Oxford Review of Economic Policy, Volume 35, Number 2, 2019, pp. 183–196

The age of electricity

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Abstract: The age of electricity is coming, driven by rapid technological change. On the demand side, the digitalization of many processes is leading to technologies that require electricity, rather than liquid or solid fuels. On the supply side, renewable energy technologies provide electricity directly, at falling cost. Electrification, directly and indirectly (e.g. using electricity to produce hydrogen fuel) can aid the decarbonization of the economy; strong climate policy would accelerate electrification. The big question is when, not if, and the transition is not occurring anywhere near fast enough to meet the Paris climate goals. The immediate impact of the coming age of electricity is the transformation of electricity markets, which need to adapt to near zero marginal costs and intermittency. In the longer term, the impact on fossil fuels will be radical. Fossil fuel prices will fall with demand, and the oil and gas majors will either completely transform themselves or will harvest profits and exit.

Keywords: electricity markets, climate change, fossil fuels, intermittency, capacity markets

JEL classification: Q40, L94, O13

I. Introduction

Access to energy, along with food and water, is a prerequisite for all economic activity. Major economic advances are often strongly associated with advances in energy (Toman and Jemelkova, 2003; Bacon and Masami, 2016). From human labour to horse power, to coal and then oil and gas, each transition to more advanced energy technologies has pushed the frontiers of population and economic growth. The industrial revolution was built on coal, and the great twentieth-century transformation was built on coal, plus oil, and then gas (Smil, 2010).

Fundamental changes in energy markets are caused by fundamental technological advances. In the nineteenth and twentieth centuries it was the steam engine, the coal power station, the internal combustion engine, and the Haber–Bosch process for manufacturing artificial fertilizers. Aircraft, modern petrochemicals, and the gas turbine provided the subsequent boost to the great age of fossil fuels.

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doi:10.1093/oxrep/grz005

In the twenty-first century, it is again technical change which is driving the next transformation. This time it is digitalization and electrification of the economy. The emergence of the internet and rapid falls in computing power have enabled mass digitalization and connectivity of economic processes, which has thrown up great opportunities in big data, machine learning, and artificial intelligence, along with advances in robotics and cutting-edge manufacturing.

All these technologies overwhelmingly consume energy, some of them intensively, in the form of electricity, rather than primary oil, gas, or coal. Fossil fuels are, of course, transformed at scale into electrical energy, but alongside the electrification of the demand side has come a host of new and renewable electricity technologies on the supply side. These technologies produce electricity directly from the sun or the wind, without the need for combustion of a fuel (with its associated environmental pollution), and without conversion of heat into electricity using a turbine (with associated efficiency losses). While such technologies are typically intermittent, the very same digitalization enables a smarter and more responsive demand side, and rapid advances in storage technologies look set to be able to better manage the imbalances between supply and demand. It is a technical transformation of both the economy and the energy sector.

This paper first reviews the main reasons for the forthcoming age of electricity (section II). We then turn to the environmental issues, particularly the carbon constraint and why reducing emissions requires not just the shift to renewables for electricity generation, but greater direct or indirect electrification of other key sectors, too (section III). While previous transitions have happened without the need for much by way of energy policy to facilitate take-up, the shift to electricity raises special questions about market design and regulation, and hence may require significant interventions. These are made more urgent because of the pressing decarbonization agenda. This paper describes the main policy strands—on innovation and R&D, on market design, on capacity and security of supply, and on the allocation of the largely fixed system costs (section IV). The impact of near zero marginal cost technologies on wholesale markets necessitates revisiting not just the market designs, but also the corporate landscape and the associated market frameworks (section V).

Once appropriate market designs and system operators are in place, the coming of the age of electricity will depend on the speed of technical change. Oil-producing companies assume that the peak in oil demand will not come before 2040, and that gas will continue much further into the second half of the century. Some argue that coal will persist, too. This is too late for the climate change agenda, but it also fails to take account of the speed of not just the technical advances but the falling costs of renewables (section VI). Finally, we draw together policy recommendations to set the framework for the great transition to the age of electricity (section VII).

II. Why we are entering the age of electricity

There has always been a close relationship between the energy industry and economic activity. Access to energy has been a question of life or death for humans for millennia. More recently, the major industrial revolutions have been correlated with advances in energy technologies. The causal link remains debated by economists, but it is likely bidirectional—the energy system evolves to support the demands made of it by the economy as a whole, while at the same time innovations in the energy sector can facilitate or enable important new technologies and production processes in the wider economy (Burke *et al.*, 2018).

Major technology revolutions often have a long fuse, and the age of electricity is no exception. The transition now under way has its origins in concepts from physics, built on phenomena observed in antiquity and gradually understood in the nineteenth century by the great scientists Coloumb, Faraday, Ampère, and Maxwell, among others. Great innovators, such as Edison and Tesla, worked out the practical applications of these new concepts in the mid-nineteenth and at the beginning of the twentieth century. Electric vehicles, for instance, are not entirely novel, having emerged in the late nineteenth century (Kirsch, 2000).

The invention of these technologies, however, only gradually led to an increase in demand for electricity. Electricity's share of final energy demand has risen from roughly 0 per cent a century ago to around 20 per cent today (IEA, 2018). The remaining demand is met through the direct use of coal, oil, and gas, particularly in heating, industrial applications, and transport.

From 20 per cent today, electricity's share of final energy demand is projected by the International Energy Agency (IEA) to rise gradually to 25 per cent by 2040 (IEA, 2018). The World Energy Council (2016) expects demand for electricity to at least double, while others model this possibility at over 60 per cent of energy demand by 2060, in a world where energy demand continues to grow, implying a fivefold increase in electricity generation (Energy Transitions Commission, 2018). While there is much uncertainty over longer timescales, and in particular in respect of the speed of the electrification of transport, all projections show a strong rise in electricity's share.

The drivers of this increase in electricity production and consumption are to be found on both the demand and the supply side.

On the demand side, the advent of computing technologies, networks, and the internet has led to the gradual digitization of much economic activity. These enabling technologies have created large-scale opportunities across a range of economic sectors. In manufacturing, the increasing use of robotics and advanced manufacturing methods is augmenting the physical capital base. These technologies do not run on oil or gas—they all require electricity, which is the energy carrier for a digitized world. These very same enabling technologies are conveniently increasing the flexibility of the demand side for electricity, just at the moment the electricity supply side is becoming more inflexible. Increasingly, manufacturing facilities will be able to speed up production when power prices are low on windy or sunny days, and slow down or even come to a pause as power prices rise in calm weather or when the sun is down (Beier *et al.*, 2015; Keller *et al.*, 2016; Helm, 2017*a*).

While electrification has many advantages, some parts of the energy system are easier to electrify than others, and in some sectors complete electrification along the entire chain seems unlikely. For instance, Cédric Philibert (2019, this issue) reviews the prospects for electrifying heat, industry, and transport, either directly or indirectly.[1] The

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[1] The idea of indirect electrification is that energy demand is met through solar and wind energy, harvested by the production of electricity which is subsequently converted by electrolysis to hydrogen or another liquid fuel. Indirect electrification is likely in situations characterized by either long-duration storage, and/or long-haul transportation, including the transport of energy itself from resource-rich areas to consuming centres.

key technologies to meet demand—such as the use of renewable electricity for electrolytic generation of hydrogen and hydrogen-rich fuels from water—are available, and the challenges of meeting heat, transport, and industrial needs from renewable energy, with electricity serving as an energy carrier at some point, are far from insurmountable.

On the supply side, the cost of renewable electricity generating technologies and storage has fallen sharply over the last decade[2] (IRENA, 2017). This has been driven by a combination of fundamental research and development (R&D), with breakthroughs achieved despite relatively low levels of public R&D support, and with generous subsidies for deployment (Kammen and Nemet, 2005; Gan *et al.*, 2007).

Renewables subsidies have been both sharply criticized and praised. Although they have contributed to declining costs, many subsidies were arguably far from efficient—cheaper strategies might have been deployed (Popp, 2006; Toke, 2007; Lesser and Su, 2008; Frondel *et al.*, 2010; Helm, 2015; Newbery, 2018). Irrespective, one of the challenges is that any policy aimed at deploying renewable electricity technologies must account for two conflicting challenges. First, investors in subsidized long-lived generation assets require some level of policy credibility (Helm *et al.*, 2003) and confidence about the commitment to maintain the support and the returns on investment. They do not want policy frameworks to change in a way that undermines their investments. On the other hand, technological progress in the sector is happening so rapidly that policy-makers rationally value the flexibility to adjust incentive structures as the facts unfold. In principle, a well-designed renewable subsidy regime could navigate these trade-offs.

However, in many instances, policy-makers have failed spectacularly. In Spain, subsidies were offered and then retroactively removed once investors had sunk capital (Espinosa and Pizarro-Irizar, 2018). The scandal surrounding the Northern Ireland Renewable Heat Incentive scheme brought down the Northern Ireland Executive.[3] The challenge is tackled analytically by Erik Gawel and Paul Lehmann (2019, this issue), who compare flexibility embedded *ex ante* in 'policy design' by formulaic changes as a function of unfolding events, with *ex post*, *ad hoc* 'policy adjustment'. They argue that some combination of both sorts of flexibility is optimally required to manage the inherent trade-offs in the transition to a decarbonized power grid. Retroactive interventions, which can also only undermine sovereign credibility, are not a sensible part of the policy mix.

In sum, for powerful reasons both on the demand and the supply side, an age of electricity now appears to be inevitable. The only question is the pace of change. It will not be stopped by policy errors, but could be accelerated by sensible interventions. And acceleration matters enormously for the environment.

III. The carbon constraint and air pollution

The pace of the coming of the age of electricity is of central importance to future climate stability. Left alone, the technological and economic forces discussed in the

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[2] Battery costs have fallen 79 per cent since 2010.

[3] See www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/about-non-domestic-rhi/northern-ireland-renewable-heat-incentive

previous section will electrify production and consumption at a reasonably rapid rate. But this is not fast enough to meet internationally agreed climate goals.

There are two central points in the economics of decarbonization. First, emissions must reach net zero for temperatures to stabilize at any level, whether well below or well above 2°C (Rogelj *et al.*, 2018). The implication is that to stabilize temperature, the entire global economy must be decarbonized, implying an unprecedented rewiring of economic production processes and supply chains. There is scant evidence that this is going to happen on the required timescale: most projections have oil production holding up until at least 2040 (McGlade and Ekins, 2015; IEA, 2016; Rogelj *et al.*, 2018) and the IEA anticipates continued high coal production, too, through the 2020s and into the 2030s (IEA, 2018). Much faster decarbonization would be required to meet the Paris objectives.

Second, and a corollary to the first point, there is a given carbon budget that should not be exceeded for any given level of warming. So to meet the 2°C or 1.5°C target, the total remaining carbon budget can be calculated (Millar *et al.*, 2016). This provides an indication of the necessary speed of decarbonization of the electricity sector and electrification of the economy.

Such calculations have, indeed, been made for the electricity sector (Pfeiffer *et al.*, 2016, 2018; Smith *et al.*, 2019). Assuming that all sectors are perfectly on track to meet a 2°C budget (which they are not), and assuming that the power plants in existence operate for their normal economic lifetime at normal levels of carbon intensity, the installed electricity generating capital stock from fossil fuels is near or already exceeds the Paris budgets (Pfeiffer *et al.*, 2016, 2018; Smith *et al.*, 2019). Moreover, while it is notable that, in 2018, 70 per cent of the new electricity generating capacity installed was renewable (REN21, 2018), this implies 30 per cent was not—the installed fossil capital base is still increasing, not decreasing as it would need to be. To give further perspective, China will soon reach 1,000 GW of coal generating capacity, is building 250 GW more, and sponsoring over 200 more coal projects abroad through the Belt and Road Initiative (BRI) (Peng *et al.*, 2017).

To meet the Paris goals, the electricity sector would need to provide a significantly greater share of demand than it does currently—many sectors of the economy need to decarbonize by electrifying themselves, directly or indirectly, as noted above. Much of transport might end up being electrified; so too with many industrial applications. The energy required for fertilizer for agriculture, currently delivered from natural gas to ammonia to urea-based fertilizers, might come from solar and wind to hydrogen before the transformations to ammonia and urea by the Haber–Bosch process. In short, not only does electricity need to be decarbonized, but other economic sectors need to be electrified, directly or indirectly, in order to be decarbonized. The gap between what is likely, on a business-as-usual trajectory, and what is required to meet the targets is enormous.

Finally, a less global but perhaps more potent environmental consideration is favouring electrification based on renewable sources—local air pollution. The latest World Health Organization report estimates that 7m people per annum lose their lives prematurely from air pollution (World Health Organization, 2018). In heavily polluted urban areas of China and India, air pollution reduces GDP due to days off work (0.3 per cent) and lower productivity at work (8.5 per cent), and also because there are fewer workers, given the early deaths (World Bank, 2016). By way of comparison, the air in many of these areas has the equivalent health impact to smoking a packet of cigarettes every day (Rohde and Muller, 2015).

So, climate change will be helped by the transition to the age of electricity (provided the sources of electricity are low carbon), but the transition is not occurring at the pace required to solve our pressing environmental challenges. Efforts to solve these environmental challenges are likely to further accelerate the prevailing trend to electrification.

IV. Policy and political economy in the age of electricity

In order to have a functioning energy system in an age of electricity, four omnipresent market failures need to be addressed by policy and regulation. First, environmental externalities (especially carbon, but also air and water pollution) need to be correctly priced. Second, market power needs to be controlled—in particular the natural monopoly of the electricity networks (the poles and wires). Third, security of supply, as a system property and hence a public good, needs to be ensured. Finally, there are market failures related to R&D and wider knowledge spillovers that need to be addressed.

Dieter Helm (2019, this issue) examines these failures in the context of considering the political economy obstacles to the reform of energy policy in Britain and specifically the *Cost of Energy Review*. One of his core points is that governments have not addressed these market failures, in part because the changes he proposes would reduce the significant economic rents in the system. The vested interests that benefit from such rents have successfully lobbied against change, resulting in higher total costs to consumers.

Helm sets out a set of solutions. On carbon, he recommends bolstering the existing carbon floor price (CFP) to a level to ensure that the UK's domestic carbon budgets are met, and coupling this price with a border carbon adjustment to achieve a level playing field between domestic and foreign emissions. With a higher and border-adjusted price, many of the other carbon-related subsidies could be reduced or eliminated. The net costs of decarbonization would be lower.

On both market power and security of supply, Helm argues for a fully independent, publicly owned, national system operator (NSO), as is currently in place in Australia, for instance, and a network of publicly owned regional system operators (RSOs). At present in Britain, National Grid both operates the system and owns many of the assets, creating conflicts of interest.

In the British context, the problems are unlikely to be rapidly addressed. Helm critiques the November 2018 response to the Review by the Secretary of State, Greg Clark, arguing in particular that while some of the principles in the *Cost of Energy Review* are accepted, Clark keeps open the door to retaining, or even adding to, the existing 'thicket' of interventions (Clark, 2018).

Interests that prevent efficient markets in energy are unlikely to vanish overnight, either in the United Kingdom or elsewhere. However, given the more even distribution of renewable electricity, compared to the geography of fossil fuels, and given the declining costs due to strongly competitive markets in solar and wind, it appears likely that the rents in the energy sector may gradually decline, eventually reducing resistance and enabling policy change.

V. Near zero marginal cost and market design

A key feature of renewable electricity generating technologies is that they have close to zero marginal costs. Unlike thermal electricity generation, which requires the purchase and combustion of coal, oil, or gas, the incoming energy from the sun and the wind is free, and marginal costs are limited. This represents a radical departure from the conventional cost structure of electricity markets.

Industries with high fixed costs and close to zero marginal costs are, in fact, increasingly common. Interestingly, many of the new digital industries share precisely this feature—once a digital product has been produced, the cost of making a copy or supplying it to an additional consumer is close to zero, given the non-rival nature of digitized information (Anderson, 2009; Rifkin, 2014). In such markets, prices cannot equal marginal costs of zero (as they do in a perfectly competitive market). If they did, companies could not recover any of their fixed costs.

There are a number of possible functional structures for a market with zero marginal cost. Producers can seek to charge a subscription for access, after which the consumer can consume without limit. This is not dissimilar to the structure in place in broadband markets. Alternatively, producers can seek to bundle other value-added products with the zero marginal cost product. Tiered pricing can also work in some instances, where there is a 'freemium' alongside a 'premium' service, that might be volume or quality related (Anderson, 2009).

In the electricity industry, it is unlikely that the conventional market structure will persist in the long term. Rather, some form of capacity mechanism (CM) or payment has already been grafted on to the existing markets, so that consumers pay for both energy and the availability of the capacity to generate that electricity. By contrast, Frank Wolak (2019, this issue) advances a largely conventional market structure, arguing that standardized futures markets for energy can still ensure security of supply, without the need for a CM. He cites findings that a standardized and liquid futures market can increase competition and drive prices down towards marginal cost. With strong liquidity, new players can enter the retail market and hedge their risk with a portfolio of forward contracts, enabling them to compete with incumbent suppliers.

Wolak argues that his approach is ideally suited to markets with a significant share of intermittent renewable generation, on the basis that the concept of 'firm capacity' makes little sense in a world of intermittent generators. However, his approach effectively pushes the requirement of security of supply on to market participants. Without government intervention, the private penalties involved for breach of contract (e.g. when a renewable generator fails to deliver as promised) are unlikely to be equal to the social costs of the lights going out.

In contrast, Paul Joskow (2019, this issue) is more sceptical of current electricity market structures. Even before the challenges created by large-scale deployment of wind and solar, wholesale electricity markets have not been particularly effective at incentivizing investment in new power generation. Joskow argues that to deal with the challenges created by intermittent renewables, traditional wholesale markets should be extended to include capacity markets, scarcity pricing mechanisms, and linkage of spot wholesale and retail prices to facilitate demand-side response. Instead of these more market-oriented extensions, however, he fears more direct government interventions, because non-market support for intermittent generation is incompatible with relying on markets for the rest of the electricity generating portfolio. Joskow thus argues that a separate market of long-term contracts is required to attract investment desired by governments.

This is largely consistent with the idea advanced by Helm (2017*b*), who also advances a CM in the form of an equivalent firm power (EFP) auction for capacity. Helm argues that such a mechanism could replace all the current mechanisms for supporting new electricity generation, such as feed-in tariffs for renewable energy, and contracts for difference to resolve security-of-supply concerns. The mechanism would de-rate, or discount the value of, intermittent capacity as a function of its contribution to overall system security at times of peak demand. As a result it places the costs of intermittency with those who cause it and incentivizes those intermittent generators to try to improve their re-rating factors by contracting with back-up suppliers, demand-side reductions, and storage directly and in secondary markets. The EFP proposal is not radically different from the current CM that was put on ice on 14 November 2018, following a procedural decision on state aid by the European Court of Justice.[4] The core differences are in the full integration of renewables into a single capacity market and in the calculation of the de-rating factors.

It is, indeed, likely that CMs will also be put in place to ensure security of supply, and this is already happening in Europe, as Fabien Roques (2019, this issue) observes, but in a somewhat ad hoc and uncoordinated manner. He provides a helpful taxonomy of the different sorts of CMs used across different countries (see his Figures 1 and 2).

This patchwork of capacity markets is not conducive to rational energy market integration across Europe. In some cases, market design choices may even undermine the very objective the mechanisms are aimed at meeting—security of supply. The core issue arises from the requirement on the part of the EU that CMs must be open to cross-border participation, such that foreign capacity can bid into such markets. But will the foreign capacity be there in a crisis? Provided there is no crisis in the neighbouring country, foreign capacity may well come to the rescue. But what are the odds of crises happening in both countries at the same time? Unfortunately, those odds increase as more renewables, subject to correlated availability of sun and wind, are added to grids.

This is not to say that wind and solar availability are always and everywhere positively correlated across neighbouring countries. But the brute reality is that in the event of power shortages in two neighbouring countries, each country is likely to keep crucial power supplies at home.

In theory, part of the solution to such problems is a fully-fledged cross-border capacity mechanism as part of the Internal Energy Market. In practice this is not going to happen in the short term, and Roques (2019) sets a more plausible pathway forwards to implement coordinated CMs.

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[4] See the decision of the General Court of the Court of Justice of the European Union in Case T-793/14 at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2015.081.01.0021.02.ENG&toc=OJ:C:2015:081:TOC.

VI. The implications for gas, oil, and coal companies of the age of electricity

The transition to the age of electricity, as the previous sections demonstrate, threatens the very existence of powerful incumbents. Companies focused on mining coal and extracting oil and gas from the ground for combustion will, over the course of the next few decades, need to change business model or face closure. There are two main drivers: the impact of zero marginal costs on market structures; and the climate-change goals. The first is sufficient to trigger major changes in company structure and strategies; the second would speed these reactions to the technology-induced changes in the cost structures of the industries.

The structure of conventional fossil fuel producers, and incumbent large electricity utilities, has been vertical integration. The internalization of production, generation, transmission and distribution pipelines, wires and ocean transport, and supply is a response to large upstream sunk costs and the dominance of wholesale energy markets.

As more zero marginal cost electricity generation comes on to the market, and as the share of electricity rises, the future role of the electricity wholesale market will gradually shrink to balancing in response to intermittency, providing price signals to batteries and other forms of storage, along with digitalized demand flexibility.

The shift in cost and market structure creates an environment in which new business models can develop and emerge, threatening the vertically integrated incumbent electricity companies. These players now face serious economic and financial challenges. The organizational structures and competencies of the incumbents will need to evolve to adapt to the new and emerging underlying cost conditions.

For the conventional oil and gas companies, whether national oil companies (NOCs), which control 90 per cent of global reserves (Tordo, 2011), or the international oil companies (IOCs), their future is constrained by their history and corporate specialisms, and by the prospect of eventual peak oil (and possibly even gas) demand, and falling long-term prices as they compete with excess supply and diminishing demand.

Though there are examples of companies that have made a transition from one set of corporate skills to another, the new context of decentralized renewable electricity, storage and demand management, is not one for which they are currently well equipped. The lessons from BP and Shell's past forays into alternative energy are salutary (Miller, 2013), and although many IOCs have returned to renewable electricity markets, the bulk of their financial returns (and corporate) emphasis at this stage remains in their conventional fossil fuel markets.

On a business-as-usual basis, the IOCs are well placed to continue to extract profits and dividends over several decades to come. The main projections from the IOCs point to a growth in demand through to around 2040 (ExxonMobil, 2017; Shell Oil, 2018; British Petroleum, 2018; IEA, 2018), even allowing for potential bans to internal combustion engines (British Petroleum, 2018; p. 45) and since the IOCs comprise a small proportion of the total market compared to the NOCs, and have technological advantages over these NOCs, remaining in oil and gas production with links to transport and the rapidly growing petrochemicals is a profit-maximizing strategy for them. The challenges to such a strategy are largely confined to global politics and policies to address climate change, since their projections are wildly incompatible with the 2°C or 1.5°C climate targets.

From a profit-maximizing perspective, are they right to assume that, notwithstanding the Paris agreement, not much is actually going to be done? The key increases in demand for energy are in China, India, and Africa. The growth in all three is still based upon fossil fuels. China, as already noted, is expanding its coal capacity, India is 80 per cent dependent on fossil fuels, and Africa depends heavily on mining and coal. Global carbon dioxide emissions have not peaked as environmentalists hoped (Le Quéré *et al.*, 2018). Russia has little or no interest in curtailing emissions: on the contrary, it has much to gain from opening up the Arctic north-eastern passage, enabling liquefied natural gas (LNG) exports to increase. It is investing in eight nuclear-powered icebreakers to speed this process (Brokeš, 2018).

Conventional oil and gas companies might consider themselves unlikely to face serious policy measures to reduce emissions in the fastest growing markets over the short to medium term. What does, however, pose a serious challenge is the impact of zero marginal costs in electricity feeding through into transport markets and more generally undercutting the growth in demand for fossil fuels as the electricity share rises in final energy demand. It is the technological changes, and the growing share of electricity, which are likely to have the more immediate impact on the incumbent companies and their strategies. The most important of these is the prospect of falling oil and gas prices.

Until the price falls in 2014, many political leaders, policy-makers, and pundits argued that oil supplies would peak (Parthermore and Nagl, 2010; Aleklett, 2012; Helm, 2015). In fact, there is no practical limit on the supplies of hydrocarbons (Maugeri, 2012; Helm, 2017*a*). Technological progress is not only found in the renewable industry, and the coming of large-scale shale oil and gas production (only a decade old) has already transformed global energy markets, with the US quickly moving to be the largest producer just ahead of Saudi Arabia and Russia, and heading to the number three slot in LNG exports (behind Qatar and Australia). As and when demand peaks, and with shale technology gradually globalizing, the supply–demand balance will shift towards falling prices. With the marginal costs of oil production at less than $10 in Saudi Arabia, with very large production potential in Iraq and Iran, and if and when Venezuela starts serious production again, with Russian marginal costs around $20, the scope for price falls is considerable.[5] Indeed, the recognition that oil tomorrow might be worth less than oil today might accelerate the scramble for market share (Sinn, 2012; Helm, 2017*a*).

There is an obvious and challenging feedback from falling oil (and gas) prices to electricity and the decarbonization agenda. The 'break even' price at which renewables are competitive with fossil fuels is a moving target. It is not enough to be cheaper than current fossil prices, given prices will eventually fall towards the extraction costs of the cheapest barrel. Recognizing this, the appropriate policy answer is to internalize the damage from carbon emissions with a carbon price accompanied by border carbon adjustments (BCAs) (Helm *et al.*, 2012). Indeed, the case for BCAs is all the more urgent, given the prospect of long-run falling fossil fuel prices. For oil companies, the strategic question is whether there is much chance that carbon taxes and BCAs will be applied. While carbon prices are expanding around the world (World Bank and Ecofys, 2018), they are a very long way off what is required, both in coverage and in price level. Investors in conventional oil and gas companies are likely to be relaxed about this threat

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[5] See http://graphics.wsj.com/oil-barrel-breakdown/

to their profit-maximizing strategies. From their perspective, harvest and eventual exit may be a dividend-maximizing strategy. (It is not surprising that IOCs tend to be high dividend paying companies.) They might eventually just 'burn out' (Helm, 2017*a*).

VII. Conclusions and policy recommendations

The age of electricity is coming. It is a question of when, not if. It is the product of deep technical change, involving the digitalization of many economic processes on the demand side and increasing direct sources of renewable electricity on the supply side. The world of the future is one that, directly or indirectly, will be overwhelmingly based upon electricity.

The fossil fuels will not, however, vanish overnight. The long lead times in two of the key markets for oil and gas—transport and petrochemicals—and the widespread failures of climate mitigation agreements and policies ensure that the fossil tail is likely to be decades long.

The most immediate impact of the coming of the age of electricity is the transformation of electricity markets. Near zero marginal costs and intermittency together create fundamentally different cost structures. The economic arrangements to reflect these new cost structures are already manifesting themselves in the emergence of new companies and business models, and especially in market structures and contracting arrangements.

There is much dispute about the future of wholesale electricity markets and the edifice of electricity and energy market policies erected upon them. Capacity markets have re-emerged, and the wholesale electricity market faces a declining relevance.

The transition is inevitably going to be a long one, but there are market interventions that aid this. Two key measures are to develop the capacity market designs, notably through addressing intermittency (and incentivizing firms to tackle it through peaking generators, storage, and demand-side technologies), and ensuring coordination of capacity markets between countries.

The papers in this issue provide a range of solutions, from increasing market depth and liquidity, to Equivalent Firm Power auctions, reforming system operation in markets like Britain's, where the operator and asset owners are not separated, and reforming the European internal energy market arrangements to explicitly address the harmonization of capacity markets and cross-border trading. These policies have the advantage of being efficient interventions, whether or not the wholesale markets wither away, and independently of how quickly the age of electricity is upon us.

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