwithstanding government commitments to this target, action continues to fall short of what is needed to transition the energy sector, and many technologies, including nuclear, are not on track to reach the long-term 2°C target.

Purpose of the *Roadmap* update

When the *Nuclear Technology Roadmap* was released in 2010, there were 16 new construction starts – a number that had not been reached since 1985 – and many were anticipating a "nuclear renaissance". However, the accident at the Fukushima Daiichi NPP had an immediate impact on the short- to medium-term development of nuclear power in many countries, and four years after the publication of the first *Roadmap*, the IEA and NEA have undertaken an update of the nuclear energy *Roadmap* to take into account recent challenges facing the development of this technology.

This nuclear *Roadmap* update aims to:

- Outline the current status of nuclear technology development and the need for additional R&D to address increased safety requirements and improved economics.
- Provide an updated vision of the role that nuclear energy could play in a low-carbon energy system, taking into account changes in nuclear policy in various countries, as well as the current economics of nuclear and other low-carbon electricity technologies.
- Identify barriers and actions needed to accelerate the development of nuclear technologies to meet the *Roadmap* vision.
- Share lessons learnt and good practices in nuclear safety and regulation, front- and back-end fuel cycle practices, construction, decommissioning, financing, training, capacity building and communication.

Rationale for nuclear energy and *Roadmap* scope

Nuclear energy remains the largest source of low-carbon electricity in the OECD and the second largest source in the world. Its importance as a current and future source of carbon-free energy must be recognised and should be treated on an equal footing with other low-carbon technologies. As a proven and mature technology that can supply firm electricity capacity, nuclear can play a key role in future energy systems in many parts of the world. However, public acceptance of nuclear energy decreased significantly in many countries after the Fukushima Daiichi accident, although it has partly recovered since 2011. The simultaneous challenges of financing such large capital-intensive projects have made the development of nuclear power even more difficult today.

The focus of the vision presented in this *Roadmap* is centred on the IEA *Energy Technology Perspectives 2015* (IEA, forthcoming 2015) 2°C scenario (2DS) vision for nuclear energy and the contribution that nuclear power can make to the decarbonisation of the power system. *ETP 2015* projects that 930 gigawatts (GW) of gross nuclear capacity will be needed globally to support the transition of the energy system. Although lower than the vision outlined in the 2010 *Roadmap*, this growth still represents a formidable challenge for governments and industry compared to the current capacity of 396 GW.

The *Roadmap* focuses essentially on nuclear fission technologies for electricity generation, and although nuclear's potential for other energy applications such as combined heat and power, district heating, hydrogen production and desalination are very promising, the actions and milestones identified in this *Roadmap* focus mainly on the electricity sector. Other energy applications are mentioned only briefly in the technology development section of the *Roadmap*. Nuclear fusion is outside the scope of the *Roadmap* and although a promising technology in the long term, it is not expected to make any contribution to power generation before 2050.

Roadmap process, content and structure

This *Roadmap* was compiled with the support of a wide range of stakeholders from government, industry, research institutions, academia and non-governmental organisations. Three expert workshops were hosted by the IEA and NEA to provide input to the development of this *Roadmap*, two workshops at the IEA in Paris, and one in Hong Kong, China, with a focus on developments in Asia. The findings and recommendations in this report reflect the discussions and key messages that emerged from the three workshops as well as from additional input gathered during the drafting and review of the *Roadmap*.

This edition of the *Roadmap* provides an update on the status of nuclear development since 2010 and highlights technology development needs for nuclear reactors, as well as front- and back-end fuel cycle issues, including decommissioning. Industrial issues such as standardisation, harmonisation of codes and standards, development of global and local supply chains, quality assurance, and integration of feedback experience from current new build projects are also covered in this report. Newcomer countries, especially in the Middle East and the Southeast Asia regions, are expected to represent a significant share of the projected growth of nuclear energy, and special attention has been paid to the conditions in which nuclear energy can be developed in these countries. Identified barriers to this development include financing, public acceptance in the wake of the Fukushima Daiichi accident, higher costs due in part to enhanced safety regulations after Fukushima Daiichi, human resource capacity building, and a lack of favourable energy policy and electricity market incentives.

Case studies have been developed together with various nuclear energy stakeholders to help illustrate lessons learnt and good practices in the development of nuclear energy. A summary of these case studies is included in the *Roadmap* document, with the full versions available in Annex[2]. These case studies aim to provide additional insights and practical support for the recommendations and proposed actions in this *Roadmap*. They cover lessons learnt from new build projects, best practices in decommissioning and waste management, setting up of geological repositories for high-level waste, financing, education and training skills programmes, and the establishment and reinforcement of the supply chain. It also covers the benefits of peer review processes among operators or regulators, allowing them to share knowledge and improve safety.

2. www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy.html.

Nuclear energy progress since 2010

When the International Energy Agency (IEA)/ Nuclear Energy Agency (NEA) *Technology Roadmap*: *Nuclear Energy* was published in 2010, nuclear energy was experiencing a so-called "nuclear renaissance". Reasons for the increased interest in nuclear power in the decade leading up to 2010 included concern over greenhouse gas (GHG) emissions from the power sector and security of energy supply, as well as the need for affordable base-load electricity supply with stable production costs. However, this trend slowed considerably in 2011, to a large extent because of the Fukushima Daiichi nuclear power plant (NPP) accident in March, which had an impact on public acceptance and on nuclear policies in several countries. Other reasons for this slowdown include the aftermath of the financial crisis of 2008-09 and the ensuing economic crisis, which led to a decrease in financing capabilities on the part of lending institutions, as well as decreased electricity needs in countries affected by the economic crisis. More than three years after the accident in Japan, the global situation is improving for nuclear energy with the number of construction starts again on the rise. Yet, the grid connection rate is still too low to meet the 2 degrees Celsius Scenario (2DS) target for nuclear power by 2025 (IEA, 2014). This updated *Roadmap* aims to identify actions that could help bring nuclear back on track to meet the 2DS target.

Fukushima Daiichi NPP accident: 11 March 2011

The Fukushima Daiichi accident was the result of the Great East Japan earthquake that registered a magnitude of 9 on the Richter scale – the largest ever recorded in Japan – and the ensuing tsunami that hit the power plant. Units 1, 2 and 3 at the power plant were in operation at the time of the accident and shut down safely following the earthquake, with emergency power generation units kicking in when the off-site power supplies were lost. However, most of these failed when the tsunami hit the plant and the basements of the reactor buildings were flooded. As a consequence, the decay heat removal capabilities of the reactors were lost, leading to a severe accident with core degradation, hydrogen generation (and subsequent explosion), and release of radioactive material into the environment following the partial destruction of the reactor buildings.

The accident was the worst of its kind since the Chernobyl accident in 1986, rating 7 on the International Nuclear Event Scale (INES), at the same level as the Chernobyl accident. However, unlike the accident in the Ukraine, tens of thousands of people were evacuated from the vicinity of the plant and sheltered before most of the release of radioactive material into the environment. In 2014, the United Nations Scientific Committee on the Effects of Atomic Radiation released its final report on the radiological consequences of the accident (UNSCEAR, 2014), which concludes that radioactive releases were between 10% and 20% of the releases of the Chernobyl accident. No fatalities were considered to have arisen from overexposure to radiation, although some injuries and deaths occurred at the NPP as a result of accidents related to the earthquake and tsunami. Large areas around the Fukushima Daiichi power plant were contaminated by the fallout from the accident, and the imposition of very low radiation exposure standards prevented evacuees from returning to their homes and villages. A multibillion USD "remediation" programme has been undertaken to decontaminate the environment, but it will take several years to complete before people are allowed to return to their homes. In parallel, work is ongoing to decommission the Fukushima Daiichi nuclear power plant and to prevent any further radioactive releases from the destroyed units.

In spite of the limited number of casualties caused by the Fukushima Daiichi accident, there has been worldwide concern about the consequences of the accident, and more generally, about the safety of nuclear power. Actions to assess the safety of operating nuclear facilities in the event of extreme external events have been taken at both national and international levels. They include comprehensive safety reviews – called "stress tests" in the European Union – of existing reactors as well as reactors under construction and other fuel cycle facilities. These reviews have reassessed the safety margins of nuclear facilities with a primary focus on challenges related to multiple external events such as those experienced at the Fukushima Daiichi NPP (i.e. the loss of safety functions, including cooling of the reactor core) or capabilities to cope with severe accidents.

The reviews examined the adequacy of design-basis assumptions, as well as provisions for beyond-design-basis events. These assessments were carried out by the operators under the guidance of their national regulators. They were then reviewed by the regulators and peer reviewed at the international level, for instance, by the European Nuclear Safety Regulators Group (ENSREG) for facilities in the European Union and neighbouring countries (Switzerland, Turkey, Ukraine) or upon request by the International Atomic Energy Agency (IAEA). Following these safety assessments, it was found that the vast majority of NPPs could continue to operate safely, but that some safety upgrades were necessary to improve the resistance of the NPPs to extreme or multiple external events. These safety upgrades are currently being implemented by the operators and reported to national regulators.

Only a few months after the accident, the IAEA Action Plan on Nuclear Safety was adopted by the IAEA's Board of Governors and subsequently endorsed unanimously by the IAEA General Conference in September 2011. The ultimate goal of the Action Plan is to strengthen nuclear safety worldwide through 12 targeted actions that address *inter alia* safety assessments, peer reviews, emergency preparedness and response, the effectiveness of regulators and operators, and safety standards.

The IAEA is nearing completion of the IAEA Fukushima Report (to be published in 2015). The NEA has already released a report entitled "OECD/NEA Nuclear Safety Response and Lessons Learnt" (NEA, 2013), describing immediate actions and follow-up actions taken by its members and by the NEA. The report provides key messages and recommendations to improve nuclear safety. Operators are also drawing on lessons learnt from the accident and sharing information and best practices as well as subjecting themselves to peer review. In particular, these peer reviews are often performed by the World Association of Nuclear Operators (WANO) (see Box 1).

Nuclear power generation and new build at the end of 2014

Global nuclear generation declined to around 2 478 terawatt hours (TWh) in 2013, a 10% decrease from 2010 levels, essentially due to the permanent shutdown of eight reactors in Germany and to Japan's operable reactors remaining offline for the majority of 2013. Japan's 48 operable reactors have remained idle since September

Box 1: Peer review process among nuclear operators: WANO (Case study 1)

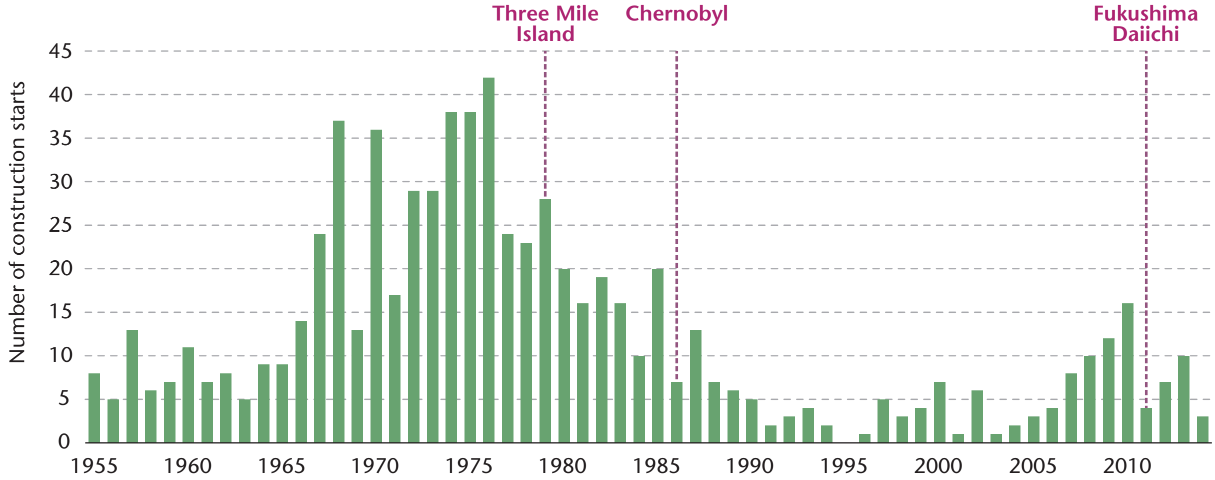
WANO brings together operators from every country in the world that has an operating commercial NPP with the objective of achieving the highest possible standards of nuclear safety. WANO helps its 130 members accomplish the highest levels of operational safety and reliability. With safety as its only goal, WANO helps operators communicate effectively and share information openly to raise the performance levels of all operators.

For the past 25 years, WANO has been helping operators through four core programmes:

- Peer reviews: these reviews help members compare their operational performance against standards of excellence through in-depth, objective analyses of their operations by an independent team from outside their organisations.
- Operating experience: this programme alerts members to mistakes or events that have occurred at other NPPs and enables them to take corrective actions to prevent similar occurrences at their own plants. Members share their operating experience for the benefit of other operators.
- Technical support and exchange: this programme has many facets, including technical support missions, which are carried out at the request of a plant or utility and allow WANO members to help each other resolve identified issues or problems.
- Professional and technical development: this programme provides a forum for WANO members to enhance their professional knowledge and skills so that they can deal with potential safety issues before they become problems.

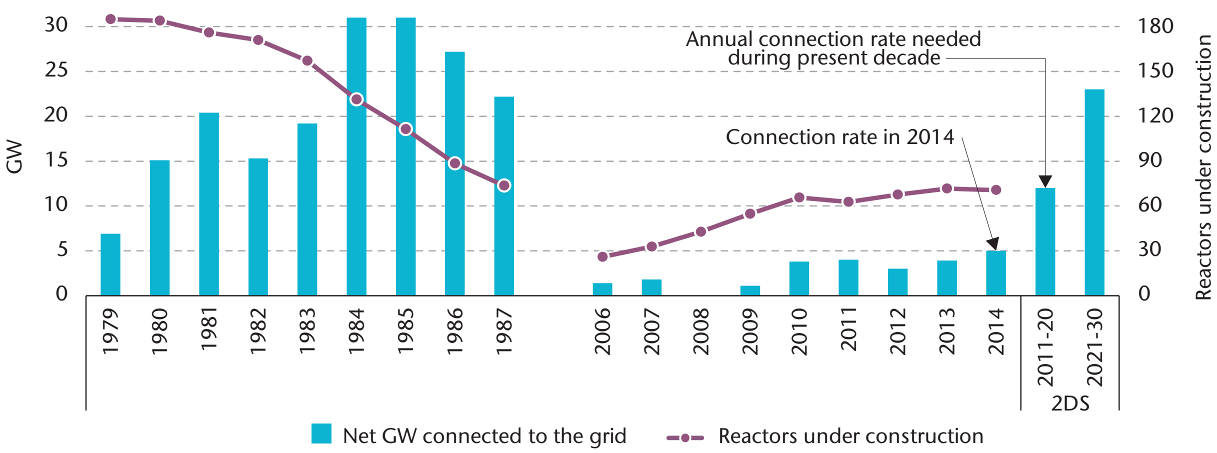
2013, and throughout 2014. Installed nuclear capacity increased only slightly between 2013 and 2014 at 396 GW (gross), and yet the number of construction starts dropped from 10 in 2013 to just 3 in 2014 (see Figure 1). A record 72 nuclear reactors were under construction at the beginning of 2014 but, in terms of grid connection, only 5 GW of nuclear capacity were connected in 2014 (4 GW in 2013), far below the 12 GW or so that would be needed each year during this decade to meet the 2DS target for 2025 (see Figure 2).

Figure 1: Nuclear reactor construction starts, 1955 to 2014



Source: IAEA Power Reactor Information System (PRIS).

Figure 2: Grid connection rates and required rates to reach the 2DS target



Source: IAEA PRIS Database, IEA and NEA analysis.

Construction of Generation III reactors

Nuclear construction projects are large complex projects involving a considerable number of suppliers and construction workers as well as high technological skills and strong architect-engineer management capabilities. Nuclear projects are also subject to strict regulatory and political control and approval. Hence, there are many reasons why new build projects can experience significant delays and run over budget. With the switch from well-established Generation II (Gen II) technologies that have established supply chains and construction planning to the potentially more complex designs of Generation III (Gen III) reactors, the nuclear industry faces additional challenges. Much publicised delays and cost-overruns for some of the first-of-a-kind projects are playing against public acceptance of nuclear power as well as investor confidence, and industry is well aware of the need to improve on its capability to deliver "on time and to budget". All vendors have taken steps to draw lessons from FOAK projects to optimise the designs of their reactors, improve the performance and quality of the supply chain, and improve project scheduling and management.

While a general perception may exist that Gen III reactors will take much longer to build than Gen II reactors because of the added complexity or improved safety and performance features that these reactors have over Gen II reactors, some of the shortest construction spans of any reactor have been achieved with Gen III designs (see Box 2).

Long-term operation of existing reactors

In addition to the need for new build capacities to be brought online, there is also a need to maintain the current fleet and to continuously improve its operation and safety. Most nuclear operators in the world are making investments to ensure the operation of their plants beyond the original design lifetime. In the United States, more than 70% of operating reactors have been granted a 20-year licence extension that allows reactors to operate for up to 60 years. In Europe, where periodic safety reviews are performed, many reactors reaching 40 years of operation will be allowed to operate for at least another 10 years. Long-term operation of existing reactors that meet certain safety requirements is very often a way to produce low-carbon electricity in the most cost-effective way for a period of 40 to 60 years (NEA, 2012a). As detailed in the technology section of this *Roadmap*, R&D in the ageing of systems and materials is being carried out to address 60+ years of operation. In some cases, however, and for single-reactor merchant plant operators in particular, market conditions can make it difficult to justify the continuous operation of NPPs.

Box 2: Lessons learnt from Generation III construction projects (Case study 2)

Vendors of Gen III reactors are aware of the need to deliver NPPs on time and to budget, and are benefitting from the experience gained during FOAK projects to optimise designs and supply chains, as well as to more effectively manage construction projects. For many vendors and equipment suppliers, especially in Europe and in the United States, Gen III projects represent the first nuclear new build projects for more than ten years, with much of the experience gained during the peak construction times of the 1970s and 1980s now outdated.

A four- to five-year construction span is a realistic target for Nth-of-a-kind (NOAK) Gen III reactors, in line with the proven construction spans of mature Gen II designs. This target has already been surpassed in Japan, where construction of Gen III units at the Kashiwazaki-Kariwa, Hamaoka and Shika NPPs were completed in less than four years.

The reasons for such impressive construction spans include the use of modularisation with very heavy lift cranes, open-top and parallel construction floor packaging, front-loaded construction engineering, detailed schedule management and an integrated construction management system. Modularisation gives a streamlined and effective on-site approach and open-top construction, and the use of heavy lift cranes allow large-scale modules to be placed directly into position. Lessons learnt during construction are also consolidated in an advanced integrated computer-aided engineering system that relies on a plant engineering database and on accumulated experience and management know-how. Finally, a quality assurance system that extends to design, manufacture, inspection, installation, and preventative maintenance after delivery contributes to better overall performance.

This was the case when two plants in the United States, Kewaunee and Vermont Yankee, shut down in 2013 and 2014 respectively, essentially for economic reasons.

For fleet operators, economies of scale can be gained by developing modernisation programmes across the fleet. This applies to both safety improvements, such as the post-Fukushima safety upgrades, as well as long-term operation investments. Maximising feedback experience across the different units of the fleet, as well as from other NPPs (through organisations such as WANO), can help optimise a modernisation programme and its cost. Nuclear utilities that have their own engineering capabilities and operate as an "architect-engineer" model can fully benefit from the return of experience and lessons learnt to optimise long-term operation investments and safety upgrades (see Box 3).

Box 3: The integrated architect-engineer model, a proven industrial model to optimise design, construction and operation of NPPs (Case study 3)

Électricité de France (EDF) has developed an industrial model called the integrated architect-engineer model – the basis of the success of the French nuclear programme, which includes 19 NPPs with a total of 58 reactors in operation and one under construction, providing 75% of the country's electricity. Thanks to strong interactions between design, procurement and operation, the operator can use this model to increase the safety and performance of the plants by maximising the use of experience feedback. Collecting experience feedback from its own plants or from other plants is the first step in the process. Then, engineering teams process this feedback and implement the measures to continuously improve the safety and performance of the facilities.

This approach was used immediately after the Fukushima Daiichi accident. EDF immediately mobilised 300 engineers who analysed each of the 19 EDF sites. A report of 7 000 pages was issued to the French Nuclear Safety Authority as part of the post-Fukushima "stress tests" evaluations. EDF was able to integrate lessons learnt from the Fukushima Daiichi accident into its lifetime extension programme and is currently investing to prepare its fleet to operate for up to 60 years. Continuous investments and improvements through integration of operational experience have meant that the cost of the Fukushima safety upgrades have been less than 20% of the cost of the lifetime extension programme.

Regional perspectives for nuclear energy

The drivers and challenges for the development of nuclear power will vary depending on a number of factors including a country's energy and environmental policy, outlook for electricity demand, availability of energy resources, the regulatory environment and the power market structure. For countries with mature nuclear operations, there will be a focus on plant modernisation and long-term operations. In nuclear newcomer countries, development of the necessary nuclear infrastructure and regulatory frameworks, of public acceptance and a skilled workforce will be important challenges. And for certain other countries, replacement of retiring plants and possible expansion of nuclear energy will be the main focus.

Given large upfront capital requirements, the financing of nuclear power plants (NPPs) is a major hurdle for most countries. The large size of Generation III (Gen III) nuclear reactors, typically in the range of 1 000-1 700 megawatts (MW), could limit the number of countries in which nuclear power is an option – the usual "rule of thumb" is that a nuclear reactor or any other single generating unit in an electric system should not represent more than 10% of the size of the grid. Smaller reactors such as small modular reactors (SMRs) could target countries or regions with less developed electric grids. This section aims to highlight some of the regional drivers and challenges for the development of nuclear power in major countries/regions that are expected to have significant nuclear power programmes in the future.

Table 1: Summary of characteristics for nuclear power development in various regions

	*Current status and electricity market design**	*Drivers for future developments*	*Key challenges*
OECD Europe	25% electricity production (833 terawatt hours [TWh], with 132 reactors (122 gigawatts [GW]). Four units under construction; three countries phasing out (Belgium, Germany and Switzerland). Average age of fleet is 27 years; about 130 units to be decommissioned by 2050. Poland and Turkey are newcomer countries. The United Kingdom is planning one of the most ambitious new build programmes in the OECD. Mix of liberalised and regulated electricity markets.	Electricity decarbonisation; energy security; competitive electricity costs.	Financing in liberalised markets; developing technology-neutral policy for low-carbon investments; market distortion (due to subsidised renewables) and decreasing wholesale electricity prices; and public acceptance.
United States	19% electricity production (822 TWh) with 100 reactors (105 GW). Five units under construction. Mature nuclear fleet; most reactors licensed for 60 years. Mix of liberalised and regulated electricity markets.	Electricity decarbonisation; competitive electricity costs; security of energy supply; redevelop nuclear industry.	Financing in liberalised markets. Economics of long-term operation in competition with shale gas.
Russian Federation	17% electricity production (172 TWh), with 33 reactors (25 GW). 10 units under construction. Liberalised electricity market.	Policy to increase the share of nuclear electricity by 2030 to 25-30%; strong support for nuclear industry, including for export markets.	Managing the gradual replacement of Reactor Bolshoy Moshchnosti Kanalnyy (RBMK) reactors (nearly half the current electricity production) with Gen III Water-Water Energetic Reactor (VVER) reactors.

Table 1: Summary of characteristics for nuclear power development in various regions (continued)

	*Current status and electricity market design**	*Drivers for future developments*	*Key challenges*
Japan and Republic of Korea	11% electricity production (148 TWh), with 71 reactors (66 GW) All of Japan's 48 reactors are presently idle. Seven units under construction (two in Japan, five in the Republic of Korea). Regulated electricity market.	Energy security; electricity decarbonisation; competitive electricity costs; strong support for nuclear industry, including for export markets.	Public acceptance. Restart of Japan's nuclear fleet.
China, People's Republic of	2% electricity production (117 TWh), with 20 reactors (17 GW). 29 units under construction. Regulated electricity market.	Energy security; rapid growth in electricity demand; stable future electricity costs; local pollution concerns; strong support for nuclear industry.	Public acceptance; developing NPPs inland; domestic supply chains.
India	3% electricity production (32 TWh), with 21 reactors (5.8 GW). Six units under construction. Regulated electricity market.	Energy security; strong electricity demand growth; stable future electricity cost.	Public acceptance; financing; foreign vendors access to market (Indian nuclear liability regime).
Other developing Asian countries	Bangladesh and Viet Nam preparing for construction. Thailand and Indonesia have plans but are not yet committed. Malaysia is studying the feasibility of an NPP. Philippines built a reactor that was mothballed. Regulated electricity markets.	Energy security; diversification and strong electricity demand growth.	Setting up regulatory and other infrastructure; creating a skilled labour force; financing; public acceptance.
Middle East	One reactor in operation in Iran (1 GW), two more units planned. Two units under construction (out of four planned) in the United Arab Emirates. Up to 17 GW planned in Saudi Arabia. Other countries (Jordan, Egypt) considering nuclear option. Regulated electricity markets.	Strong electricity demand growth; stable future electricity costs; saving oil/gas reserves for export markets.	Setting up regulatory and other infrastructure, and training staff; financing for non-oil/gas-rich states; desalination.

* Values in parenthesis are shown for electricity generation in TWh and installed capacity in GW at the end of 2013.

OECD Europe

In OECD Europe, country policy on nuclear development varies widely with Belgium, Germany and Switzerland phasing out nuclear (in 2025, 2022 and 2035 respectively), while the Czech Republic, Finland and Hungary plan to increase their nuclear capacity. The United Kingdom has a significant new build programme (on the order of 15 GW by the late 2020s) to replace retiring plants. Nuclear newcomer countries such as Poland and Turkey are expected to have their first nuclear reactors in operation by the early 2020s. France, which today generates 75% of all its electricity from nuclear, still plans to reduce this share to 50% by 2025 while proposing to maintain nuclear capacity at its present level. Former nuclear country Lithuania is planning to build a new nuclear plant by the early 2020s.

For many countries in OECD Europe, the main focus for nuclear development will be on long-term operation and the eventual replacement of ageing fleets. While 30% of the nuclear reactors currently in operation globally are in OECD Europe, the region only accounts for four of the 70 nuclear reactors currently under construction (two Gen III EPR reactors and two Gen II VVER 440 reactors). Approximately half of the 132 reactors operating today are more than 30 years old, and many utilities are planning and investing in long-term operation as well as power uprates while regulators are assessing on a case-by-case basis whether these reactors can operate for another 10 years or more. Many reactors will be shut down and decommissioned in the next decades, probably at a higher rate than new build construction, and nuclear could see its share of total generation decline. This base-load capacity will be partially offset by renewable power, but also by increased gas and coal power generation, which would lead to higher CO_2 emissions from the power sector.

Although public acceptance of nuclear power is low in several OECD Europe countries, in others, such as in the United Kingdom, nuclear power is perceived as an important option for energy and electricity security as well as a key contributor to decarbonising the power sector. Europe's nuclear industry is mature, has strong well-functioning regulatory systems, and significant R&D capacities with highly experienced and skilled staff. These advantages make the development of nuclear power particularly attractive for the region.

With growing shares of variable renewables in Europe spurred by renewable feed-in tariffs (though many countries are now revising these tariffs downwards as they have proven to be very costly), the challenges of developing nuclear will be complicated by the need for more flexibility and load-following capacity. NPPs have the capacity to load follow to some extent, as has been demonstrated for many years in France and Germany, and new designs also comply with flexibility requirements. Compared to base-load operation, load following could impact the economics of nuclear plants and undermine the profitability of nuclear projects unless operators are adequately paid for services to the grid. The introduction into the grid of large amounts of renewable electricity has also led to falling wholesale prices, which affect the profitability of dispatchable technologies, including NPPs. As a consequence, many gas-fired power plants (i.e. those having the highest marginal costs) have been mothballed, with the market capitalisation of Europe's utilities deteriorating over the last decade. This poses a challenge to future investments and profitability of dispatchable technologies. Governments will need to help manage these risks through policy mechanisms that can help to provide predictability on electricity prices.

United States

The United States has the largest nuclear fleet of any country in the world. The first new build projects in more than 30 years are currently underway at the VC Summer and Vogtle sites in Georgia and South Carolina (each with two Gen III AP1000 units), with the first unit expected to be operating by the end of 2017. All new build projects in the country have been limited to regulated electricity markets, which are more favourable in terms of providing a stable long-term policy framework for capital-intensive projects such as nuclear, for they allow utilities to pass construction costs on to customers through rate adjustments.

In the absence of new build projects, significant power uprates[3] have occurred in the United States that have helped to increase capacity by over 6 GW between 1977 and 2012. The potential for further uprates is limited and expansion of nuclear generation will rely essentially on new builds. Shale gas development, and the resulting low energy prices, has posed additional challenges to the development of nuclear power as cheap gas has led to rapid growth of natural gas combined-cycle plants. Four nuclear reactors shut down in 2013: Crystal River, Kewaunee and San Onofre units 2 and 3. Kewaunee was shut down for economic reasons, Crystal River due to the cost of repairs to the containment, and San Onofre 2 and 3 due to regulatory uncertainty following problems encountered after the replacement of the units' steam generators. Another reactor, Vermont Yankee, was shut down in December 2014 after 42 years of operation, allegedly for lack of competitiveness and in spite of having received a licence renewal. It is also possible that more reactors could be taken out in the coming years because of unfavourable economics. However, gas

3. "Power uprate" is the term used when an existing reactor is modified to generate more power above its nominal output size.

prices are expected to increase in the mid to long term, making nuclear more attractive, particularly if tougher carbon dioxide (CO_2) emissions standards are also implemented.

There is strong interest in the United States to redevelop its nuclear industry, and particular attention has been focused in recent years by the US Department of Energy on the development of SMRs. SMRs could potentially replace coal-fired power plants that will need to shut down because of new, strict regulations on air pollution from the Environmental Protection Agency. Recently, however, the outlook for the deployment of SMRs has been revised, with some leading SMR design companies reducing developing efforts since no near-term deployment is expected in the United States.

Japan and Republic of Korea

Unlike the United States and Europe, which have generally struggled to build new nuclear plants on time and to budget, both Japan and the Republic of Korea were able to maintain successful new build programmes with impressive construction times thanks to sustained construction programmes over the last decades, increased modularity of designs, and well-managed supply chains. This contrasts with the situation in the United States and in Europe, where the last nuclear construction projects to be completed were launched in 1977 and 1991 respectively. With the exception of the two reactors currently under construction, prospects for new build in Japan are unclear and probably limited, given low public acceptance for nuclear after the Fukushima Daiichi accident and the challenge of restarting its nuclear plants as they await regulatory and local political approval. The government hopes that it will be able to restart several reactors at the beginning of 2015.

The Republic of Korea currently has 20.7 GW of nuclear capacity, accounting for 27% of total electricity generation in 2013. To reduce reliance on imported fossil fuels and to enhance energy security, the country has, for a long time, had a strategic goal to increase the share of nuclear generation. However, after the Fukushima Daiichi accident, a more moderate policy has been put forward which will see nuclear capacity increase up to 29% of the total electricity generation capacity by 2035, down from a previous target of 41%. With average capacity factors in recent years of 96.5%, the Republic of Korea has developed strong operating experience and competence. In 2009, the Republic of Korea won its first export contract from the United Arab Emirates and hopes to expand exports to other Middle East countries and Africa.

Under the terms of its co-operation agreement with the United States (the 123 Agreement), the Republic of Korea is currently prohibited from uranium enrichment and reprocessing activities, which constrains its ability to develop the full fuel cycle. If an agreement were reached, the ability to reprocess spent fuel would allow it to increase energy from its imported uranium by 30% and also reduce the amount of high-level waste.

Russian Federation

With Japan's nuclear fleet idle, the Russian Federation is currently the third largest nuclear power country – behind the United States and France – with 33 reactors in operation and a total installed capacity of 25 GW. The State Atomic Energy Corporation, Rosatom, is also one of the leading providers of nuclear technology globally with extensive industry experience. Most of Russia's reactors are being considered for lifetime extensions; to date, 18 reactors with total capacity of over 10 GW have received 15- to 25-year licence extensions. VVER reactors, which comprise half of the fleet, are also likely to be uprated, which would provide an additional 7% to 10% capacity. The oldest VVERs and all of the operating RBMK reactors are expected to be retired by 2030.

The main drivers for future nuclear energy development in Russia include the replacement of ageing reactors due to be decommissioned and the development of additional new capacity to increase the share of nuclear electricity from 17% today to 25% to 30% by 2030. Increased nuclear generation would also free up natural gas for export. Currently, there are ten reactors with a total installed capacity of 9.2 GW under construction (one of them, Rostov 3, was actually connected to the grid on 29 December 2014) and a further 24 reactors (about 29 GW) planned by 2030, including advanced Gen III VVER reactors and sodium-cooled fast neutron reactors, and a BN-800 under construction that reached criticality in June 2014. Russia has invested significantly in nuclear R&D and is one of the leading developers of fast neutron reactors and of small floating reactors that provide nuclear power to remote areas. Two floating SMR KLT-40S units on the Lomonosov barge are under construction in Russia.

People’s Republic of China

The People’s Republic of China is the fastest growing nuclear energy market in the world. According to the “Mid- to Long-Term Nuclear Development Plan (2011-2020)” issued in October 2012, China aims to have 58 GW (net) in operation by 2020, and 30 GW under construction at that time. China’s nuclear energy programme began in the 1980s, and its first reactor started commercial operations in 1994. Of the 27 units currently under construction, eight are of Gen III design (four AP1000, two EPR, two VVER), 18 are of Gen II design, and one is a prototype reactor with Gen IV technology features. The country’s nuclear fleet is based on technology developed nationally as well as technologies transferred from Canada, France, Japan, the Russian Federation and the United States.

Following the Fukushima Daiichi accident, China revised its targets for nuclear from 70-80 GW to 58 GW by 2020 with another 30 GW under construction. Safety requirements were also enhanced, and only Gen III designs will now be approved in China. The Hualong-1 and CAP1000 designs will represent the bulk of the new developments. The latter design is based on Westinghouse’s AP1000 design. China will deploy the technology domestically, including on inland sites, and hopes to begin exporting the technology with a larger version, the CAP1400, also being designed. China’s nuclear programme has evolved significantly in the last decade with more rapid development of domestic reactor designs and domestic supply chains. The country has made an impressive transition from importing nuclear technology to developing local capabilities that have already been exported.

Local air pollution concern from coal-fired plants is one of the main drivers today of nuclear power development in China. Other key drivers include improved energy security, and stable and economic electricity production costs. With China’s impressive rates of economic development and continued urbanisation, the demand for electricity is expected to continue its rapid ascension. The attractive economics of nuclear power, stable base-load operations and siting near the main demand centres along the Eastern coast, combined with its environmental benefits, make it an attractive alternative to coal-fired power.

Continued training and development of a skilled nuclear workforce focused on safety culture will be the biggest challenge to meeting China’s ambitious nuclear targets. Also, for the deployment of NPPs inland, the issue of cooling on rivers with degraded water quality due to pollution or low flow rates will need to be addressed.

India

India has been developing nuclear energy technology since the 1950s, and its first reactor began operations in 1969. As it is not party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), India’s nuclear industry has essentially evolved indigenously, with a longer-term objective of developing nuclear power reactors that can operate on the thorium cycle, the country having significant thorium reserves and very little natural uranium reserves. India has a long history of nuclear energy R&D and is currently constructing a sodium-cooled fast neutron reactor which could operate on the thorium cycle. India expects to have an estimated 20 GW of nuclear capacity by 2020 and has announced ambitious targets to increase the share of nuclear electricity in the following decades. It is estimated that India could become the third-largest nuclear energy country in the world by 2040.

Rapid economic and population growth, combined with increased urbanisation, are expected to fuel strong electricity demand. The need for reliable base-load electricity at competitive costs is the main driver for nuclear energy development in India. Other drivers include enhanced energy security and local pollution concerns. Financing and public acceptance are challenges that will need to be overcome as India seeks to expand its nuclear power supply. Opening the Indian nuclear market to foreign investment and technology is another challenge. Although the country has seen two Gen III Russian VVER reactors built at the Kudankulam site (in the frame of an intergovernmental agreement), other vendors have not yet penetrated the market. Many co-operation agreements have been signed and joint ventures set up between engineering and supply chain companies to prepare the ground for future projects with high levels of localisation. Remaining difficulties include the Indian nuclear liability legislation adopted in 2010 – more specifically, whether it is consistent with the internationally accepted nuclear liability principles – and the cost of foreign nuclear technologies.

Middle East

The Bushehr NPP in Iran that began commercial operation in September 2013 was the first nuclear power plant to operate in the Middle East. The United Arab Emirates (UAE) is the most advanced newcomer country in the region, with construction started on three of four units of the Korean-designed APR1400 (the construction of the third unit stated in 2014), which will have a total installed capacity of 5.6 GW, at the Barakah site. The first unit is expected to start generating electricity in 2017, and the final unit is scheduled for operation in 2020. With electricity demand expected to exceed 40 GW by 2020, nearly doubling 2010 levels, the UAE has identified nuclear energy as an important source of future electricity supply. Electricity needs are currently met almost exclusively by natural gas. As a proven, cost-competitive and low-carbon source of electricity, UAE is developing nuclear power to provide a significant source of base-load electricity.

With rapid electricity demand growth expected over the next decades, some countries in the region are looking at nuclear power to improve energy security through energy diversification and also to reduce domestic consumption of natural gas and oil, freeing up more resources for export. In addition to rising electricity demand, the region's rising demand for fresh water makes desalination from nuclear an attractive opportunity in the mid to long term. Saudi Arabia has announced plans to construct 16 nuclear reactors with a total capacity of 17 GW by 2032 and hopes to have its first reactor operating by 2022. Jordan is also planning the construction of up to two reactors and signed an agreement with Russia in October 2013.

For the Middle East, the main challenges in developing nuclear power will be in setting up the needed nuclear infrastructure and training, as well as the education of a highly skilled nuclear work force. The region is working closely with the IAEA to set up the necessary infrastructure and the UAE's implementation of the IAEA milestones has been recognised as exemplary (see Box 4). For oil- and gas-rich countries in the region, overcoming these challenges has been facilitated by the significant resources made available to attract foreign experts, who provide training thereby passing

Box 4: IAEA Milestone Approach for national nuclear infrastructure: UAE experience (Case study 4)

To help guide newcomer countries in the development of a nuclear energy programme, in 2007 the IAEA released a publication outlining the major milestones to be achieved in establishing the required infrastructure for the development of nuclear power.* This guideline, known as the IAEA Milestone Approach, consists of 19 elements that are central to the development of a nuclear programme. Each element contains detailed conditions that should be met over three milestone phases. The UAE has worked in close partnership with the IAEA in the development of its nuclear energy programme and the IAEA has provided support on legal and regulatory framework, licensing, infrastructure and capacity building, safeguards implementation and peer reviews. On the request of the UAE, the IAEA undertook an Integrated Nuclear Infrastructure Review (INIR) in January 2011.

The review team concluded that the UAE had accomplished all of the conditions to enter phase 2. The review team recognised 14 good practices, which other countries developing nuclear infrastructure should consider. The UAE's experience with developing a national nuclear infrastructure and its establishment of a regulatory framework and system has been impressive. However, it should be noted that the UAE's success implementing its nuclear programme in such a relatively short timeframe – nine years from the publishing of its nuclear policy to commissioning of the first unit, as opposed to the 10-15 years estimated by the IAEA – benefited from the ability to hire personnel with a cumulative experience of over 100 years in the Federal Authority for Nuclear Regulation (FANR) and the Emirates Nuclear Energy Corporation (ENEC), the owner and operator of the future plant. This was made possible by the availability of significant financial resources from the government. New nuclear countries are advised to work closely with the IAEA and other relevant organisations and countries with extensive operating experience in the development of their programmes.

* Further details of the IAEA milestones to be found at www-pub.iaea.org/MTCD/publications/PDF/Pub1305 _web.pdf.

their expertise and knowledge on so that local expertise and capacity are developed. However, there remains some concern about the availability of highly skilled and experienced nuclear experts if nuclear programmes are to develop extensively in the region.

Other developing Asian countries

Among developing Asian countries, Viet Nam is the most advanced with respect to its nuclear programme. The country has committed plans for developing nuclear and is in the process of developing its legal and regulatory infrastructure. Viet Nam is planning at least 8 GW of nuclear capacity by the end of the 2020s and hopes to have a first unit in operation by 2023. Bangladesh is also planning to start the construction of its first reactor by 2015. Thailand and Indonesia have well-developed plans but have yet to make a firm commitment, while Malaysia is currently studying the feasibility of developing an NPP. The Philippines, which began construction of a nuclear plant in the late 1970s (never completed), is suffering from electricity shortages and high electricity costs, and is still considering nuclear as a possible future option. Singapore is monitoring the progress of nuclear energy developments to keep its options open for the future. In these countries, SMRs could potentially offer an alternative to larger Gen III units, as they would be more easily integrated in small electricity grids.

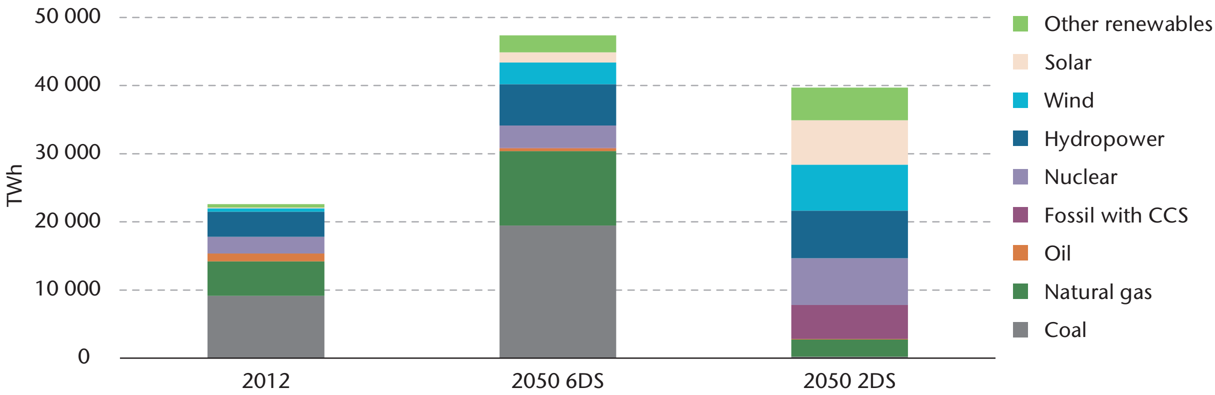
Strong expected electricity demand growth and stable electricity production costs are the main drivers for nuclear development in the region. For Viet Nam, Thailand and the Philippines, which import the majority of their energy needs, nuclear would help to improve energy security and reduce dependence on imported fossil fuels. For these newcomer countries, the development of the necessary nuclear regulatory infrastructure, a skilled nuclear workforce, financing, and public acceptance are major challenges to the development of nuclear energy. International collaboration to support the development of a regulatory infrastructure, as well as training and capacity building to develop local expertise, are needed.

Vision for deployment to 2050

The vision presented in this *Roadmap* is based on the *Energy Technology Perspectives 2015* (*ETP 2015*) (IEA, 2015) 2°C Scenario (2DS) which calls for a virtual decarbonisation of the power sector by 2050 (see Box 5). A mix of technologies including nuclear, carbon capture and storage, and renewables will be needed to achieve this decarbonisation. In the *ETP 2015* 2DS, the share of nuclear power in global electricity production is projected to rise from 11% in 2011 to 17% in 2050. Renewables will account for the largest share of production at 65%, with variable renewables supplying 29% of total global electricity production (see Figures 3). The high share of variable renewables, which in some countries reaches well over 40%, significantly changes the operating environment of nuclear. Nuclear power is traditionally operated to meet base-load demand, although it can be operated in load-following mode, with less flexibility than gas-fired peaking plants.

Regionally significant differences exist in terms of nuclear energy's contribution to decarbonising the electricity sector with many countries such as Finland, Russia and South Africa projecting shares of nuclear at 20% or above in 2050 under the 2DS. The Republic of Korea and countries in Eastern Europe have the highest share of nuclear reaching nearly 60% and 55% respectively. The share of nuclear in the three largest nuclear producers – China (19%), India (18%) and the United States (17%) – show similar or slightly higher shares to those reported globally.

Figure 3: Electricity production by technology in the 6DS and the 2DS



Revised targets for nuclear compared with the 2010 *Roadmap*

Since the release of the nuclear energy *Roadmap* in 2010, two major factors have led to a downward revision of the *ETP 2015* 2DS projections for growth in nuclear power capacity at the global level. The first is the Fukushima Daiichi accident, which led many countries to re-evaluate the role of nuclear power within their electricity mix, and the second is the faster-than-anticipated declines in busbar costs[4] of solar photovoltaics (PV) and onshore wind. Enhanced safety standards for nuclear plants following Fukushima Daiichi, as well as an increase in raw materials prices, design complexity, and supply chain quality requirements, have led the assumptions for nuclear costs to be revised upwards by about 20% compared with 2010 estimates. These factors, combined with reductions in the costs assumed for solar PV and onshore wind, have impacted the competitiveness of nuclear energy. As a result, the *ETP 2015* 2DS projections for nuclear power capacity in 2050 were revised to just over 930 GW, compared with 1 200 GW in the 2010 Nuclear *Roadmap*. Despite this downward revision, growth in nuclear still represents more than a doubling of nuclear capacity, which in 2014 was approximately 396 GW.

Under the *ETP 2015* 2DS, growth in nuclear capacity will be driven by non-OECD countries (see Figure 4). Currently, OECD member countries, Russia and the Ukraine account for over 90% of

4. Busbar costs, also known as levelised costs of electricity, refer to total costs of electricity generation including, fuel costs, operating and maintenance costs as well as total costs of financing.

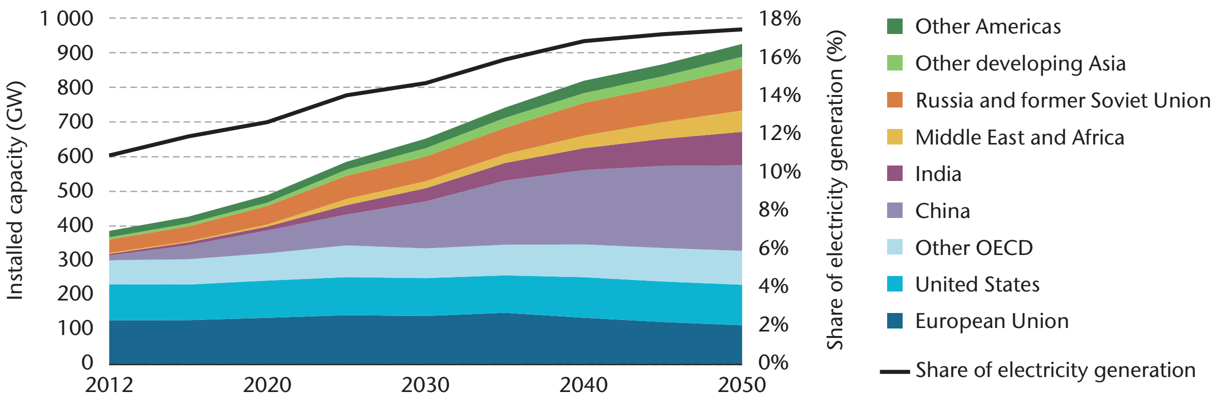
Box 5: *Energy Technology Perspectives 2015* 6DS and 2DS

This *Roadmap* is based on the IEA *ETP 2015* analysis, which describes diverse future scenarios for the global energy system in 2050. The base case scenario, the 6 degrees Celsius scenario (6DS), which is largely an extension of current trends, projects that energy demand will almost double during the intervening years (compared to 2009), and associated CO_2 emissions will rise even more rapidly, pushing the global mean temperature up by 6°C.

The IEA *ETP* 2DS describes how technologies across all energy sectors may be transformed by 2050 to give an 80% chance of limiting average global temperature increase to 2°C. It sets the target of cutting energy-related CO_2 emissions by more than half by 2050 (compared with 2009) and ensuring that they continue to fall thereafter. The 2DS acknowledges that transforming the energy sector is vital but not the sole solution: the goal can only be achieved if CO_2 and greenhouse gas emissions in non-energy sectors (such as agriculture and land-use change) are also reduced. The 2DS is broadly consistent with the *World Energy Outlook* 450 Scenario through to 2035.

The model used for this analysis is a bottom-up TIMES (The Integrated MARKAL-EFOM System) model that uses cost optimisation to identify least-cost mixes of technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The *ETP* global 28-region model permits the analysis of fuel and technology choices throughout the energy system, including about 1 000 individual technologies. The TIMES model is supplemented by detailed demand-side models for all major end uses in the industry, buildings and transport sectors.

Figure 4: Nuclear generation capacity in the 2DS by region



total installed capacity. In 2050, these countries combined will see only a modest increase in capacity from 350 GW to 400 GW. With a number of countries planning to phase out nuclear and with older plants reaching the end of their operating lifetimes in the next decades, the EU will see its capacity decline from 2040, while in Russia and the Republic of Korea, which show the largest increase in growth, capacity will more than double by 2050.

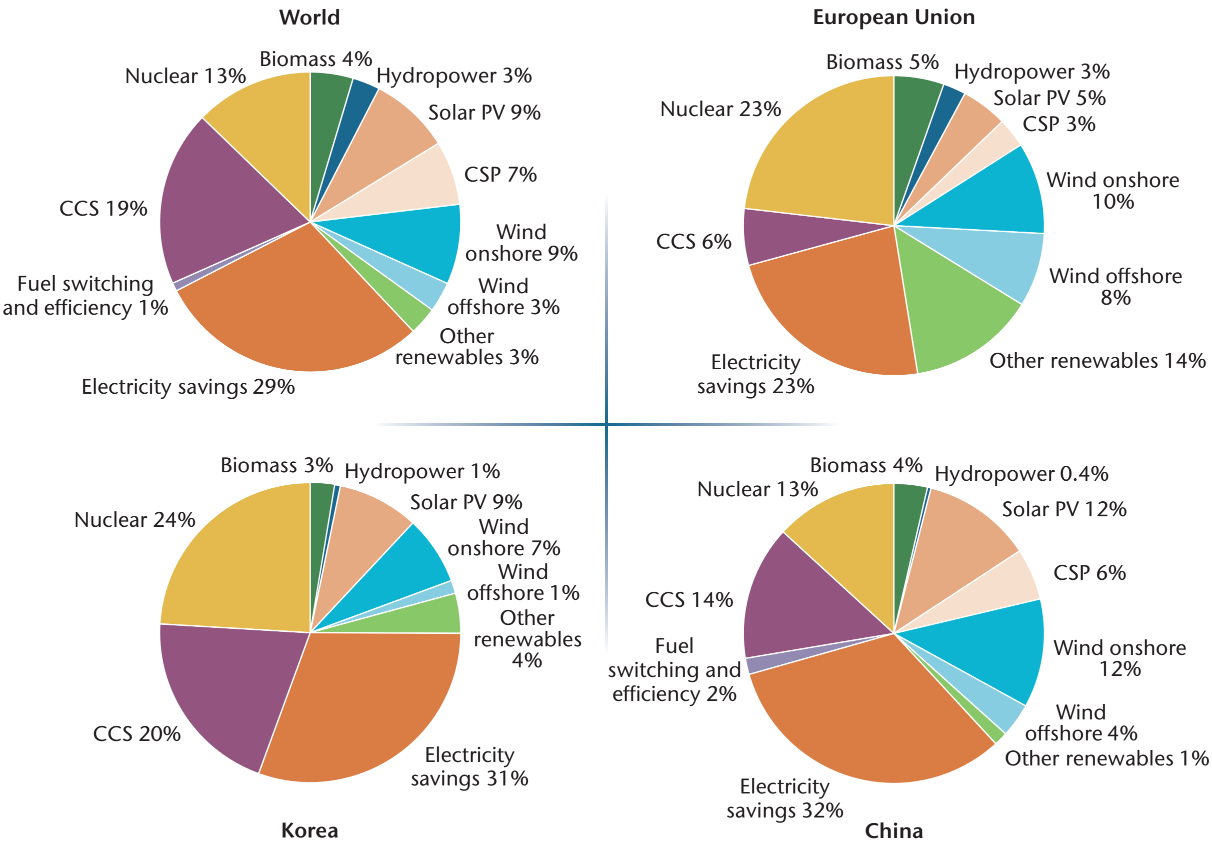
Growth in nuclear capacity will be led by China, which under the 2DS could surpass the United States by 2030 and, with 250 GW of nuclear, would have more than twice the installed capacity in the United States in 2050. India, which represents the second-fastest growing market for nuclear, would have about 100 GW of capacity in 2050, making it the third-largest market for nuclear after the United States. Other growth markets for nuclear include the Middle East, South Africa and ASEAN (Association of Southeast Asian Nations) countries.

Emissions reductions from nuclear

Nuclear energy currently contributes to a reduction of CO_2 emissions from the power sector of about 1.3 to 2.6 gigatonnes (Gt) of CO_2 every year, assuming it replaces either gas- or coal-fired generation. It is estimated that since 1980 the release of over 60 Gt CO_2 has been avoided thanks to nuclear power.[5] The contribution of nuclear energy to decarbonising the electricity sector would result in annual CO_2 emission reductions of 2.5 Gt CO_2 in the 2DS compared with the 6DS (see Figure 5). Globally, this represents 13% of the emissions reduction needed in the power sector with the contribution in different regions varying from as high as 24% in the Republic of Korea to 23% in the European Union and 13% in China. Nuclear clearly plays an important role in providing reliable, low-carbon electricity in most regions of the world.

5. The avoided CO_2 emissions were calculated by replacing nuclear generation by coal-fired generation.

Figure 5: Emissions reduction in the power sector in 2050 in the 2DS



Global investment in nuclear to 2050

An estimated investment cost of USD 4.4 trillion would be needed to reach the 930 GW of installed capacity under the *ETP 2015* 2DS by 2050. About 40% of these investments (USD 2.0 trillion) would be required in OECD member countries to extend lifetimes of existing plants, to replace retiring plants and to add new capacity. China, which accounts for one-third of capacity in 2050, would need to invest approximately a quarter of the overall investment cost, or just over USD 1 trillion in new nuclear capacity.

Table 2: Investment needs in the 2DS (USD billion)

Country/region	*2012-20*	*2021-30*	*2031-40*	*2041-50*	*2010-50*
United States	90	216	288	118	713
European Union	113	168	259	164	704
Other OECD	83	153	178	162	577
China	209	309	350	157	1 025
India	21	120	114	158	412
Middle East and Africa	18	70	82	133	303
Russia and former Soviet Union	96	94	176	182	548
Other developing Asia	14	68	40	31	153
Other Americas	12	5	3	6	25
World	656	1 210	1 493	1 115	4 473

Regional costs assumptions for nuclear

The lower share of total investments compared to capacity in China reflects the regional differences in overnight costs[6] for nuclear power. China's average overnight cost of approximately USD 3 500/kilowatts (kW) is less than two-thirds of the European Union's cost of USD 5 500/kW. Costs in the United States are about 10% lower than the European Union, but still 30% higher than in China and India, and 25% above the Republic of Korea. Higher costs in the European Union and the United States can be attributed to a lack of recent experience in building new nuclear plants compared to Asia, as well as to higher labour costs for engineering and construction. In the 2DS, 2050 assumptions for overnight costs of nuclear in the United States and European Union are estimated to decline somewhat, reaching levels closer to those in the Republic of Korea, while costs in Asia are assumed to remain flat.

6. Overnight costs include the cost of site preparation, construction and contingency costs.

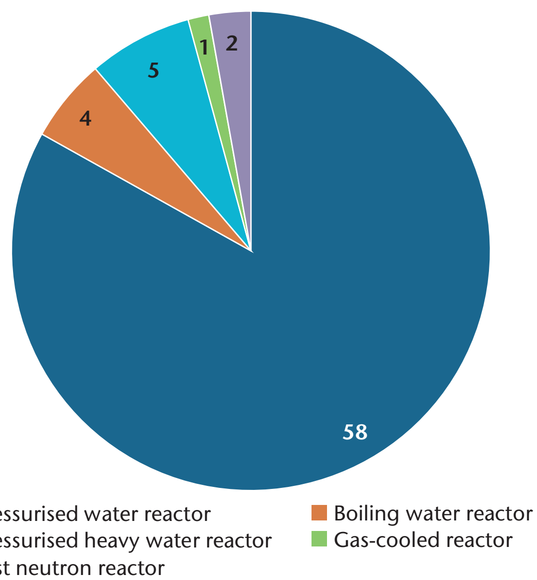
Nuclear energy technology development: Actions and milestones

Reactor technology

This Roadmap recommends the following actions:	*Proposed timeline*
Governments to recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met. Clearer policies are needed to encourage operators to invest in both long-term operation and new build so as to replace retiring units.	2015-30
R&D in ageing of systems and materials is needed to support safe, long-term operation of existing nuclear power plants (NPPs) for 60 years operation or more.	Ongoing
Vendors to optimise Gen III designs to improve constructability and reduce costs. The learning rate from new build construction needs to be accelerated by rapidly integrating lessons learnt from FOAK projects (design optimisation, project management, supply chain, interactions with regulators) to ensure that NOAK plants are built on time and to budget.	Ongoing
To open up the market for small modular reactors (SMRs), governments and industry should work together to accelerate the development of SMR prototypes and the launch of construction projects (about 5 projects per design) needed to demonstrate the benefits of modular design and factory assembly.	2015-25
Governments to recognise the long-term benefits of developing Generation IV (Gen IV) systems in terms of resource utilisation and waste management, and support R&D and development of at least one or two Fast Neutron Reactor Gen IV prototypes.	2015-30
Public-private partnerships need to be put in place between governments and industry in order to develop demonstration projects for nuclear cogeneration in the area of desalination or hydrogen production.	2015-30
Incorporate feed-back from operation of Gen IV prototypes to develop FOAK Gen IV commercial plants.	2030-40

As of end of December 2014, there were 438 operable nuclear reactors in the world, representing about 396 GW (gross) capacity. Nearly 82% of those reactors are light water reactors (LWRs), 63% of which are pressurised water reactors (PWRs) and 19% boiling water reactors (BWRs). Eleven percent of the world's reactors are pressurised heavy water reactors (PHWRs), operating mainly in Canada (the CANDU technology ["CANada Deuterium Uranium"]) and in India. A little more than 3% of the world's fleet consists of gas-cooled reactors (GCRs), all in operation in the United Kingdom. Most of these will be retired within the next decade. Another 3% consist of graphite-moderated light water-cooled reactors (LWGR), which are better known under their Russian abbreviation RBMK. These reactors are today only in operation in Russia and will probably be retired before the end of the next decade. Finally, 1 out of the 438 reactors is a sodium-cooled fast neutron reactor (FNR), an example of one of the main technologies of future Gen IV reactors, and a further 2 are expected to be connected in 2015.

Figure 6: Reactor types under construction worldwide (2014)



Source: IAEA/PRIS.

Even more interesting are the technology types for the 70 reactors under construction (see Figure 6). Nearly 89% are LWRs, mostly PWRs, with PHWRs representing the second technology of choice (7%), all being built in India with indigenous technology. There are two FNRs under construction, one in Russia (BN-800) and one in India (PFBR), and both are to be connected to the grid in 2015. Finally, there is one GCR under construction, a high-temperature reactor being built in China.

From these trends, one can observe a consolidation of reactor technology towards LWRs. Nearly half the reactors under construction are Gen III LWR reactors, which have enhanced safety features (i.e. systems to mitigate the risk of severe accidents) and improved fuel economy performance compared to the Gen II reactors. There is also a continued but more limited development of PHWR as India continues its domestic programme. PHWRs are also being pursued in other countries as a means to derive additional energy from used PWR and BWR fuel through the development of recycled uranium (RU) and mixed oxides of plutonium and uranium (MOX) advanced fuel cycles. Both China and India are considering PHWR designs for a thorium fuel cycle. Advanced reactors such as FNRs or high-temperature reactors will be developed as well but at a much smaller scale. SMRs will also be developed, especially those that rely on LWR technologies, though their deployment is not expected to be significant by 2030. At that time, one can expect the world's nuclear fleet to be more homogenous than at the present time in terms of reactor technology, with the retirement of all the old GCRs (in the United Kingdom) and LWGRs (in Russia) expected by 2030.

Technological trends that will shape the future of the nuclear fleet include: managing the existing fleet to allow for safe and economical long-term operation; continuous development of Gen III water-cooled technologies with a focus on simplification, standardisation and cost reduction; more innovative development of reactor technologies including SMRs, Gen IV reactors and non-electric applications of nuclear energy to address the need for low-carbon process heat, actinide management, district heating, or desalination. R&D in nuclear fusion will continue for the next decades, but given the challenges still to be addressed, fusion reactors are not expected to be deployed in the first half of this century.

Safety upgrades and long-term operation

Nuclear reactor operators in the world today face two challenges. The first is to implement the recommended safety upgrades that were identified during the post-Fukushima safety evaluations, (with most operators having already started this work). Although the reviews concluded that these reactors were safe and could continue to operate, a number of actions and upgrades were recommended that include the reinforcement of NPPs against major seismic hazards and floods, multiple external events affecting multi-unit sites and severe accidents as well as improved emergency preparedness. Rapid implementation of these safety upgrades under the supervision of nuclear regulators, as well as better information on the safety of NPPs, are necessary to reduce public concern.

The second challenge is to continue to operate reactors economically, especially given the average age of the nuclear fleet. This means that operators have to address long-term operation issues. Provided safety requirements are met, long-term operation is needed to maintain capacity in low-carbon generation and is one of the lowest cost options to produce low-carbon electricity. R&D in ageing and improved safety is needed to support this objective. Research into back-fitting requirements for 60+-year operations is also required. Very often, long-term operation retrofits and safety upgrades can be combined to upgrade NPPs in a cost-effective manner.

In 2013, 316 out of the 434 operating reactors in the world (73%) were more than 25 years old, and many of those could be retired in the coming decades, leading to a dramatic decrease in nuclear capacity. Thus, extending the operating lifetime of reactors to enable them to operate safely beyond their original design lifetime until they are replaced by new reactors[7] is essential to maintaining low-carbon generation capacity. In 2012, the NEA published a report on the *Economics of Long-Term Operation of Nuclear Power Plants* (NEA, 2012b), concluding that, in nearly all cases, continued operation of NPPs for at least a decade more than the original lifetime is profitable, even taking into account the cost of post-Fukushima safety upgrades. However, this can be undermined by market conditions. In the United States, competitiveness of NPPs in deregulated markets

7. *ETP 2015* assumes 60 years for NPPs in the United States and 55 years for other countries, with the exception of NPPs already scheduled to shut down.

is being undermined by the low cost of gas. In Europe, introduction of large shares of renewables is driving down wholesale electricity prices, affecting the competitiveness of dispatchable technologies, nuclear included.

Power uprates have contributed to a significant increase in capacity over the last two decades at a time when new build rates were low – Sweden's current ten-reactor fleet capacity, for instance, was increased to compensate for the closure of two units. The potential for further uprates in the United States and in a number of other countries is now limited, but there is still potential to exploit uprates in other European countries and in Russia.

Regulatory processes to approve the extension of operating reactors' lifetimes vary from country to country, but essentially fall into two classes: periodic safety reviews (i.e. every ten years) or licence renewal. In the United States, where 93 reactors out of 100 in operation at the end of 2013 were more than 25 years old, a regulatory process has been developed under the so-called 10 CFR Part 54 rule, entitled "Requirements for Renewal of Operating Licences For Nuclear Power Plants", published in 1991 and amended in 1995. Environmental impact assessments are also required to examine the possible environmental impacts that could occur as a result of renewing any commercial NPP licence. As of December 2014, 74 reactors in the United States had been granted a licence renewal, allowing them to operate up to 60 years, and the applications for 19 other reactors were under review.

Extensive refurbishment and replacement of equipment is usually carried out as part of the process to extend the lifetime of an existing plant. In addition, a number of technical and scientific studies are necessary to assess the integrity and safety of components and systems that cannot be replaced, such as pressure vessels or containment buildings. Research has been carried out, for instance, by the European network NUGENIA ("NUclear GENeration II and III Association"), or in the United States, by the Electric Power Research Institute and Nuclear Energy Institute (see Box 6), and continues to be performed in the areas of material performance and ageing – for reactors 60 years of age or more – as well as monitoring and equipment qualification.

The prospect of obtaining regulatory approval for long-term operation is not enough to encourage operators to invest in the refurbishment needed to meet safety and performance requirements. There needs to be a clear national policy on long-term operation, whether it is allowed from a political point of view or whether limits are set as to the lifetimes of existing reactors. Some countries have clear policies. In Canada, for instance, the Ontario Long-term Energy Plan has committed to refurbish nuclear units at the Darlington and Bruce Generating Stations, with the potential to renew up to 8 500 megawatts (MW) nuclear capacities over 16 years.

Box 6: Research for extended operation (beyond 60 years) of NPPs (Case study 5)

The current fleet of US NPPs was licensed initially to operate for 40 years. To date, 74 reactors have received 20-year licence renewals and 19 applications are under review. Twenty-four reactors have already passed the 40-year mark and are operating safely and reliably with renewed licences in this extended period. By 2040, it is estimated that half the fleet will turn 60 and, if these reactors are retired, the country might face possible shortages of electricity and will certainly lose diversity of supply. Hence, research is ongoing to develop the technical and scientific knowledge needed to support nuclear plant operation beyond 60 years, up to 80 years or beyond. The Electric Power Research Institute, the US Department of Energy (DOE) (which has an extensive network of national laboratories), and several universities are conducting research on management of ageing in NPPs in order to understand and devise strategies to identify and mitigate the effects. The research is essentially dedicated to the long-lived components that are not replaced during regular refurbishments. These include the containment building and the reactor vessel, and can also include piping and electric cables.

New reactor development

Most of the anticipated growth in nuclear capacity in the coming decades will come with the deployment of "large" Gen III reactors (in the range 1 000-1 700 MW unit size, see Table 3), either PWRs or BWRs, though some deployment of SMRs, PHWRs or Gen IV reactors. Gen III reactors have enhanced safety features and higher efficiency, as well as improved fuel economy compared with Gen II reactors.

Only evolutionary changes and innovations in Gen III technology are foreseen up to 2050, with efforts to simplify and standardise the designs. This will help to improve their constructability and modularity which should reduce costs and shorten construction spans.

Following the Fukushima Daiichi accident, the safety of existing reactors was assessed by regulators for the type of events that led to the accident, as well as for other beyond-design-basis accident conditions and safety upgrade measures taken to improve the resistance of these plants. For Gen III reactors, very few design changes were recommended, since these plants already take severe accidents into account in their design. More focus is being placed, however, on the qualification of systems designed to mitigate severe accidents, and more research on severe accident management is being performed, in particular on decay heat removal, core degradation mechanisms and hydrogen risk management.

Table 3: Examples of Gen III reactor designs

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
AREVA	France	EPR	PWR	1 600	0	4 (Finland, France, China)
AREVA/MHI	France/ Japan	ATMEA	PWR	1 100	0	0
CANDU Energy	Canada	EC6	PHWR	700	0	0
CNNC-CGN	China	Hualong-1	PWR	1 100	0	0
GE Hitachi – Toshiba GE Hitachi	United States/ Japan	ABWR ESBWR	BWR BWR	1 400-1 700 1 600	4 (Japan) 0	4 (Japan, Chinese Taipei) 0
KEPCO/KHNP	Korea	APR1400	PWR	1 400	0	7 (Republic of Korea, United Arab Emirates)
Mitsubishi	Japan	APWR	PWR	1 700	0	0
ROSATOM	Russia	AES-92, AES-2006	PWR	1 000-1 200	1	10 (Russia, Belarus, China, India)
SNPTC	China	CAP1000, CAP1400	PWR	1 200-1 400	0	0
Westinghouse/ Toshiba	United States/ Japan	AP1000	PWR	1 200	0	8 (China, United States)

*: As of 31 December 2014.

Cost reduction of Gen III reactors is an objective shared by all vendors and operators which can be achieved through a number of options including design simplification, standardisation, improved constructability, modularity and supply chain optimisation, as well as by taking full advantage of lessons learnt during the FOAK projects.

In terms of operation, base-load power production is the most cost efficient way to operate an NPP. Having large shares of variable renewable electricity production will require more thermal plants to deal with backup and provide flexibility. Thus, there needs to be a better integration of nuclear, thermal and renewables from an electricity system and market perspective, to avoid loss of production and improve cost efficiency, taking into account the peculiarities of each technology. Operators supply electricity to customers in a competitive marketplace, where overall cost is an important parameter.

In the long term, there is also a need to take into account possible changes in the climate to ensure that NPPs are resilient both in the face of extreme weather events as well as under higher ambient air and cooling water conditions. Issues such as increased risk of flooding through intense precipitations, storms or sea level rise need to be addressed, by designing appropriate barriers and selecting less exposed sites. The availability and quality of water for cooling of NPPs will also be a matter for concern, especially for inland plants located on rivers that use once-through cooling. High cooling water temperatures reduce the thermal efficiency and electrical output of NPPs, and this can be compensated by more efficient heat exchangers. Closed cycle cooling or advanced cooling technologies that reduce the consumption of water, as well as the use of non-traditional sources of water (treated waste water, for instance), will need to be developed.

SMRs

SMRs could perform a useful niche role as they can be constructed in regions or countries that have small grid systems that cannot support larger NPPs, or they can address specific non-electric applications such as district heating or desalination. However, the economics of SMRs have yet to be proven. Interest in SMRs is driven both by the need to reduce the impact of capital costs and to provide power and heat in small or off-grid systems. For some SMR designs, the use of passive safety systems also represents an attractive feature, allowing, for example, decay heat removal in the case of accidents without the need for operator intervention. The creation of a market for SMRs will first require successful deployment of FOAK reactors in the vendor’s country before other countries will consider deploying the technology. Unless governments and industry work together in the next decade to accelerate the deployment of the first SMR prototypes that can demonstrate the benefits of modular design and construction, the market potential of SMRs may not be realised in the short to medium term.

Table 4: Examples of small modular reactor designs (under construction or with near-term deployment potential)

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
Babcock & Wilcox	United States	mPower	PWR	180	0	0
CNEA	Argentina	CAREM-25	PWR	25	0	1
CNEC	China	HTR-PM	HTR	210	0	Twin units
CNNC	China	ACP-100	PWR	100	0	0
KAERI	Korea	SMART	PWR	110	0	0
NuScale	United States	NuScale SMR	PWR	45	0	0
OKBM	Russia	KLT-40S	Floating PWR	2x35	0	Twin units (one barge)

*: As of 31 December 2014.

There are different types of SMRs, some already under construction in Argentina (CAREM), China (HTR-PM) or Russia (KLT-40S), others with near-term deployment potential such as mPower, NuScale, the Westinghouse SMR or the Holtec design in the United States, and SMART in the Republic of Korea, and others with longer-term deployment prospects (liquid metal-cooled reactor technologies) including designs of dedicated burner concepts for countries having to dispose of plutonium stockpiles. The KLT-40S (for electricity generation, heat processing and possibly desalination) are mounted on the Lomonosov barge and suited to isolated coastal regions or islands.

Table 4 gives an overview of SMRs under construction or with near-term deployment potential. SMRs can address complementary markets (countries with small grids, and/or geographical constraints, or cogeneration applications), and could be competitive with other forms of generation suitable for those markets, depending on the manufacturing and construction rates. The competitiveness of SMRs compared with large nuclear reactors, in countries where both could be accommodated, needs to be assessed in a systems approach, where both generation and grid requirements are accounted for.

The United States has had a very active SMR programme over the last years. Its objective is to accelerate the timelines for the commercialisation and deployment of these technologies by developing certification and licensing requirements for US-based SMR projects through cost-sharing agreements with industry partners, as well as to resolve generic SMR issues. SMRs in the United States could replace coal-fired power plants that do not meet newly released emissions regulations. Two SMR technologies have been selected so far by the DOE, Babcock & Wilcox's (B&W) mPower design and Nuscale's SMR design. Though industry was hoping to find customers for near-term deployment of their SMR designs, it seems that customers in the United States are not yet ready for SMR technology. B&W has reduced the scale of the mPower development programme, while Westinghouse, which also developed an SMR design, is concentrating its development efforts on the AP1000 design.

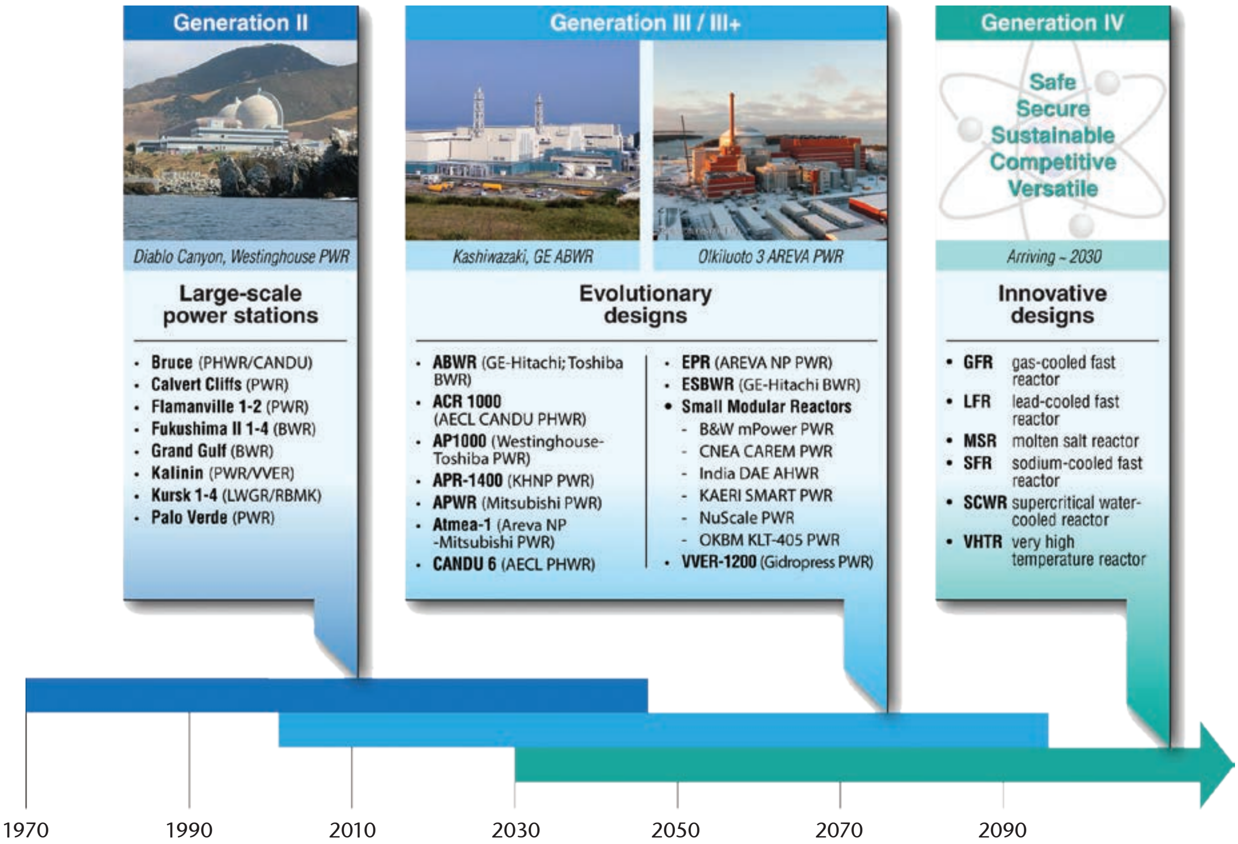
Generation IV reactors

The Generation IV International Forum (GIF), a framework for international co-operation in R&D for the next generation of nuclear energy systems, was launched in 2001 by Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, the United Kingdom and the United States. Switzerland, the European Commission, China and the Russian Federation have since joined this initiative. The goals set forward for the development of Gen IV reactors are improved sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection. GIF published *A Technology Roadmap for Generation IV Nuclear Energy Systems* in 2002, which describes the necessary R&D to advance six innovative designs selected as the most promising: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR). A *Technology Roadmap Update for Generation IV Nuclear Energy Systems* was published in 2014 (GIF, 2014), and assesses progress made in the first decade, identifies the remaining technical challenges and the likely deployment phases for the different technologies. It also describes the approach taken by GIF to develop specific safety-design criteria for Gen IV reactors, building on lessons learnt from the Fukushima Daiichi accident.

According to the GIF 2014 *Technology Roadmap Update for Generation IV Nuclear Energy Systems*, the first Gen IV technologies that are the most likely to be demonstrated as prototypes are the SFR, the LFR, the supercritical water-cooled reactor and the VHTR technologies. Benefits of fast reactors include a better use of the fuel – for the same amount of uranium, fast reactors can produce 60 or more times the energy than Gen III LWRs by multi-recycling of the fuel – and improved waste management by reducing long-term radiotoxicity of the ultimate waste. The main advantage of the SCWR is its improved economics compared to LWRs, which is due to higher efficiency and plant simplification. The benefits of VHTRs include the passive safety features of high-temperature reactors and the ability to provide very-high-temperature process heat that can be used in a number of cogeneration applications, including the massive production of hydrogen.

As seen in Figure 7, the start of the deployment of Gen IV reactors is not foreseen before 2030. For many decades after that, Gen IV reactors will likely be deployed alongside advanced Gen III reactors, but in far smaller numbers. Yet, because of the potential benefits that these reactors can bring, R&D and demonstration projects, especially in the area of fuels and materials that can withstand higher temperatures, higher neutron fluxes or more corrosive environments, are needed to bring concepts towards commercialisation. Prototype development and testing is seen as particularly important. Construction and operation of Gen IV prototypes in the period 2020-30 are necessary if Gen IV technology is to be deployed commercially from 2030 onwards.

Figure 7: Evolution of fission reactor technology



Source: Generation IV International Forum, www.gen-4.org.

A number of countries are already pushing ahead with the design and/or construction of reactor prototypes that prepare the ground for future Generation IV designs. For fast reactor technology, the Russian Federation, which has a long history of operating sodium-cooled reactors – the 600 MW BN600 reactor, connected to the grid in 1980, is the world's largest sodium reactor in operation – is in the process of commissioning the 800 MW BN800 reactor and designing an even larger reactor called BN-1200, which could be deployed by 2030. France is moving ahead with the detailed design study of the advanced sodium technological reactor for industrial demonstration (ASTRID) reactor, which could be completed by 2019. China is operating the China experimental fast reactor (CEFR), a 20 MW research reactor connected to the grid in 2011, and is designing a 1 000 MW prototype reactor. Finally, India, which is not a member of GIF, has been working on sodium-cooled FNRs for decades, for their potential to operate on the thorium cycle, and is planning to start the commissioning of the 500 MW prototype fast neutron reactor (PFBR) before the end of 2014. Modular SFRs, such as the PRISM reactor ("Power Reactor Innovative Small Module") based on the integral fast reactor technology developed in the United States in the 1980s, are also being considered by some countries as part of a plutonium (from reprocessed spent fuel) recycling strategy.

Box 7: Nuclear fusion: A long-term source of low-carbon electricity

Nuclear fusion, the process that takes place in the core of our Sun where hydrogen is converted into helium at temperatures over 10 million °C, offers the possibility of generating base-load electricity with virtually no CO_2 emissions, with a virtually unlimited supply of fuel (deuterium and tritium, isotopes of hydrogen), small amounts of short-lived radioactive waste and no possibility of accidents with significant off-site impacts. However, the road to nuclear fusion power plants is a long route that still requires major international R&D efforts. The International Thermonuclear Experimental Reactor (ITER) is the world's largest and most advanced fusion experiment, and is designed to produce a net surplus of fusion energy of about 500 MW for an injected power (to heat up the plasma) of 50 MW. ITER will also demonstrate the main technologies for a fusion power plant. According to the *Roadmap to the Realisation of Fusion Electricity* (EFDA, 2012), ITER should be followed by a prototype for a power-producing fusion reactor called DEMO. During the period from 2021 to 2030, exploitation of ITER and design and construction of a prototype for a power-producing fusion reactor called DEMO.

DEMO should demonstrate a net production of electricity of a few hundreds of MW, and should also breed the amount of tritium needed to close its fuel cycle. Indeed, while deuterium is naturally abundant in the environment, tritium does not exist in nature and has to be produced. Thus, it is essential that tritium-breeding technology is tested in ITER and then demonstrated at large scale in DEMO. DEMO will also require a significant amount of innovation in other critical areas such as heat removal and materials. Beyond the demonstration of fusion power, the success of the technology as a source of electricity will require that it is competitive with respect to other low-carbon technologies such as renewables or nuclear fission. Major efforts in reducing the capital costs of fusion reactors through optimised designs and materials will be needed.

As far as high-temperature reactors are concerned, China is building a first prototype (HTR-PM), a twin-unit 210 MW prototype to be used for electricity generation. China has been operating a 10 MW research reactor (HTR-10) for more than a decade. The deployment of high-temperature reactors will depend essentially on the development of non-electric applications such as desalination or industrial process heat (see section below).

Fusion reactors: Beyond 2050

The *Roadmap* covers the development of technologies for NPPs up to 2050 and their contribution to the decarbonisation of the global electricity generation sector in the 2DS. All of today's NPPs, whether Generation II-type plants that constitute the bulk of today's fleet or the new Gen III plants that are being deployed, rely on nuclear fission as the source of heat. More innovative nuclear technologies, such as SMRs or Gen IV nuclear energy systems also rely on nuclear fission. Fusion reactors have more long-term deployment perspectives than Gen IV reactors, which are anticipated to be deployed in parallel with more advanced light water reactor designs from around 2030-40. According to the recently published *Roadmap* on fusion energy (EFDA, 2012), no industrial fusion reactor is foreseen before the second half of the century (see Box 7).

Non-electric applications of nuclear energy

Nuclear cogeneration, in particular but not exclusively with high-temperature reactors, has significant potential, and nuclear energy could target markets other than just electricity production, offering low-carbon heat generation alternatives to fossil-fired heat production. This would have several benefits, such as reducing greenhouse gas emissions from industrial heat applications, and it would improve the security of energy supply in countries that import fossil fuels for such applications. Although not widespread, nuclear cogeneration is not an unproven concept; in fact, there is significant industrial experience of nuclear district heating, for example in the Russian Federation and in Switzerland. In the latter country, the Beznau NPP (2x365 MW) has been providing district heating for over

25 years. About 142 GWh heat is sold each year to nearly 2 500 customers, thus avoiding about 42 000 tonnes CO_2. Nuclear district heating is an option that is being considered for some new build projects, for instance in Finland or in Poland.

Cogeneration could also provide "energy storage" services by allowing NPPs to switch from electricity to heat or hydrogen production while maintaining base-load operation, depending on the price of electricity on the wholesale market (for instance, when a large inflow of wind-generated electricity enters the grid). Hydrogen can then be converted back to electricity using fuel cells, or it can be injected into natural gas pipelines, providing additional revenue streams to the operator of the NPP. These are just some concepts of so-called "nuclear hybrid energy systems" that optimise the co-existence of nuclear and renewable technologies in future low-carbon energy systems.

Process heat applications, in particular those with a view to producing hydrogen (for transport or for the petrochemical industry or for coal to liquids), are one of the major non-electric applications of nuclear energy – high-temperature reactors, and in particular the Gen IV concept of VHTR, are well suited for this purpose. At present, the Republic of Korea is pursuing a programme that has the interest of one of the major steel manufacturers of the country. Other initiatives, in Europe, in Japan and in the United States, are looking at attracting industry support to nuclear cogeneration. The lack of a demonstration programme with a prototype high-temperature reactor coupled with a process heat application is seen as a major hurdle. Public-private partnership could be an effective way to initiate such a programme and demonstrate the benefits of using nuclear reactors as a source of low-carbon electricity and process heat.

There is also a potential for desalination to become a new market for nuclear power. The production of fresh water during off-peak hours would allow NPPs to operate economically well above usual base-load levels. The Middle East region, which gathers half of the world's desalination capacities (using gas and oil-fired processes) is also likely to experience a significant growth in nuclear electricity generation, which could be coupled with desalination. Many SMR designs, for instance the Korean SMART, the Chinese ACP-100 or the Russian KLT-40S, target desalination markets, but no firm project has yet been launched. Challenges include the development of a robust business model that includes the operator of the NPP, the operator of the desalination plant and the customers of the electricity and water produced by the cogeneration plant.

Nuclear fuel cycle

This roadmap recommends the following actions:	***Proposed timeline***
Investments in environmentally sustainable uranium mining should be developed to address expected long-term demand.	2015-35
Governments to continue to co-operate to discuss international fuel services as a means to secure the development of nuclear power.	Ongoing
Governments should ensure that policies are in place for long-term storage and disposal, including deep geological disposal (DGD) of high-level waste, and should not defer nuclear waste planning – "wait and see" is not an option.	2015-50
Studies should be carried out to ensure that extended (dry) storage of spent nuclear fuel (SNF) satisfies the highest safety and security requirements.	Ongoing
Governments to continue to support R&D in advanced recycling technologies to reduce volume and toxicity of high-level waste.	Ongoing

Every year, about 11 000 tonnes of heavy metal (tHM) of used fuel is unloaded from the world's reactors. This annual discharge rate will increase as the number of reactors in operation increase. Uranium supply is currently more than adequate to meet demand up to 2035 and beyond (NEA/IAEA, 2014). However, given the long lead time of mining projects, it is recommended that investments and the promulgation of best practices continue to be made so as to develop environmentally safe mining operations.

The current world market for fuel services (uranium supply, conversion, enrichment services, fuel fabrication) provides a considerable degree of security of supply and thus can play a major role in supporting the further development of nuclear energy. Increased security of supply can also be achieved through intergovernmental or international agreements dealing with fuel leasing and fuel banks. Maintaining the highest levels of nuclear security for transport of nuclear material from providers to customers is essential.

In terms of enrichment, laser enrichment is a technology that could potentially bring costs down, but this needs to be proven at industrial scale. There is no clear push at present to accelerate its deployment. Since the Fukushima Daiichi accident, there has been a renewed interest in the development of so-called accident-tolerant fuels, which is designed to offer additional coping times to operators in case of a severe loss of coolant accident. However, there is a long way ahead to develop and qualify these fuels and this will depend on the level of budgets devoted to this research.

Research into advanced fuel cycles, and in particular into partitioning and transmutation, is ongoing. The objective of this research is to allow for the recycling of reusable material from spent fuel and separate elements such as minor actinides that are responsible for the thermal load and radiotoxicity of high-level waste. These can be conditioned and disposed of, or burned within fast neutron reactors – as they are with some Generation IV concepts – or in dedicated burners such as accelerator-driven systems (ADS).

DGD is the recommended strategy for dealing with high-level waste, but it requires long-term planning, political commitment and strong engagement with local communities. Finland, Sweden (operating once-through cycles) and France (recycling route) will be the first countries to have operational DGDs in the 2020s (see Box 8). The Radioactive Waste Directive adopted by the EU in 2011 requires all member states to draw up national programmes for the management of spent fuel and radioactive waste. The directive advocates the disposal of high-level waste in geological repositories and opens the possibility for regional repositories.

Box 8: Progress towards implementation of a deep geological disposal site in Sweden (Case study 6)

Sweden has for many decades been actively pursuing research activities for the development of a safe long-term concept and technology for geologic final disposal of SNF from existing nuclear power reactors. A final repository is now planned in Forsmark (Östhammar municipality) as well as an encapsulation plant in Oskarshamn. The construction and testing of the DGD will take place between 2019 and 2029, with the transfer of spent fuel from Clab to the DGD facility to start around 2029 until 2075. The characteristics of the KBS-3 DGD site are as follows:

- Multiple barrier geologic final disposal system based on copper canister, buffer and bedrock.
- Deposition of canisters vertically in tunnels at a depth of around 470 metres below surface. Tunnels and shafts will be refilled with bentonite buffer, clay and rock spoils.
- No surveillance or monitoring should be needed for safety or security reasons after decommissioning and closure.
- Surface area will be restored and impact on land use will be limited during operation and afterwards.

To achieve a successful implementation of a DGD project, a stepwise process with clear roles and responsibilities based on dedicated funding is necessary. Time, consistency, patience and a transparent and open listening approach are needed. A process based on voluntary participation from host municipalities with clarified withdrawal possibilities/ conditions is recommended. It is also very important to include and explain alternatives (e.g. disposal options, choice of sites) from the beginning.

The concept of regional repositories should be evaluated in more detail, as it would offer countries with small nuclear programmes and geological and geographical limitations, the possibility to pool resources and find the most appropriate DGD site – in terms of geology, safety and economics – in another country.

Finally, in countries where there are no short- to medium-term prospects for having an operational DGD site, studies should be carried out to ensure that extended (dry) storage of SNF satisfies the highest safety and security requirements. However, this cannot be considered an alternative to DGD.

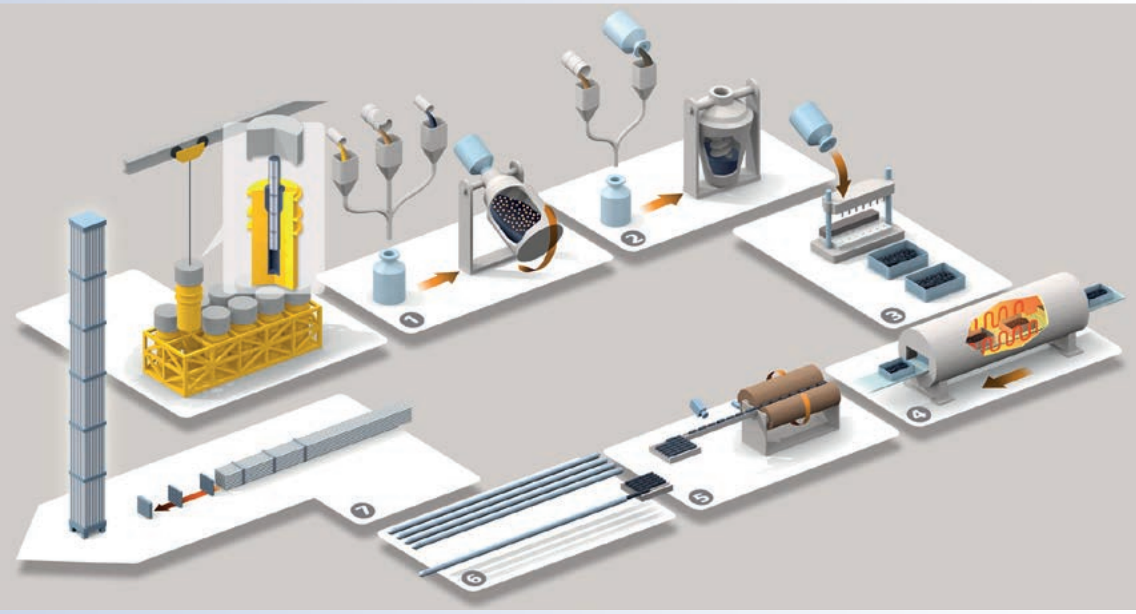
Recycling of spent fuel has advantages in terms of resource management (for instance, through the use of MOX fuel) but also in terms of conditioning of the high-level waste (vitrification process), and hence the sizing of the DGDs (see Box 9). Further progress is expected with the development of multi-recycling in fast neutron reactors (FNRs), and later with the industrial-scale demonstration of the use of minor actinide-bearing fuels, or targets in FNRs.

Other routes to recycling spent fuel can be offered by heavy water reactors operating in synergy with LWRs, as is currently being demonstrated in China, where a fuel consisting of recycled and depleted uranium was successfully irradiated in the Qinshan CANDU unit 1 (NEI, 2014).

Box 9: Recycling of spent fuel (Case study 7)

Used nuclear fuel recycling is today a fully industrial process with more than 45 years of experience, allowing reuse of uranium and plutonium to manufacture new nuclear fuel, while conditioning the non-reusable parts in a stable waste form. In France alone, more than 30 000 tonnes of used fuel has been reprocessed to date, of which 20 000 tonnes was from French reactors. This has effectively reduced the interim storage capacity for used fuel by 50%, while allowing up to 20% annual savings on natural uranium consumption. The main steps of the process are the separation of reusable and non-reusable materials, conditioning of the non-reusable material and the fabrication of new fuel.

Figure 8: MOX fuel fabrication



Source: AREVA.

Decommissioning

This roadmap recommends the following actions:	*Proposed timeline*
Governments need to ensure that dedicated funds are set aside for decommissioning activities and that operators accumulate sufficient funding during the operation of NPPs to cover the future costs of decommissioning these facilities. Operators should regularly review the adequacy of the accrued funds.	Ongoing
Nuclear operators to ensure that shutdown nuclear facilities are decommissioned in a timely, safe and cost-effective manner.	Ongoing

Decommissioning will become an increasingly important part of the nuclear sector activity in the coming decades, as dozens of reactors will be shut down. Industry must provide further evidence that it can dismantle these plants safely and cost-effectively. Further improvements in technology (for instance, robotics) and adaptation of regulations (for instance, allowing the clearance of non-radioactive material from a power plant as ordinary or municipal waste) can help to reach these objectives. It is important that decommissioning activities are covered by sufficient funds, and governments have a responsibility to ensure that this financial security is in place. In most countries, operators are required to set aside dedicated funds, the costs of which are internalised in the cost of nuclear electricity.

Once a nuclear facility is closed permanently, whether it is for technical, economic or political reasons, it needs to be put into a state where it can do no harm to the public, workers or the environment. This includes removal of all radioactive materials, decontamination and dismantling, and finally demolition and site clearance. This process, known as decommissioning, consists of several stages that can take place over many years. The general public is often not well informed about decommissioning activities, and the ill-founded belief that decommissioning of nuclear facilities is an unsolved issue is one of the factors that can explain poor public acceptance of nuclear power.

This *Roadmap* recognises that decommissioning is a significant challenge given the size of the fleet that will be retired in the coming decades. However, it is also a great opportunity for new business and skills to be developed. Demonstrating that NPPs that have been shut down can be dismantled safely and in a financially controlled manner is a key factor for allowing new build projects to move ahead. Today, decommissioning is a well-regulated activity of the nuclear fuel cycle, with specific safety guides and standards (e.g. IAEA, Western European Nuclear Regulators Association [WENRA]). As of December 2014, 150 power reactors had been permanently shut down and were in various stages of decommissioning. International information exchange forums exist, where processes are reviewed, lessons learnt and best practices shared. But it is also an area of technological expertise where operators and new industries compete (see Box 10).

There are essentially two main strategies for decommissioning: (i) immediate dismantling, where after the nuclear facility closes, equipment, structures, and radioactive materials are removed or decontaminated to a level that permits release of the property and termination of the operating licence within a period of about 10 to 15 years; (ii) deferred dismantling, where a nuclear facility is maintained and monitored in a condition that allows the radioactivity to decay – typically for about 30-40 years, after which the plant is dismantled and the property decontaminated. A third strategy exists called entombment, where all or part of the facility is encased in a structurally long-lived material. It is not a recommended option, although it may be a solution under exceptional circumstances (such as after a severe accident).

Increasingly, utilities are choosing the immediate dismantling option, to benefit from the knowledge of the plant's operating staff, as well as to limit the burden borne by future generations.

Box 10: Decommissioning in Germany (Case study 8)

German utility E.ON has gained substantial experience in the direct dismantling of Stade NPP (a 630 MWe PWR) and Würgassen NPP (a 640 MWe BWR) over the past 15 years. E.ON's NPPs Isar 1 (878 MWe BWR) and Unterweser (1 345 MWe PWR) reactors were both shut down in 2011 as a result of the phase-out policy, and the company has started the preparation for the decommissioning of these units. E.ON's expertise relies on a number of technologies that it has developed and mastered, as well as on qualified staff and established processes and practices, including radiation protection, surveillance, material and surface decontamination, and project and team management.

A key aspect of any decommissioning project is the planning phase, starting from the back end, in particular the disposal of the radioactive waste. Critical path analysis is required to avoid any bottlenecks in the project (related to easy-to-use decommissioning technology, interference between parallel dismantling work packages, licensing or staffing aspects) and ensure that all phases run smoothly. The purchase and delivery of containers and casks licensed for the storage and transport of waste also has to be planned and controlled carefully.

In addition to planning, challenges exist in managing financial and human resources: as funds are based on current decommissioning cost estimates, project management is crucial to ensure that the work is performed within the expected budget. From a human resource point of view, the challenge is to motivate staff who have worked part of their professional lives to maintain the existing asset. However, as decommissioning is the final end in the lifetime of the plant, the company has to develop career paths to keep staff motivated so that they will participate in the decommissioning project and remain within the company once the plant has been dismantled.

Although technologies and processes for decommissioning an NPP exist today, further technological developments and process improvements can help accelerate future decommissioning activities and reduce costs. For example (E.ON, 2014):

- improve standardisation in the design
- improve automation
- develop more flexible remote controlled tools
- develop tools to measure decontamination during the processes
- improve techniques for decontamination.

Facilitating the deployment of nuclear technologies: Actions and milestones

In this chapter, actions that can facilitate the deployment of nuclear technologies by 2050 are identified. They cover a wide range of areas such as licensing and regulation, nuclear safety, financing, training and capacity building, codes and standards, supply chain and localisation issues, communication and public acceptance. International collaboration plays an important role in facilitating information exchange between governments and experts to ensure the development of nuclear energy in countries wanting to use nuclear power is efficient and meets the highest standards of safety, security and non-proliferation. This is for instance the mission of the International Framework for Nuclear Energy Cooperation (IFNEC).

Licensing and regulation

This roadmap recommends the following actions:	***Proposed timeline***
Governments must ensure that regulators are strong, independent and staffed with enough skilled, competent and adequately remunerated personnel to carry out their missions.	Ongoing
International co-operation should continue to be promoted, whether among industry (e.g. WANO or the World Nuclear Association [WNA]) or regulators (IAEA, the Western European Nuclear Regulators Association [WENRA], the Multinational Design Evaluation Programme [MDEP], NEA Committee on Nuclear Regulatory Activities [CNRA]) or technical organisations.	Ongoing
Licensing frameworks for advanced reactors, including SMRs and Gen IV reactors need to be developed.	2015-30
Site analysis including Environmental Impact Assessments and stakeholder consultations to be carried out thoroughly prior to the development of new nuclear projects, taking into account lessons learnt from the Fukushima Daiichi accident and the possible effect of Climate Change in the long term, so as to ensure a high level of public support for the projects.	Ongoing

Regulators, whether in newcomer countries or established nuclear countries, should be strong and independent. They need to have sufficient, well-qualified and resourced staff to carry out their missions (NEA, 2014a). There is an important role for international organisations to promote efficient regulation, harmonise requirements and share experience (see Box 11). In particular, peer review processes, whether among operators or among regulators, is seen as an effective process to improve the overall level of nuclear safety.

The nuclear industry is sometimes concerned about the risk of over-regulation, through the multiplication or duplication of regulatory requirements. Better co-ordination and harmonisation of these requirements is needed in order to have an efficient regulation of the industry.

Finally, to accelerate the deployment of new technologies, licensing frameworks should be flexible enough to regulate such technologies in a risk-informed manner. The United States is addressing this challenge for SMRs through the DOE's Licensing Technical Support programme, which supports the development of certification and licensing requirements for US-based SMR projects. Similar initiatives should be launched in other countries, for SMR and advanced technologies such as Gen IV designs, so as to facilitate the deployment of these technologies once they have been demonstrated. It should be noted, however, that there are examples of regulatory regimes around the world (United Kingdom and Canada) whose frameworks already contain this flexibility and are prepared to address SMRs and Gen IV technologies. In general, greater international collaboration is needed so that a design approved in one major nuclear-competent country can be built elsewhere with a minimum of duplicated effort and time.

Box 11: International collaboration among regulators: The Multinational Design Evaluation Programme (MDEP) (Case study 9)

MDEP was established in 2006 as a multinational initiative to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities that are currently or will be tasked with the review of new reactor designs. MDEP has evolved from primarily a design evaluation programme for two new reactor designs (EPR and AP1000) to a multinational co-operation programme involving several new reactor designs and issues related to new reactor challenges.

MDEP gathers the nuclear regulatory authorities of 14 countries. It has five design-specific working groups (EPR, AP1000, APR1400, ABWR and VVER) and three issue-specific working groups (digital instrumentation and control, mechanical codes and standards and vendor inspection co-operation). MDEP produces common positions and technical reports for public use. Design-specific common positions describe common conclusions reached by the working group members during design reviews. MDEP has also encouraged international organisations to work together on the harmonisation of standards. MDEP has been a decisive trigger for their co-operation and will continue to encourage such initiatives, including the standard development organisations' code convergence board and WNA/CORDEL's working groups ("World Nuclear Association's working group on Cooperation in Reactor Design Evaluation and Licensing").

Siting and planning

Siting of nuclear facilities is an essential part of a nuclear programme, and it is one which requires thorough analysis, as well as interactions with local communities well ahead of any decision. The analyses supporting site suitability, although established at the onset of a project, need to be revisited periodically throughout the lifecycle of the facility to confirm that the design continues to be adequate in the face of changing site characteristics. Characteristics may also change as a result of new analysis techniques. There are many guidelines on how to carry out siting activities (IAEA, 2012). Criteria for assessment and selection of suitable sites for the construction of NPPs include:

- health, safety and security factors
- seismicity of the site, and vulnerability to extreme natural or man-made events
- engineering and cost factors (for instance, availability of cooling water, electricity infrastructure, distance to load centres)
- socio-economic factors
- environmental considerations.

For the siting and analyses, environmental impact assessment (EIA) processes should be carried out (see Box 12). It should also be mentioned that when an operator wants to operate a facility beyond the original design lifetime, or when the design conditions change (for instance, due to power uprates), an EIA should be performed again to take into account the new operating and environment conditions. At all stages of siting, stakeholder involvement in the decision-making process is necessary.

Following the Fukushima Daiichi accident, renewed attention has been paid to the vulnerability of existing (and future) sites with respect to the possibility of major earthquakes and flooding, whether from tsunamis or other causes (dam breaks, extreme precipitation events). This may reduce the number of possible new sites that a country can select for its nuclear programme. Another aspect that has received more attention is the particular case of multi-unit sites, i.e. sites that accommodate several nuclear reactors.

Building several hundreds of GW of new capacity by 2050 will require the extension of existing sites to accommodate additional units, if the sites are suitable, as well as the assessment and selection of new sites. For countries that already have nuclear power plants (NPPs), it is often easier to consider building nuclear facilities on existing sites as local communities are already informed about the risks and benefits of nuclear energy.

Box 12: Environmental impacts assessments in Finland (Case study 10)

In Finland, EIAs are an integral part of the licensing process for nuclear facilities. An EIA is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made.

In Finland, EIAs cover the whole lifetime of the nuclear facility, as well as the front and back ends of the nuclear fuel cycle. Of particular importance are aspects related to the use of cooling water (large quantities of water are needed to cool NPPs and thermal releases can be significant), impact on fauna, flora and biodiversity, and nuclear accidents and their consequences. An EIA typically lasts for about a year. An essential part of the EIA process is the consultations with civil society through public hearings.

In 2008, the Finnish company TVO performed an EIA related to the expansion of the Olkiluoto NPP (two units in operation, one unit under construction), adding fourth unit, OL-4.
The report addresses the impacts during construction, operation (including impact on land use, air quality, water system and fishing industry) of exceptional situations such as accidents or phenomena related to climate change.

Nuclear safety

This roadmap recommends the following actions:	***Proposed timeline***
Operators of NPPs to implement post-Fukushima safety upgrades in a timely manner.	2015-25
Safety culture needs to be enhanced and monitored across the nuclear sector (operators and industry, including the supply chain, and regulators) and at all levels of staff.	Ongoing
Governments should support efforts in safety research, and ensure that results are communicated to a wide audience.	2015-25

In parallel to the safety upgrades that were requested after the Fukushima Daiichi accident, enhanced safety requirements were put in place by regulators to ensure that nuclear plants operate to even higher safety standards. Japan in particular reviewed and reorganised its regulatory system, establishing its independence and setting out new safety requirements (see Box 13). The country's 48 reactors will now be assessed against these new standards before they can be allowed to restart. At the end of 2014, four units had been approved for restart by the Japanese regulator. In the European Union, the Nuclear Safety Directive was amended in July 2014 based on the lessons learnt from the Fukushima Daiichi accident, the EU "stress tests" and the safety requirements of the Western European Nuclear Regulators Agency and the IAEA.

In the Russian Federation, the regulatory framework is now being updated to take into account the "stress test" results and lessons learnt from Fukushima Daiichi accident, in particular with regard to requirements for special procedures beyond-design-basis accidents and severe accidents management. Requirements accounting for external, natural and human-induced impacts at NPP designing and siting, (as well as combination of such impacts) and requirements for the contents of safety analysis reports are also considered.

Safety assessment methodologies, such as probabilistic safety assessment (PSA) methods, are also being improved and further developed. Recommendations for level two and three PSAs of external events or fire and flooding have been revised and their use encouraged as a tool to improve on-site and off-site emergency planning. In general, governments should devote more efforts to safety research, including severe accident research, and the results communicated to a wider audience.

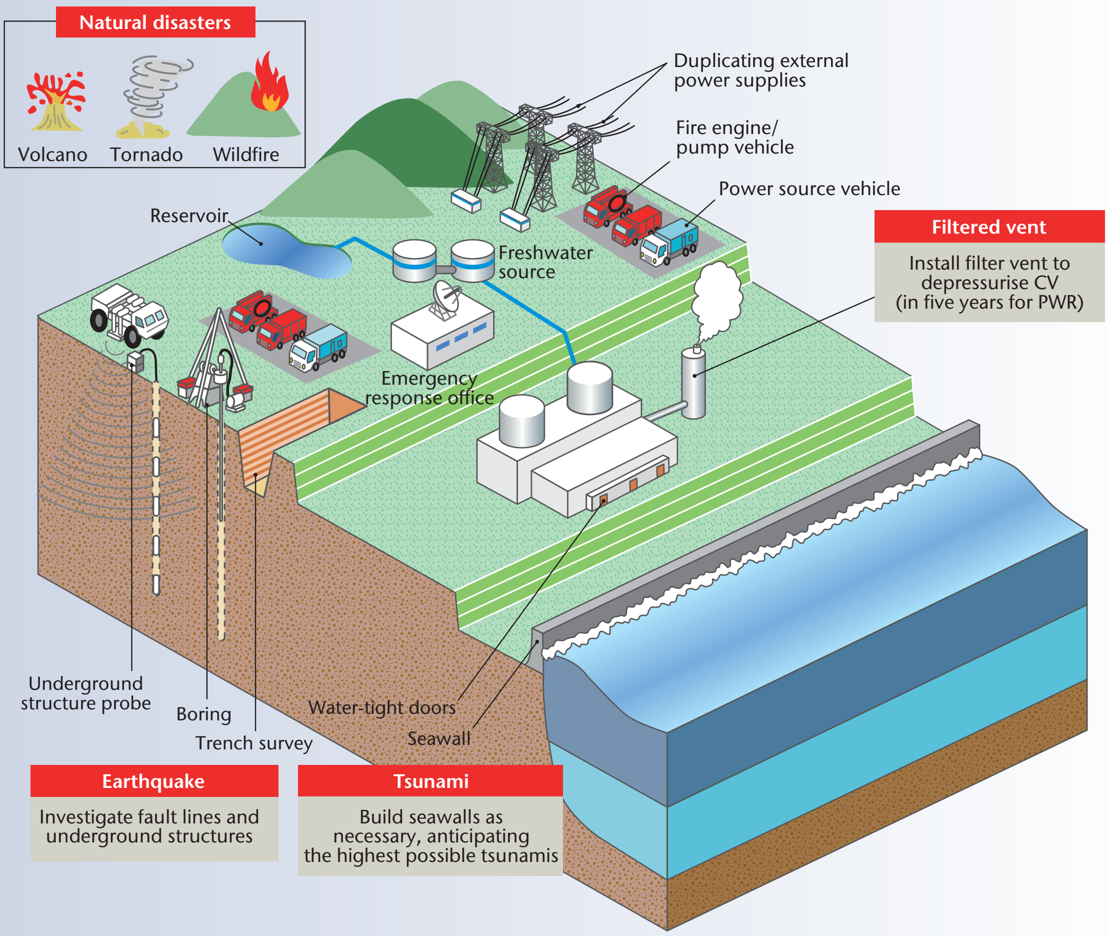
The Fukushima Daiichi NPP accident emphasised the importance of promoting safety culture across organisations. Safety culture can be defined as a set of characteristics and attitudes in organisations and individuals. that ensures that nuclear safety issues receive appropriate attention as an overriding priority over other considerations.

Safety culture needs to be enhanced across the whole nuclear sector (operators and industry, including the supply chain, and regulators) and at all levels of staff.

Box 13: New enhanced safety standards in Japan (Case study 11)

Following the Fukushima Daiichi NPP accident, Japan undertook a review of its nuclear regulatory structure and implemented significant reforms aimed at improving the nuclear industry's oversight and tightening safety requirements. The nuclear regulatory body was separated from nuclear promotion and the Nuclear Regulation Authority (NRA) was established as an independent commission. In addition to the administrative reform of Japan's nuclear regulatory institutions, new safety standards were introduced to prevent accidents with significant radioactive releases (Figure 9). Of the 48 NPP units in Japan, 17 are currently undergoing review by the NRA in accordance with these new enhanced safety standards. It is expected that a few of them could complete the review and could be considered ready to restart at the beginning of 2015. The restart of Japan's NPPs will help the country to significantly reduce CO_2 emissions from the power sector.

Figure 9: New enhanced safety requirements in Japan



Source: FEPC (Federation of Electric Power Companies of Japan) (2014), *Electricity Review Japan*, FEPC, www.fepc.or.jp/english/library/electricity_review_japan/_icsFiles/afieldfile/2014/07/11/2014ERJ_full.pdf.

Financing nuclear development

This roadmap recommends the following actions:	*Proposed timeline*
Governments favouring nuclear power to provide clear policies and a stable long-term strategy for nuclear development.	2015-25 and beyond
Governments should ensure price transparency and the stable policies required for investment in large capital-intensive and long-lived base-load power. Policies should support a level playing field for all sources of low-carbon power projects.	2015-20 and beyond
Loan guarantees by both vendor governments and host governments may be needed to reduce financing costs.	Ongoing
Governments to enable investment in low-carbon electricity sources through carbon trading schemes, carbon taxes or mandates for low-carbon electricity.	2015-35
Industry needs to develop communication strategies targeted at educating institutional investors and other financial institutions on the economic benefits of investment in NPPs.	2015-25
A refinancing strategy should be developed as part of a project financing plan and implemented once the plant is operational and construction risks are no longer applicable. Other strategies could include widening the source of financing to longer-term sources of financing such as pension funds and other institutional investors.	Ongoing
Industry needs to improve on its capacity to deliver "on time and to budget", thereby reducing the investment risks associated with construction and the need for government guarantees.	2015-20

An estimated USD 4.4 trillion would need to be invested in nuclear energy between 2011 and 2050 to reach the 930 GW of installed capacity under the 2DS. With an average NPP taking five to seven years to build and costing approximately USD 3.5 billion to 5.5 billion per plant, the financing of nuclear projects presents its own unique challenges. The risks associated with construction delays and cost-overruns are particularly important considerations in financing NPPs. Most plants under construction today have strong government involvement through state-owned enterprises or through loan guarantees, and are often government sponsored or financed projects. Few utilities today have the ability to develop new plants solely on their balance sheet without some sort of government guarantee or long-term power purchase agreement at predictable prices.

A clear commitment and long-term strategy for nuclear development at the national level is critical in raising financing for nuclear projects. Governments have a critical role to play in streamlining electricity market regulations to ensure that they work effectively and efficiently in order to limit the impact of associated risks on financing costs. The high investment cost of a nuclear plant means that its overall economics, and the feasibility of its financing, depend greatly on the cost of capital. This cost will be determined by the evaluation of various risk factors, and hence the key to successful financing is first to minimise the financial risks and then to structure projects using appropriate ownership and contracting models so that the remaining risks are appropriately shared among the parties involved.

The roles and responsibilities of different stakeholders such as the vendor, utility, host country, international contractors, local supply chain participants and regulators, as well as investors and financing institutions, need to be clearly defined. This will help to better allocate risks across relevant stakeholders. The main risks associated with nuclear plants are construction risks (cost and duration), electricity price risks and regulatory risks which can impact planning and construction times (nuclear safety regulation), as well as load factors (electricity market regulation).

In addition, country (political stability) and currency risks are also important but manageable via different hedging or insurance mechanisms or through government guarantees.

Electricity markets

Governments have a key role in providing sufficient confidence to investors in new generation projects. Clear and predictable long-term electricity prices that enable adequate return on investment are central to developing bankable projects. In regulated electricity markets, investor confidence can be gained via the regulated electricity price. Provided clear litigation clauses are included within contracts, investors are generally confident that utilities operating in regulated markets will be able to repay debts through electricity tariffs. These tariffs, which are fixed by the energy market regulator, on average cover the cost of fuel, operating and maintenance costs, waste management and decommissioning, depreciation, debt repayment and a return on capital. Regulated electricity markets effectively protect against construction and market risks, thereby facilitating the financing of large capital-intensive projects (see Box 14).

In liberalised markets, financing of nuclear energy can be significantly more difficult due to uncertainties in long-term electricity prices and hence higher interest costs. This is reflected in an increase in the cost of capital that makes most projects unattractive. To overcome these uncertainties, a long-term power purchase agreement such as the UK contract for difference (CfD) pricing model can provide the needed investor confidence to finance nuclear projects. The UK CfD fixes the price of energy from the plant, the "strike" price, and consumers are committed through legislation to pay or receive the difference between a market reference price and the strike price, depending on which one is higher. CfDs are designed to shield investors from power market volatility, particularly when there are expected to be high levels of intermittent

Box 14: Financing of new units at the Vogtle Power Plant in Georgia, USA (Case study 12)

The Southern Nuclear Operating Company is developing two new nuclear units at the Vogtle plant in Georgia, which already has two operating Westinghouse PWRs. This is the first nuclear reactor construction in the United States in 30 years and will consist of two AP 1 000 units of 1 200 MW each. Vogtle is operated by Southern Nuclear Operating Company and is owned by four companies: Georgia Power (45.7%), Oglethorpe Power (30%), MEAG Power (22.7%) and Dalton Utilities (1.6%). To facilitate the development of new advanced nuclear facilities, the United States government has established, under the 2005 Energy Policy Act, two forms of incentives. First, a production tax credit of USD 18 per megawatt hour is granted for the first eight years of operation of NPPs. Second, a system of loan guarantees is proposed that could cover up to 80% of the construction costs of a new advanced nuclear facility.

Market and regulatory conditions in Georgia also played an important role in the successful development of the nuclear new build at Vogtle. Georgia is a regulated electricity market, with a limited number of players and an overall limited level of competition. The particular structure of Georgia's electricity market, which ensures the stability of the demand and a low-risk environment for electricity generating companies, is favourable to the development of nuclear projects that are highly capital-intensive but can provide a lower and stable electricity generation cost in the long term. During the construction of Vogtle, Georgia Power was allowed to charge a construction work in progress (CWIP) tariff to customers, increasing electricity tariffs by about 7%. Under the CWIP, Georgia Power can more effectively meet the financial needs of a new nuclear build, which in turn will result in reducing long-term electricity cost for the customers. The two other main shareholders of Plant Vogtle have a similar company structure and electricity price arrangements that protect them effectively from construction and market risks.

renewables, which can drive electricity prices to zero or below in some extreme cases. This arrangement also helps offset future political risks or changes in government policies on nuclear energy. In the risk allocation, the developer of the nuclear project retains all project risk while vendors often carry most of the construction risk.

Carbon pricing remains the central pillar of any low-carbon policy. Whether as a carbon trading scheme, carbon tax or as a mandate on utilities to use low-carbon sources, incentives for investing in low-carbon energy are needed to help accelerate the deployment of nuclear energy. In the absence of a sufficiently high carbon price that reflects the externalities of fossil-fuelled generation, governments will have to continue providing policy solutions that improve the net present value of low-carbon investments and mitigate the market risks for project developers and financial investors.

Financing schemes supporting nuclear power development

Since the 2010 IEA/NEA *Technology Roadmap*: *Nuclear Energy*, two events have further added to the challenges of financing nuclear energy by commercial banks. The first is the adoption of Basel III regulations in the banking sector, which set limits to the amount that banks can lend and effectively reduced the availability of long-term debt. The second is the Fukushima Daiichi NPP accident, which led many banks to re-evaluate lending policies for nuclear projects. However, some of the banks that were financing nuclear projects before the accident appear to be considering financing nuclear projects again. Unfortunately, in many of the markets that have an interest in developing nuclear, the wholesale prices are extremely low, which for these capital-intensive projects, creates greater challenges for financing.

Governments and operators will need to review methodologies for estimating damages associated with nuclear accidents and for assessing their costs, and consider the implication for existing liability regimes. Sharing of lessons learnt that assist stakeholders in assessing improvements in technical areas, organisation management, planning and budgeting can result in risk profiles that are more acceptable to investors. Reputational risk considerations, environmental responsibility and commitment to international regimes and standards also need to be considered with respect to financing nuclear projects. The Fukushima Daiichi accident has led many banks to develop lending policies specific to nuclear energy, and some have adopted environmental and social guidelines, with projects classified according to their environmental and social impacts.

Government involvement in financing through Export Credit Agencies and in the form of government loan guarantees will remain critical for the nuclear industry as it will help to lower overall financing costs by hedging a number of risks including geopolitical, regulatory and construction risks.

Box 15: The Akkuyu build, own and operate model (Case study 13)

The Akkuyu NPP project will be Turkey's first NPP and also the first project to be built under a BOO financing model. Rosatom, Russia's state-owned nuclear company, is responsible for engineering, construction, operation and maintenance of the plant and will also initially hold 100% ownership. Akkuyu will have a total installed capacity of 4.8 GW comprised of four VVER1200 units (AES 2006 design), Gen III design with advanced safety requirements, and passive and active safety systems.

Initial funding for the project will be provided by Rosatom and up to 49% of the project may be sold to investors at a later stage. The total cost of the project is estimated at USD 20 billion and is backed by a 15-year power purchase agreement for 70% of the electricity generated by the first two units and 30% of the last two units at an average price of US cents 12.35/kWh.

Akkuyu has benefited from the strong support of both the Russian and Turkish governments, highlighting the importance of government-to-government relationships in the development of large nuclear projects. The Rosatom BOO model is an extremely attractive full-service model for new nuclear countries with limited expertise and resources. Under the BOO model, Rosatom will provide engineering, construction, operation and decommissioning services for NPPs.

Given the impact of recent events, vendor financing in the form of equity, for example, could increase as the utilities have become less effective at raising large amounts of long-term debt, or it has become uneconomical. Rosatom's "build, own and operate" (BOO) model is one example of this potential financing option (see Box 15). Most vendors are reluctant to engage in financing of nuclear projects, but current financing conditions could make it difficult to finance projects without such support. Vendor financing can address shorter-term financing constraints, but in the longer term a more sustainable model will be needed that allows utilities to finance these projects in the market. In certain regions, Islamic bonds could also be a potential financing instrument to support investments in nuclear projects.

The "Mankala" principle (co-operative model between shareholders) used in Finland is an original approach that brings together a consortium of electricity consumers (typically, energy-intensive industries such as pulp and paper, as well as municipalities) who have shares in the electricity generation plant, which can be a hydro-electric or an NPP. These shareholders receive the corresponding shares of electricity produced by the plant at full cost. Thus a Mankala-type project is not subject to electricity price risk, and its shareholders benefit from the equivalent of a long-term supply contract and stable electricity rates.

The role of development banks in the financing of nuclear plants is at present unclear. While they have financed past projects, development banks are not currently financing NPPs, but could potentially play a role in assisting developing countries interested in developing nuclear energy. For multilateral development banks, political factors and capital availability to fund such large projects will likely make it difficult for these institutions to fund entire projects. However, they could play an important role in catalysing higher levels of private finance by providing insurance against political risks.

Incentives for investment in low-carbon energy sources, such as carbon markets, carbon taxes and targets or mandates for carbon-free electricity supply could also encourage nuclear investments. Nuclear energy should be treated on an equal footing with other low-carbon technologies.

Finally, to help reduce the overall financing costs of an NPP, a refinancing strategy should be developed and implemented once the construction is completed and the plant is operational. With the construction risk no longer a factor, and the plant generating large cash flows, the risks associated with the project are significantly lowered and financing costs reduced. Refinancing could also free up much needed capital by the vendor or utility to invest in other projects.

Training and capacity development

This roadmap recommends the following actions:	***Proposed timeline***
Countries undertake a national skills evaluation to quantify the need for a skilled nuclear workforce to maintain the operation of existing fleets and for future decommissioning needs, as well as for nuclear new build, where relevant. Evaluation should also include requirements for nuclear regulators and researchers, as well as for the need to replace those due to retire.	2020-25
Newcomer countries should evaluate the need for skilled nuclear workers during the construction and operation phases, including for those who will be employed by nuclear regulators.	2015-25
Newcomer countries to develop local training programmes aimed at developing a nuclear-aware and nuclear-competent workforce.	2015-25
In countries with mature nuclear industries, companies and governments will need to implement programmes aimed at knowledge preservation of those workers who will be retiring in the next decades. Mentoring programmes could be implemented to ensure a transfer of knowledge; lessons learnt and best practice among operators, regulators, waste management and decommissioning experts.	2015-30

This roadmap recommends the following actions:	Proposed timeline
International co-operation is needed to help transfer nuclear training programmes from existing nuclear countries to newcomer countries. Opportunities will be needed for newly trained/educated workers to gain practical experience and develop and maintain skills while waiting for their countries nuclear fleet to begin operations.	2015-30
Existing nuclear countries with post-graduate nuclear training programmes should develop student exchange programmes aimed at newcomer countries. Where possible, these programmes should include a period of practical work experience at a nuclear facility and potentially the creation of equivalent training programmes in the newcomer country.	2015-30
Implement policies to attract and maintain highly skilled regulators.	Ongoing
International collaboration is needed to harmonise training programmes so as to develop mutual recognition of qualifications at an international level.	Ongoing

The distinctive characteristics of nuclear energy and its fuel cycle give rise to special requirements for education and training. In all countries with nuclear programmes, there exists a substantial nuclear fleet to be safely operated, maintained and eventually decommissioned. An essential element in the implementation and safe operation of all nuclear facilities, in addition to nuclear technology research and development (R&D), is a knowledgeable and skilled workforce. The importance of education and training in maintaining safety must be a priority for all nuclear countries. Although seen as two separate processes, education and training are intertwined in the preparation and maintenance of a competent nuclear workforce.

The future demand for global employment in nuclear-related activities is in the tens to hundreds of thousands of skilled workers (NEA, 2012c). The demand for nuclear skills are generally set against an ageing workforce, which highlights the urgency for targeted programmes to maintain an adequately skilled and competent workforce and attract a flow of new recruits for long-term sustainability. Policy decisions need to be made today to ensure that an adequate nuclear education and training infrastructure is available in the decades to come.

In 2012, the NEA published *Nuclear Education and Training: From Concern to Capability,* which assesses the current state of nuclear education and

Figure 10: An illustrative taxonomy: Sectors and functions

Nuclear power plant New build	▪ Design ▪ Supply	▪ Construction ▪ Commission
Nuclear power plant Operation	▪ Operation ▪ Maintenance	▪ Waste management ▪ Safety and environment
Nuclear power plant Decommissioning	▪ Decommissioning operation ▪ Maintenance	▪ Waste management ▪ Safety and environment
Nuclear research reactors	▪ Design and engineering ▪ Utilisation	▪ Operation and control
Nuclear regulation	▪ Assessment and review ▪ Authorisation	▪ Inspection and enforcement ▪ Regulation and guidance

Source: NEA (2012c), Nuclear Education and Training: From Concern to Capability, OECD/NEA, Paris.

training and identifies remaining gaps and actions that are required to address skills development needs in NEA member countries. Part of that work included the development of a classification system for nuclear job profiles or "job taxonomy". This taxonomy encompasses the full lifecycle of a nuclear reactor from new build to operation and decommissioning, as well as research and nuclear regulation, and classifies them according to functions (Figure 10). Each function of each sector contains a job specification which defines the occupational levels and competencies required, as well as sets of initial qualifications, advisory training and continuous professional development to support them. As only a few countries are active in the entire nuclear fuel cycle, the taxonomy did not cover fuel cycle issues.

Human resource assessments

Since a large number of workers in the nuclear energy sector will retire in the coming decades, policies must be put in place to ensure trained and qualified personnel and workers are available to support the development of nuclear programmes and the required regulatory function. In some countries, maintaining and attracting highly skilled regulators will need to be a priority. A number of countries have recognised this need and are promoting education and training programmes to increase human resources for the nuclear sector. Countries such as France, Japan, the Republic of Korea and the United Kingdom have implemented national assessments for nuclear human resource needs to maintain existing nuclear operations, as well as to staff new build construction and operation (see Box 16).

Box 16: Nuclear skills assessment in the United Kingdom (Case study 14)

The UK government recognised nuclear skills development as a key component in developing new nuclear build and set up the Nuclear Energy Skills Alliance to address current and future nuclear skill needs for the UK nuclear programme. The alliance brings together government, skills bodies, higher education and R&D communities to develop labour market intelligence for nuclear and to develop interventions and mitigation options that will ensure that the UK nuclear industry has the required skills to support current and future programmes. Based on scenario analysis for 16 GW of new build by 2025, the alliance estimated that 110 000 to 140 000 person years (excluding manufacturing) would be required to complete the programme and a peak annual employment of 14 000 in the period 2020-22.

A risk register was established to provide ongoing assessment that would be used to inform the evolving skills landscape. Of the 34 skill areas identified by the risk register, 13 were given a high priority rating. *Nuclear Labour Market Intelligence* was published in December 2012 and outlined a common skills delivery plan. The plan sets out 22 priority skill areas for the delivery of the UK nuclear programme and identified over 100 key actions. A combination of qualitative and quantitative assessments can be used to support national skill assessments, which should be regularly monitored and updated as a country's programme evolves.

In newcomer countries, training of personnel in preparation of the launch of a nuclear programme is a significant investment, which requires incentives to be put in place to attract young talent, train them and ensure they are available when the programme starts. Given the long lead times to develop and implement a nuclear energy programme and the need to gain practical operational experience, these programmes should include practical training and operational experience in a foreign country. Once educated and trained, these nuclear-skilled workers from newcomer countries will need sufficient incentives to return or remain in their countries. R&D activities, possibly linked to the use of a research reactor are seen as an effective way to develop and maintain skills and competence.

Internationalisation of nuclear training and education

In parallel to an increased globalisation of the nuclear industry, there has been an increase in the internationalisation of R&D. This is to a large extent due to decreasing R&D budgets at national levels, which encourages research organisations to pool resources, share experimental facilities and carry out projects at the international level. There are a number of international and bilateral initiatives focused on collaborative research, education, training and knowledge management, including the Sustainable Nuclear Energy Technology Platform in the European Union, which gathers industry, research and academia, or the Generation IV International Forum, which provides a framework for international R&D on Gen IV systems. The NEA itself provides support to international projects such as code validation benchmarks or safety-related experiments.

The global nuclear industry is acutely aware of the need to ensure a high level of nuclear skills development in existing and newcomer countries and has well-developed training programmes that are shared across countries, providing an important source of nuclear training. In addition, global partnerships such as the World Nuclear University (WNU) and the European Nuclear Education Network (ENEN) have been developed to enhance international education and training for the development of nuclear energy.

WNU was created in 2003 with the support of the IAEA, OECD/NEA, WANO and WNA to provide global guidance on preparing the future generation of nuclear industry leaders and to enhance nuclear education worldwide. WNU activities include the Summer Institute (a six-week intensive course for future nuclear leaders), the Radiation Technologies School (a two-week course for future leaders in the radiation and radioisotope field) and a one-week course focused on key issues in the nuclear industry today. These courses are offered in host countries where significant interest exists for the development of nuclear energy[8]. Training events are held in partnership with other organisations and trainers come from industry, government and academia. The WNA provides administrative support to the WNU. To date, almost 900 professionals have attended the Summer Institute, while 200 have attended the Radiation Technologies School and approximately 6 000 have benefited from the one-week training courses.

Mobility of nuclear literate workers across borders will be particularly important both in terms of providing sufficient specialised nuclear workers (such as nuclear engineers and welders) as well as facilitating a transfer of expertise to newcomer countries. The UK skills passport and French ticketing system provide a good basis for developing mutual recognition of qualifications from one country to another and help to support workforce mobility.

8. Additional information on WNU courses can be found at www.world-nuclear-university.org.

Codes and standards, supply chain development and localisation issues

This roadmap recommends the following actions:	***Proposed timeline***
Industry to continue to work towards harmonisation of codes and standards to improve the integration of a global supply chain.	Ongoing
Newcomer countries' legitimate demands for localisation in nuclear projects should be appropriately balanced by the need to have an overall cost efficient and qualified supply chain. Guidance on how to reach the balance between global and local supply chains should be elaborated.	2025

There are currently 70 reactors under construction in 15 countries, and several newcomer countries are either in various stages of planning a nuclear programme (for example Indonesia, Jordan, Malaysia, Poland, Turkey, Saudi Arabia, Viet Nam) or sometimes already constructing NPPs (Belarus and the United Arab Emirates). To reach 930 GW of nuclear capacity by 2050, many more construction projects will need to be launched, and the nuclear industry will need to address two particular challenges if it is to achieve this long-term objective in a cost-effective way: (i) improve the standardisation of reactor designs through a harmonisation of codes and standards and (ii) ensure that nuclear supply chains, both local and global, are qualified, and that there are no bottlenecks that could delay projects.

Improved standardisation and harmonisation of codes and standards are seen as effective ways to improve new build performance and to reduce costs. However, given the number of different designs and national regulatory frameworks, it would be unrealistic to imagine that, in the short term, there might be an international licensing process or reciprocal acceptance of approvals between countries. Information exchange and lessons learnt during licensing and safety reviews can ease regulatory processes and align regulatory requirements (this is the objective of the MDEP initiative). On the industry side, work is being done to advance reactor design standardisation – this is the main focus of the WNA's CORDEL initiative.

In terms of supply chain issues, the availability of large heavy forgings, once identified as a potential barrier, is no longer a problem as a number of facilities in China, France, Japan and the Republic of Korea, for instance, are able to manufacture these large components, and their industrial capacity meets the demand in the short to medium term. The main issue facing nuclear project developers is the qualification of the supply chain that is required for the project, as well as reaching the appropriate balance between localisation demands in countries that do not necessarily have a nuclear industry and a proven and qualified global supply chain.

Localisation can be challenging when a new nuclear project is established in a newcomer country, particularly if the contract to build a new plant stipulates a high local content requirement. For countries that have a large nuclear programme, localisation can be successful and help drive down the costs of future plants (see Box 17).

Box 17: Setting up and qualifying a supply chain for Generation II and Generation III reactor technology: The case of heavy component manufacturing in China (Case study 15)

With 26 reactors under construction (at end 2014), China's new build programme represents about 40% of the world's nuclear reactor construction projects. Half of these reactors are Gen II+ CPR-1000 reactors derived from the Daya Bay and Ling Ao 900 MW reactor technology from vendor Framatome (now AREVA), with localisation rates that now reach more than 80%. The equipment localisation programme that AREVA initiated with China General Nuclear Power Corporation (CGN) started with the Ling Ao phase I project in 1995, but really developed with the acceleration of the Chinese nuclear programme ten years later to initiate a supply chain localisation programme, while minimising project risks in terms of schedule and cost, CGN defined a realistic localisation plan with AREVA, and this plan was included in the supply contract. During the project implementation, CGN and AREVA set up strict monitoring to follow and secure the components' delivery according to the project's schedule.

The successful experience gained in China will help to address localisation targets in countries planning new build with partial localisation of the supply chain, such as Brazil, India, the Republic of South Africa, Saudi Arabia, and the United Kingdom.

Table 5: Progression in terms of localisation

Equipment	***Ling Ao phase 1, 900 MW reactor (1994)***	***Ling Ao phase 2, CPR-1 000 (2004)***	***Taishan 2nd unit, EPR 1 600 MW (2009)***
Steam generators	1 (out of 3)	3 (out of 3)	4 (out of 4)
Reactor pressure vessel	0	1	1
Pressuriser	1	1	1

There needs to be a good balance between supply chain localisation and globalisation, which depends on the extent of the past and future nuclear programme in the country of localisation. Guidance on how to reach this balance would be beneficial. Qualification of a new supply chain remains a challenge. Establishing a nuclear supply chain in a country that had a nuclear industry in the past can also be difficult. The absence of activity over one or two decades is sufficient to lose precious know-how and manufacturing capabilities. Italy, which recently reconsidered the nuclear option, organised a comprehensive survey of its industry with the objective of identifying companies that could participate in a new build programme (see Box 18). The United Kingdom, whose new build programme is now moving ahead dynamically, has been promoting the development of a British nuclear supply chain with the publication of the "Supply Chain Action Plan" in 2012 and a Nuclear Industrial Strategy document in 2013. In parallel, industry has set up a supply chain portal through the Nuclear Industry Association. Initiatives taken by Enel in Italy, and by government and industry in the United Kingdom, are good examples of action to promote a solid industrial base for nuclear projects.

Box 18: Preparing for a new build programme in an industrial country: Supply chain survey (Case study 16)

In preparation for a future new build programme, in 2009 the Italian government asked Enel to develop a nuclear awareness and qualification process for Italian companies. The government's goal was to make it possible for the Italian industry to have a large role in the new build programme (i.e. 70% target localisation for the last units to be built). In October 2009, Enel and EDF, supported by the Italian Industries Association, started a market survey aimed at screening the Italian industry. Unfortunately, this initiative was abandoned after the Fukushima Daiichi accident when a moratorium on nuclear activities was decided.

However, the preparatory work allowed Enel to conclude that in order to increase localisation content, a series of measures were needed, such as government incentive programmes, partnerships with qualified nuclear international suppliers and national experts' support for industry. Critical points found during the market survey were related to nuclear steam supply system equipment and to aspects related to quality management for nuclear work. In particular, the need to implement programmes for nuclear equipment qualification and the need to intensify the knowledge of nuclear codes and standards and of documentation configuration management processes were identified. Sixty Italian companies were identified as currently active in the nuclear field, with qualifications by nuclear technology vendors. An additional 60 to 70 companies had nuclear experience in the past, and these had dormant nuclear skills that could be recovered within a reasonable timeframe with relatively minor efforts in view of the new opportunities. From a qualitative point of view, the survey gave a wide and detailed picture of the Italian industry's present capabilities and future potential and made the industry aware of its strengths and areas that would need improvement.

Communication and public acceptance

This roadmap recommends the following actions:	***Proposed timeline***
Development of education and information centres to support effective, transparent communication and public knowledge about the facts related to the nuclear industry. In newcomer countries, it will be particularly important to ensure broader public awareness of nuclear power development.	2015-30 and beyond
In many countries, the operator of the nuclear facility plays a front-line role in communicating with stakeholders in real-time during an event. In this case, the regulatory authorisation for activities involving a nuclear facility should include a review and acceptance of the operator's strategy and programme. Performance of the programme should also be assessed by the regulator on a periodic basis.	Ongoing
Targeted communication programmes with influential stakeholder groups such as politicians, media, teachers and local leaders need to be implemented to improve understanding about the benefits and risks of nuclear energy. Communication should be transparent and occur at regular intervals and via a range of personal, print and online sources.	Ongoing
Measures to be implemented to share information in a timely manner on any safety events proposed by national regulatory organisations.	Ongoing
National regulatory organisations need to implement communication mechanisms and tools for discussion between interested parties and the regulator.	Ongoing
Clear and regular communication with host municipalities in the identification and development of deep geological disposal sites. A process based on voluntary participation with clarified withdrawal conditions is recommended and should include alternative sites from the beginning.	2015-30 and beyond

Introducing nuclear energy or expanding its role requires the support of all stakeholders, including the public, and should be based on an assessment of risks and benefits. The benefits of nuclear in terms of energy security and threats of climate change are often overshadowed by concerns over nuclear safety, risks of an accident, radioactive waste management and disposal and potential proliferation of nuclear weapons.

A successful strategy for nuclear communication will vary depending on the local situation. Understanding and responding to the concerns and needs of the local community will be key in devising a successful communication strategy. Project developers need to be sensitive and responsive to stakeholder concerns. Communication strategies aimed at improving public acceptance of nuclear energy should be transparent and achieved via fact-based information. Education should be the focus of communication. Public education programmes clearly explaining the risks and benefits of nuclear energy need to be developed as part of a country's decision to develop nuclear energy. Nuclear safety and radiological protection needs to be explained simply, with easy to understand language, and the positive aspects of nuclear energy (e.g. the creation of jobs and boosting of local and regional economies) need to be highlighted in nuclear public acceptance programmes.

In 2009, the European Commission conducted a Eurobarometer survey in the 27 member states on public perception of nuclear safety (EC, 2010). Results of this survey found that, overall, European public opinion accepts the value of nuclear energy to some extent as a means of reducing energy dependence, and opposition to nuclear development is mostly related to the perception of risks associated with nuclear energy. The study found that most Europeans considered themselves ill-informed about nuclear safety, obtaining most of their information from mass media, which they considered insufficient. Respondents who felt they were well informed about issues linked to nuclear safety were clearly more supportive of the value of nuclear energy and hence had higher acceptance.

Finland and France have been identified as two examples where communication and public acceptance for nuclear has been successful. In Finland, significant time and resources were invested in educating local communities with respect to the local benefits and risks for nuclear facilities such as waste repositories or new reactors. In France, LCIs (Local Commissions of Information) have been operating for several decades around nuclear facilities. They provide an efficient framework for all stakeholders to meet, and for the public to have access to information.

Transparent communication and information from regulatory organisations is particularly important to build confidence and trust in their ability to regulate operations of nuclear facilities. Lack of consistency in messages from one national authority could affect confidence in regulators elsewhere. Close contact should be maintained by national regulatory organisations and information about safety events shared in a timely manner.

Finally, governments, and intergovernmental organisations, in particular bodies working on climate change, have a role to play in communicating to the public about the positive contributions that nuclear energy makes and will make in the future in the reduction of greenhouse gas emissions from the power sector. This *Roadmap* and the underlying 2D Scenario highlight the significant role that nuclear energy has to play in the decarbonisation of the world's energy system.

Conclusion: Near-term actions for stakeholders

This *Roadmap* has been designed with milestones that the international community can use to measure progress and assess efforts to ensure that nuclear energy development is on track in achieving the emissions reductions required by 2050.

Below is a summary of the near-term actions required by nuclear energy stakeholders, presented to indicate who should take the lead in specific efforts. In most cases, a broad range of actors will need to participate in each action. The IEA and NEA, together with government, industry and non-governmental organisation stakeholders, will report on this progress and recommend adjustments to the *Roadmap* as needed.

Lead stakeholder	Actions
Governments	• Provide a clear commitment and long-term strategy for nuclear development. • Recognise the importance of long-term operation to maintain low-carbon generation capacity and security of energy supply; provide clear prospects to encourage operators to invest in refurbishments. • Support efforts in safety research, and ensure that results are communicated to a wide audience. • Continue to co-operate to discuss international fuel services as a means to secure the development of nuclear power. Ensure that policies are in place for long-term storage, including DGD of high-level waste. • Continue to support R&D in advanced recycling technologies to reduce the volume and toxicity of high-level waste. • Ensure that dedicated funds are set aside for decommissioning activities and that operators provide sufficient funding to these funds during operation of NPPs by regularly reviewing the adequacy of accrued funds. • Work with industry to open up the market for small modular reactors by accelerating the deployment of SMR prototypes that can demonstrate the benefits of modular design and construction. • Support R&D and prototype development for Gen IV systems to ensure technologies are ready for deployment in 2030-40. • Ensure regulators are strong, independent and staffed with enough skilled and competent personnel to carry out their missions. • Encourage the development of licensing frameworks for advanced reactors, including SMRs and Gen IV reactors. • Expand public-private partnerships with industry to develop demonstration projects for nuclear cogeneration, in the areas of desalination or hydrogen production. Develop education centres to support effective communication and public knowledge about the facts of nuclear.
Industry	• Implementation of Post-Fukushima safety upgrades by operators of NPPs in a timely manner. • Optimisation of Gen III designs to improve constructability and reduce costs. • Lessons learnt from current FOAK projects should be used to ensure that NOAK plants are built on time and to budget. • Investments are needed in environmentally sustainable mining to address expected long-term demand. • Nuclear facilities that have been shut down should be decommissioned in a timely, safe and cost-effective manner. • Enhance safety culture across the nuclear sector and at all levels of staff. • Improved communication with institutional investors and other financial institutions to better educate investors on the economic benefits of investment in NPPs. • Continued harmonisation of codes and standards to improve the integration of a global supply chain.

Lead stakeholder	*Actions*
Universities and other research institutions	• R&D in ageing and improved safety is needed to support long-term operation of existing NPPs for 60 years of operation or more. • Studies should be carried out to ensure extended (dry) storage of spent nuclear fuel satisfies the highest safety and security requirements. • Devote more effort to safety research and communicate results to a wide audience. • A national skills evaluation should be undertaken to quantify the need for a skilled nuclear workforce. • International co-operation is needed to help transfer nuclear training programmes from existing nuclear countries to newcomer countries. • Student exchange programmes aimed at newcomer countries should be developed and where possible include a period of practical work experience at a nuclear facility.
Financial institutions	• Export credit agencies should continue to support nuclear financing by providing loan guarantees. • Pension funds and other institutional investors should consider investments in NPPs. • Development banks could support nuclear training and capacity development needs in new comer countries.

Annex

Nuclear energy case studies

www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy.html

Case studies have also been developed together with various nuclear energy stakeholders to help illustrate lessons learnt and good practices in the development of nuclear energy. The inclusion of these cases within the roadmap are aimed at providing additional insights and practical support for the recommendations and proposed actions in this roadmap.

Topic	***Case study description***
Nuclear new build	Lessons learnt from Gen III construction projects: Experience in Japan on construction of Gen III reactors.
	IAEA milestone approach for national nuclear infrastructure: UAE's experience.
	Environmental impact assessments: Lessons learnt from Finland.
	Setting up a supply chain in China.
	Preparing for new build in Italy.
Decommissioning	Decommissioning in Germany: E.ON's experience with decommissioning of Stade NPP and Würgassen NPP.
Waste management	Recycling of spent fuel: Experience with nuclear fuel recycling in France.
	Deep geological disposal in Sweden: Lessons learnt on implementation of a DGD facility.
Operations	WANO peer review process: The World Association of Nuclear Operators brings together operators from every country in the world with the objective of achieving the highest levels of operational safety and reliability.
	Integrated architect-engineer model: France's experience with implementing a model to increase safety and performance of plants by maximising the use of experience feedback.
	Research for extended operation of NPP: US research focused on life time extensions of up to 80 years or beyond.
	International collaboration amongst regulators: Multinational Design Evaluation Programme is an initiative to develop innovative approaches to leverage resources and knowledge of national regulators.
	Enhanced safety standards in Japan: Summary of new measures implemented after the Fukushima Daiichi accident.
Financing	Financing of new units at the Vogtle plant: Measures used in the United States to facilitate financing.
	Akkuyu build, own and operate model: Rosatom's model to facilitate deployment of nuclear projects.
Education and training	Nuclear skills assessment in the United Kingdom.

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

2DS	2 degrees Celsius Scenario in *Energy Technology Perspectives 2014*
6DS	6 degrees Celsius Scenario in *Energy Technology Perspectives 2014*
ADS	accelerator-driven systems
ASEAN	Association of Southeast Asian Nations
ASTRID	advanced sodium technological reactor for industrial demonstration
BOO	“build, own and operate” model
BWR	Boiling water reactor
CANDU technology	CANada Deuterium Uranium
CEFR	China experimental fast reactor
CGN	China General Nuclear Power Corporation
CNRA	Committee on Nuclear Regulatory Activities
DGD	Deep geological disposal
EDF	Électricité de France
ENEN	European Nuclear Education Network
FANR	Federal Authority for Nuclear Regulation
FNR	fast neutron reactors
FOAK	first-of-a-kind
GCR	gas-cooled reactor
Gen II	Generation II
Gen III	Generation III
GFR	gas-cooled fast reactor
GHG	greenhouse gas
GIF	Generation IV International Forum
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFNEC	International Framework for Nuclear Energy Cooperation
IFNEC	International Framework for Nuclear Energy Cooperation
INES	International Nuclear Event Scale
INIR	Integrated Nuclear Infrastructure Review
ITER	International Thermonuclear Experimental Reactor
LFR	lead-cooled fast reactor
LWR	Light water reactor
MDEP	Multinational Design Evaluation Programme
MOX	mixed oxides of plutonium and uranium
MSR	molten salt reactor
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
NPP	Nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRA	Nuclear Regulation Authority
NSREG	European Nuclear Safety Regulators Group
NUGENIA	NUclear GENeration II and III Association
OECD	Organisation for Economic Co-operation and Development
PFBR	prototype fast breeder reactor
PHWR	pressurised heavy water reactor
PSA	probabilistic safety assessment
PV	photovoltaics
PWR	Pressurised water reactor
R&D	Research and development
RBMK	Reactor Bolshoy Moshchnosti Kanalnyy (High-power channel-type reactor – graphite-moderated boiling reactor)
RU	recycled uranium
SCWR	supercritical water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SNF	Spent nuclear fuel
UAE	United Arab Emirates
VHTR	very-high-temperature reactor
VHTR	Very-high-temperature reactor
VVER	Water-moderated water-cooled power reactor
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association
WNA	World Nuclear Association
WNU	World Nuclear University

Units of measure

°C	degree Celsius
Gt	gigatonnes
GW	gigawatt
GWel	gigawatt electrical capacity
GWh	gigawatt-hour (109 watt hour)
kW	kilowatts
kWh	kilowatt-hour (103 watt hour)
MW	megawatt (106 watt)
MWh	megawatt-hour (106 watt hour)
tHM	tonnes of heavy metal
TWh	terawatt hours

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INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its mandate is two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply and to advise member countries on sound energy policy.

The IEA carries out a comprehensive programme of energy co-operation among 29 advanced economies, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports.

The Agency aims to:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

IEA member countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea (Republic of), Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also participates in the work of the IEA.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

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