DNV·GL

ENERGY TRANSITION OUTLOOK 2018
POWER SUPPLY AND USE

Forecast to 2050

SAFER, SMARTER, GREENER

UNDER EMBARGO UNTIL 10 SEPTEMBER 2018

FOREWORD

The energy transition is under way. Every day, we experience, hear, and see examples of how the energy sector is embracing the opportunities of transitioning to a cleaner future while addressing the uncertainties and challenges of unprecedented change.

DITLEV ENGEL

CEO
DNV GL - Energy

Companies across the sector tell me regularly that they see profound change ahead both short- and long-term. This relates to energy policies; emerging energy sources/technologies; and the pricing of existing and new technologies. A high fraction of solar and wind, for example, creates the need for increased use of market mechanisms and changes to the electricity market fundamentals currently in place in many countries.

Dramatic and rapid though the change is, our 2018 Energy Transition Outlook (ETO) unfortunately also tells us that the pace is insufficient to achieve the Paris Agreement's objective to limit global warming to 'well below 2°C'. Regulators and politicians will therefore need to re-think, re-shape and take major policy decisions about market models and the optimum allocation of future risks, including the unavoidable associated costs of stranded assets, if we are to decarbonize the world's energy system at the required speed.

In our 2017 ETO, I urged the sector, and all relevant industries and stakeholders, to take responsibility for ensuring a rapid global transition. Reinforcing this message, but with more urgency, I stress that more combined action is needed for a decarbonized energy future. It is important to remember that the costs of the world's energy system see a shift from operational expenditure (principally fuel) to capital expenditure. Despite major expansion of high-capital-cost renewables and electricity networks, total energy expenditures will fall substantially as a fraction of GDP over the period to 2050.

This annual Outlook, based on DNV GL's independent model of the world energy system, is undertaken to aid analysts and decision makers in the energy sector in developing strategic options. The model has been refined for 2018 with updated data and assumptions, and more detail on electricity grid expansion and costs, hydrogen, and the impacts of digitalization. Greater attention is also given to energy use and efficiency.

The implications outlined in this Power Supply and Use report are relevant to stakeholders across the energy value chain: consumers, investors, operators, owners, policymakers, regulators and suppliers. It foresees massive expansion of transmission and distribution networks, driven by increased electrification of energy use and the dispersed nature of wind and solar. We also predict that electric vehicles will proliferate rapidly.

We present key takeaways for stakeholders and discuss near-term trends to monitor. Although our model forecasts long-term trends, we have felt it useful to discuss developments such as rural electrification. This will likely coincide with expansion of solar photovoltaic generation to bring significant social and economic benefits to some of the world's poorest communities. 'Solar plus storage' could become the default option in many parts of the world.

> "We conclude that it will take several dedicated, synchronized actions to accelerate the transition if we are going to deliver on the Paris Agreement. Much is happening, but it is still not enough.

As in last year's Outlook, we conclude that it will take several dedicated, synchronized actions to accelerate the transition if we are going to deliver on the Paris Agreement. Much is happening, but it is still not enough.

Please explore for yourself the report and its wealth of information that can help steer your course of action for contributing to a safe, sustainable future. We all play a role, and can all do more.

Ditlev Engel

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Decades of rapid and extensive change lie ahead for the world's energy systems, particularly for power generation, networks, and electricity use.

The DNV GL Energy Transition Outlook model draws on our understanding and global experience to forecast these changes.

THE MAIN GLOBAL THEMES EMERGING OVER OUR OUTLOOK'S FORECASTING PERIOD ARE:

- Final energy demand growth slows, peaks in the mid-2030s at around 470 exajoules per year (EJ/yr), 17% higher than in 2016, then declines gently to 450 EJ/yr by 2050. This trend is driven by slowing population and productivity growth, greater efficiency of end-use (particularly in electrification of transport), and a lower share in the energy mix for fossil fuels at relatively low thermal efficiency.
- Growth in electricity consumption increases rapidly from now onwards, more than doubling its share of energy demand to 45% in 2050. This is driven by massive electrification of energy demand in all regions and sectors, particularly electric vehicles (EVs). In turn, this leads to major expansion of electricity transmission and distribution systems.
- Global primary energy supply also peaks in the early 2030s, and ceases to be dominated by coal, oil and gas. By 2050, the energy supply mix is split equally between fossil and non-fossil fuels, with much more renewables, and volumes of oil and coal more than halved.
- Electricity production becomes dominated by renewables; solar photovoltaic (PV), onshore wind, hydropower, and offshore wind, in that order. These renewables together account for 80% of global electricity production in 2050. Much of this will be large-scale, i.e. utility-scale PV and offshore wind farms. The variability of solar and wind will require the provision of additional flexibility through several options, including storage and demand-side response.
- The costs of the world's energy systems see a shift from operational expenditure (principally fuel) to capital expenditure. Despite major expansion of high-capital-cost renewables and electricity networks, total energy expenditures fall substantially as a fraction of GDP over the period to 2050.

MAIN IMPLICATIONS

These main themes, and others stemming from the model's results, generate several important implications for stakeholders across the energy value chain, and for consumers, policymakers and regulators. Here, we summarize some of these prior to discussing them more fully later in this report.

MAJOR CHANGES INVOLVING ESTABLISHED ENERGY INDUSTRY PLAYERS WILL SPREAD AND DEEPEN

We are already seeing large investments by the oil majors, for example in EV charging networks. Some are beginning a transition from 'oil and gas' to 'gas and oil' and, eventually, 'energy' suppliers. On this journey, they find themselves competing with established electricity utilities (both as electricity network owners and as electricity suppliers), who are also looking for new roles and business models. These trends will continue.

It is also noticeable that large technology companies such as Google and Amazon, and long-established engineering companies, are developing new business models and considering new roles in energy supply and use. Business model changes may cause significant shifts in demand for products, and therefore for energy, as some sectors of the economy move from ownership to service 'pay-as-you-use' models. Major drivers are:

- The new possibilities provided by digitalization
- Large-scale electrification of energy demand, as reflected in our forecast
- A wider range of electricity generating technologies, principally solar and wind, at very different scales from rooftop PV upwards.

DOMINANT VARIABLE RENEWABLES WILL BE A MAJOR FACTOR IN MARKETS, REGULATION, AND NETWORKS

High fractions of solar and wind will create the need for increased use of market mechanisms and changes to the electricity market fundamentals currently in place in many countries. This requires major regulatory intervention.

There is an issue with income for renewables, caused by the time-dependent impact on wholesale electricity prices. This results in lower average prices for wind and solar.

The variability of solar and wind will require provision of additional 'flexibility' through several options. They include storage, demand-side response, and greater interconnection capacity. Fossil-fuelled generators will move towards 'peaking' roles. Variability on seasonal timescales will be critical for the higher latitudes, particularly for northern Europe, North America and Greater China; in lower latitudes, different solutions are likely. Market-based price signals are crucial to incentivise innovation and development of economically efficient flexibility options.

The model estimates the costs required for coping with the variability of solar and wind, and finds that they are not high enough to significantly constrain the growth of renewables.

Variable renewables also encourage so-called 'sector-coupling', the use of surplus renewable electricity to produce hydrogen or other fuel gasses or liquids, or to supply heat networks. Both options offer opportunities for storage on longer timescales.

WE FORESEE MASSIVE EXPANSION AND AUTOMATION OF TRANSMISSION AND DISTRIBUTION NETWORKS

This will be driven by electrification of demand as well as the dispersed nature of wind and solar. For example, installation rates for transformers for distribution systems will double.

The timescales involved in planning and constructing electricity networks may require network operators to make decisions amid considerable uncertainty. Regulators will need to make decisions about the optimum allocation of the risks and associated costs of stranded assets. Large thermal generators will face considerably increased uncertainty.

In rural areas currently with weak or non-existent electricity networks but good renewable resources, 'microgrids' at household to village scale are expected to increase; it is not clear whether these will win out eventually over traditional network reinforcement.

There will be more 'behind-the-meter' generation on industrial, commercial, and residential premises, and increased demand-side response. The system operators' tasks will become substantially more complex: yet there may well be less energy flowing across networks in total, resulting in fixed costs becoming a greater part of the bill.

Increased reliance on electricity networks will require sufficient operational security. They may be vulnerable because they are spread across extensive territories, serve huge numbers of end-points, and use equipment from multiple suppliers, with items being added or modified daily. Increased capability in monitoring and automation of networks is a clear response. Very high levels of cyber security will be needed.

USE OF EVs WILL ESCALATE RAPIDLY AND CHANGE THE WAY CONSUMERS VIEW ENERGY SUPPLY

Electrification of transport, especially private vehicles and 'last-mile' freight, will be quick. Home-charging of an EV may become a household's dominant load, and can be used to provide services to the energy supplier and to the electricity network operators. Business models for EV charging may evolve to incorporate all a household's electricity supply, including behind-the-meter solar PV and storage.

Total volumes of EVs are likely to provide substantial flexibility benefits to aid integration of renewables. It will be important to establish how much of these benefits can or will be made available by the vehicle users.

> "Regulators will need to make decisions about the optimum allocation of the risks and associated costs of stranded assets.

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

Driven by our purpose of safeguarding life, property, and the environment, DNV GL enables organizations to advance the safety and sustainability of their businesses.

We are a global provider of risk management, assurance, and technical advisory services in more than 100 countries. Approximately 70% of our business is energy-related. Two of our main business areas are focused on the oil and gas, and renewables and power sectors. As the world's largest ship classification society, vessel fuels and the seaborne transportation of energy as crude oil, liquefied natural gas (LNG), and coal are also key topics for us.

This publication is one element of DNV GL's suite of Energy Transition Outlook (ETO) reports. In all, four publications provide predictions through to 2050 for the entire world energy system. The Outlooks are based on our own independent energy model, which tracks and forecasts regional energy demand and supply, as well as energy transport between regions.

Our ETO was first published in September 2017. Based on our insights and knowledge of these industries, we have since updated and refined our independent forecast of the world's energy future and how the energy transition may unfold. We have shared with stakeholders and customers our foresight into and high-level analyses of supply and demand trends, and have secured feedback from them to update our model.

The revised forecast is included in this 2018 Energy Transition Outlook, which also considers the implications for industries involved in electricity generation, transmission and distribution.

Alongside the company's main Outlook report[1], the suite includes three reports discussing implications for separate industries: oil and gas[2]; power and renewables[3] (this report); and maritime[4].

Our core ETO model is a system dynamics feedback model, implemented with the Stella modelling tool. It predicts energy demand and the energy supply required to meet it. Key demand sectors such as buildings, manufacturing, and transportation (air, maritime, rail and road) are analysed in detail.

In a somewhat crowded field of energy forecasting, our work seeks to create value through:

- Source-to-sink treatment of the entire energy system, including, for example, the impact of increased global transport of LNG on emissions from ships
- Focus on technology trends and needs for the future
- Focus on the ongoing transition rather than on the status quo of the energy system.

1 'Energy Transition Outlook 2018, A global and regional forecast to 2050', DNV GL, September 2018
2 'Energy Transition Outlook 2018: Oil and gas, Forecast to 2050', DNV GL, September 2018
3 'Energy Transition Outlook 2018: Power supply and use, Forecast to 2050' DNV GL, September 2018
4 'Maritime, Forecast to 2050, Energy Transition Outlook 2018'

In this report for the power and renewables industries, we review our ETO forecasts' implications for key stakeholders in several industries which DNV GL advises and assists: electricity generation, including renewables; electricity transmission and distribution; and energy use[5].

Amongst other changes from the 2017 approach, there is greater attention to energy use and efficiency, as it is now clear that the complexity and range of options are of major significance for many of our customers. Electricity grid costs and hydrogen (H_2) are considered in more detail, as are the impacts of digitalization. Further, our treatment of renewable generation, especially solar and wind, reflects their status as the 'new conventionals' rather than challenger technologies.

The implications are intended to be relevant for investors, owners, operators, suppliers, consumers, regulators and policymakers.

More detailed analysis, based on our model, is available from DNV GL on request. We can tailor such content to the needs of individual organizations and companies.

We also stress that we present only one 'most likely' future, not a collection of scenarios. The coming decades to 2050 hold significant uncertainties. These are notably in areas such as future energy policies; emerging energy sources such as H_2; human behaviour and reaction to policies; the pace of technological progress; and trends in the pricing of existing and new technologies. A full analysis of sensitivities related to our energy system modelling is available in our main report.

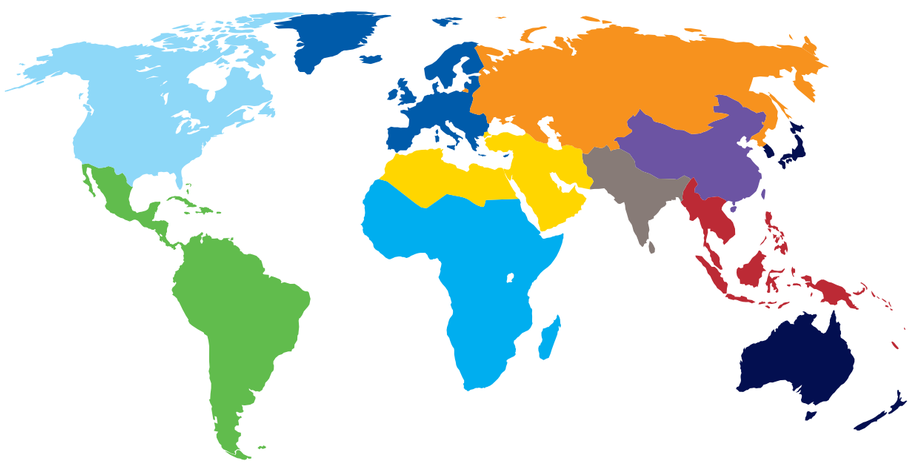
It should also be noted that we have modelled oil and gas production independently of each other. They are often interconnected, and this limitation should be considered when reviewing the results.

> "The coming decades to 2050 hold significant uncertainties. These are notably in areas such as future energy policies; emerging energy sources such as H_2; human behaviour and reaction to policies; the pace of technological progress; and trends in the pricing of existing and new technologies.

5 A large part of total energy consumption is due to water and space heating. However, most heat is generated by the end user; so, its impact appears in our results as demand for fuels. Consequently, this report does not cover heat supply as a separate topic.

This Outlook divides the world into 10 geographical regions as show in the map below. They are chosen based on location, resource richness, extent of economic development, and energy characteristics. Each region's input and results are the sum of all the countries in it. Typically, weighted averages are used; countries with the largest populations, energy use, and so on, are assigned more weight when calculating averages for relevant parameters. Prominent characteristics of certain countries are averaged over the entire region. More detailed country-specific issues may be included in future analyses.

Map of the ten Outlook regions



- North America
- Latin America
- Europe
- Sub-Saharan Africa
- Middle East and North Africa
- North East Eurasia
- Greater China
- Indian Subcontinent
- South East Asia
- OECD Pacific

CHAPTER 2

KEY CONCLUSIONS FROM OUR 2018 MODEL

2 KEY CONCLUSIONS FROM OUR 2018 MODEL

This chapter summarizes the main results from our model which are relevant for this report. Full details are in the main ETO report.

2.1 PRINCIPLES

The model incorporates the entire energy system from source to end-use, and simulates how its components interact. It includes all sources supplying the energy, and the main consumers of energy (buildings, industry, and transport). We model the flow of energy carriers from primary energy supply to final energy demand, the point at which energy carriers are in final tradable form. This means, for example, that in modelling final energy demand we account for how much fuel is used by vehicles, but do not calculate the mechanical work done by these.

The model uses a merit order cost-based algorithm to drive the selection of energy sources. The evolution of the cost of each energy source over time is therefore critical, and learning-curve effects are taken into account.

WHAT IS NOT COVERED BY THE DNV GL OUTLOOK?

The focus of this Outlook on long-term transition means short-term changes receive less attention, and are generally not covered. They include both cyclical and one-off impacts; for example, from policies, conflicts, and strategic moves by industry players.

This Outlook does not reflect fluctuating energy prices caused by demand and supply imbalances, which, in the real world, and at certain times, may be quite different from costs.

This Outlook is built up by energy demand and supply considerations focusing on yearly averages. This approach does not in itself fully reflect the differential nature of variable energy sources. We do not model daily or seasonal variations, nor do we model grid stability or other short-term renewable energy dynamics. Instead, we add storage and back-up capacity to energy value chains with large shares of variable renewables. We regard the costs of these additions as part of the overall cost of renewables.

Technologies which in our view are marginal are typically not included, but we do include those new technologies which we expect to scale. Breakthrough emerging technologies are discussed, but not included in the model forecast. The exception is hydrogen, which is modelled and discussed.

Changing consumer behaviour, evolving travel and work patterns, social media and other sociological trends are discussed, but are included and quantified only in a few areas in our forecast.

Population and economic growth are the two main drivers of the demand side of the energy system in the model.

By design, the level of detail throughout the model is not uniform. Sectors where DNV GL has strong expertise and large business exposure, such as oil and gas, and power, are reflected in more detail than where we have little exposure, like coal. In addition, demand categories critical to the energy transition, such as road transport, are treated more thoroughly than more marginal ones.

It is also important to state what we have not reflected in our model. We have no explicit energy markets with separate demand and supply determining prices; our approach concentrates on energy costs, with the assumption that, in the long run, prices will follow costs.

The ETO model makes economic decisions to build new assets, such as electricity generating plants and gas import plants. It does not 'retire' assets until the end of their anticipated lifetime, even if revenue turns out to be less than operating costs: 'stranded assets' are assumed to continue in use.

The ETO model includes flows of fossil fuels between the 10 regions, but does not include cross-border electricity flows. This is justified by the very low levels of such flows at present, though this may change in future.

MEASURING ENERGY: TONNES OF OIL EQUIVALENT, WATT-HOURS, AND JOULES

Tonnes of oil equivalent (toe), watt-hours (Wh), or joules (J)? The oil and gas industry normally presents energy figures in multiples of toe; 1 million toe (Mtoe), for example. The power industry uses kilowatt hours (kWh). The SI system's main unit for quantifying energy is joules, but exajoules (EJ) when it comes to the very large quantities associated with national or global production. One exajoule is 10^{18} J, a billion billion joules.

As a practical example, it takes a joule of energy for a person to lift a 100-gramme smartphone by one metre. It is also the amount of electricity needed to power a one-watt (W) light-emitting diode bulb for one second. These examples illustrate that a joule is a very small unit of energy. When discussing global energy trends, we use EJ.

Another way of understanding energy quantities is to estimate the energy needed per person. The present amount of primary energy used per person averages 78 gigajoules (GJ) per year. A gigajoule is a billion joules. Shell (2016) estimates that it takes 100 GJ of primary energy per person each year to support a decent quality of life. In the much more efficient energy system of the future, we think less will be needed. We forecast that Europe's' average primary energy use per person will be 83 GJ in 2050, for example.

In this Outlook, we mainly use J or EJ as the unit of energy. In a few places, we use multiples of watt-hours (GWh, TWh) or Mtoe. The conversion factors that we apply are:

1 EJ = 23.88 Mtoe
1 EJ = 277.8 TWh

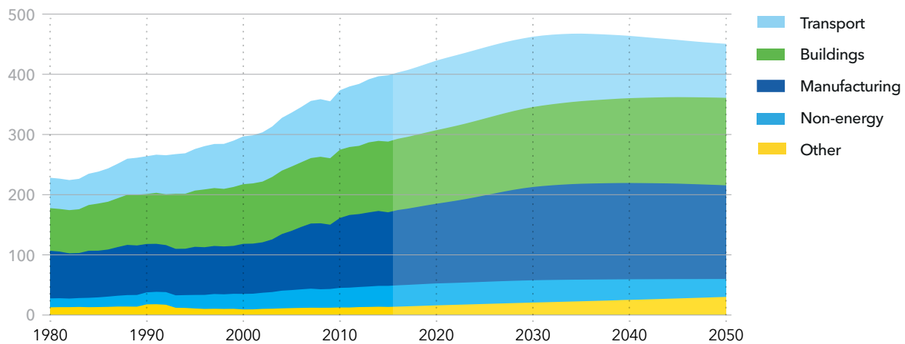
For example, the State Grid Corporation of China proposes ultra-high voltage direct-current transmission systems on an intercontinental scale.

We also do not incorporate political instability or disruptive actions that may revolutionize energy demand or supply, accepting that what constitutes 'disruption' is subjective. For example, we assume that the share of electric vehicles (EVs) in new light vehicle sales will increase from less than 10% to more than 90% within 10 years in many regions, though from varying starting dates. Some industry players are likely to experience this as disruptive, but the main focus of the ETO model is the impact on the energy system. The main report also contains analyses of uncertainties, i.e. the effects on the results of changing the most important or most uncertain assumptions.

FIGURE 2.1

World final energy demand by sector

Units: EJ/yr



2.2 ENERGY DEMAND

In our forecast, we see a world where energy demand will peak in the mid-2030s, a very distinct characteristic we have not seen since the dawn of the industrial revolution.

In 2016, total final energy demand was estimated at 400 exajoules per year (EJ/yr); we forecast an increase to 470 EJ/yr by 2035, thereafter slowly reducing to 450 EJ in 2050 (Figure 2.1). The world's energy demand rose by 35% over the last 15 years. In the coming 15 years, we forecast energy demand to increase by just 15% before peaking and levelling off then declining. This profound demand down-shift is linked to a deceleration in population and productivity growth, and to accelerating decline in energy intensity[6].

There is a marked transition by 2050 in the type of energy used across sectors (Figure 2.2). In 2016, electricity represented 75 EJ/yr (19%) of world final energy demand; by 2050, its share will be 45% at more than 200 EJ/yr. Electricity displaces both coal and oil in the final energy demand mix.

TRANSPORT

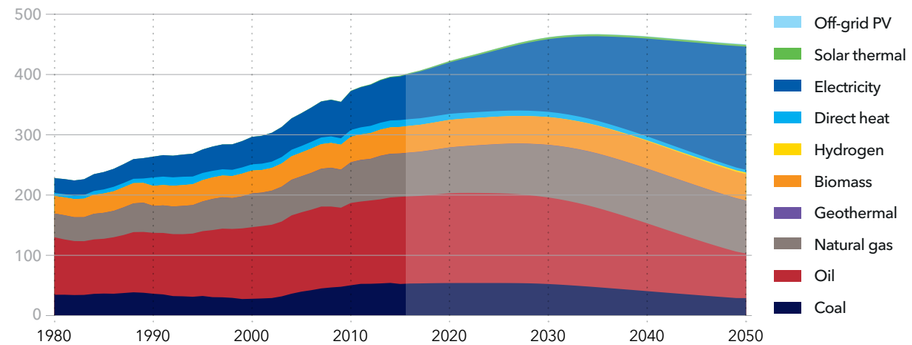
Energy demand for transport shows continuing growth, then plateaus at about 120 EJ/yr over the period 2020–2030 before declining to less than 100 EJ/yr by 2050 as mass electrification of the road sub-sector materializes. Our analysis indicates that uptake of EVs will follow an S-shaped curve resembling the fast transition seen with digital cameras, for example.

6 Energy intensity: the energy used per unit of output.

FIGURE 2.2

World final energy demand by carrier

Units: EJ/yr



The point at which half of all new cars sold are EVs will be just after 2025 for Europe; just before 2030 for the North America, OECD Pacific, and Greater China regions; and, just beyond 2030 for the Indian Subcontinent. The rest of the world will not follow until closer to 2040.

Recent advances in heavy-vehicle electrification and hydrogen (H_2) fuel cells entering the vehicle power mix indicate that 50% of sales of such vehicles could be powered by alternatives to internal combustion engines. We see this happening by just after 2030 in Europe and Greater China, followed five years later in both North America and OECD Pacific. The trend will be led by bus and city municipal fleets.

There will be a degree of electrification of shipping for some short-sector vessels, creating a requirement for charging infrastructure at harbours and ports. This is discussed in more detail in a companion report on the implications of our ETO model[7]. Where rail can be electrified, it will be by 2050[8]. We expect electrification of air travel to still be in its infancy by 2050.

BUILDINGS

World building energy demand will grow around 0.7% annually, heading towards 150 EJ/yr in 2050, about 30% of total demand. Energy use in the sector will change dramatically. Use for space heating remains relatively stable, and cooking with gas and electricity leads to more efficient use of energy to feed a larger population. However, urbanization and rural electrification in the developing world lead to significant growth in energy demand for appliances, space cooling, and lighting. Continued digitalization of industry and society will see increased demand for related communication infrastructure and storage-server buildings, but this will account for only 2% of total energy demand by 2050.

MANUFACTURING

The manufacturing sector's energy demand will grow 1.2% per year to peak at a little less than 160 EJ/yr in 2039 and then decline slightly towards 2050. Due to improved energy efficiency and increased recycling, energy demand for mining and processing of base materials remains almost constant through to 2050 despite increased economic output in the sector. Growth in energy demand in this sector comes largely from production of manufactured goods, but there is a rapid displacement of coal by gas and electricity as energy carriers. This is partly due to an increased electrification of industrial processes.

Nevertheless, China and India's dependency on coal, even in later decades, means a slower transition there. Given their size, these two economic giants influence the global picture. This is despite significant growth in China's tertiary or service economy.

Outside the three big sectors of buildings, manufacturing and transport, the remaining 10% of energy demand is split between agriculture, forestry, other smaller categories, and the non-energy use of fossil fuels (for example, as feedstock for asphalt, lubricants, and petrochemicals).

7 'Energy Transition Outlook 2018, A global and regional forecast to 2050', DNV GL, September 2018
8 'Energy Transition Outlook 2018: Oil and gas. Forecast to 2050', DNV GL, September 2018

2.3 ELECTRICITY DEMAND

We forecast that world electricity demand (excluding own use within the energy industry) will increase by 170% from 21 petawatt hours per year (PWh/yr) in 2016 to 57 PWh/yr in 2050 (Figure 2.3).

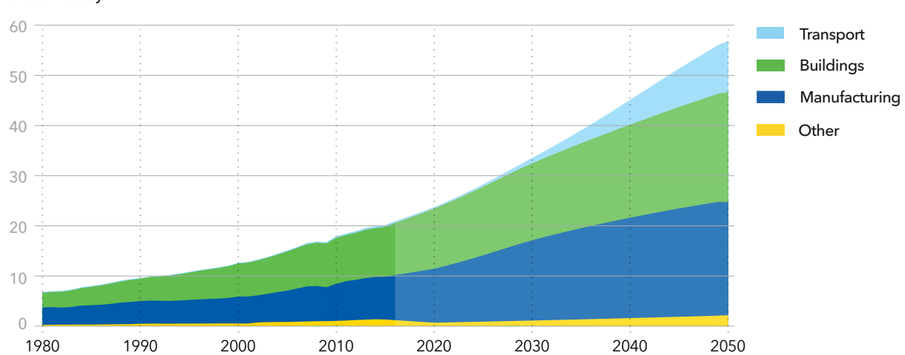
This is because of the increased energy demand and greater electrification described in the previous section. Taking into account transmission and distribution losses and self-consumption by generators and storage, global electricity generation is expected to increase from 25 PWh/yr to 66 PWh/yr in that time.

Although demand for electricity from the transport sector increases greatly by 2050, it remains relatively small compared with the dominant sectors, buildings and manufacturing.

FIGURE 2.3

World final electricity demand by sector

Units: PWh/yr



2.4 ENERGY SUPPLY

Energy supply shows more dramatic transitions than energy demand, as electrification of industry and society accelerates towards 2050 (Figure 2.4).

GLOBAL PRIMARY ENERGY SUPPLY TO PEAK

The global primary energy supply required to satisfy demand mirrors the ETO model's prediction that energy demand will peak in the mid-2030s and then slowly decline. However, although demand drops by only 17 EJ/yr from the peak to 2050, supply drops by 76 EJ/yr. The major contributor to this effect is the rising energy efficiency in power generation as fossil-fuelled plant, which typically has 35–45% efficiency, is replaced by renewable generation with no equivalent energy-conversion losses.

HYDROCARBONS TO PEAK

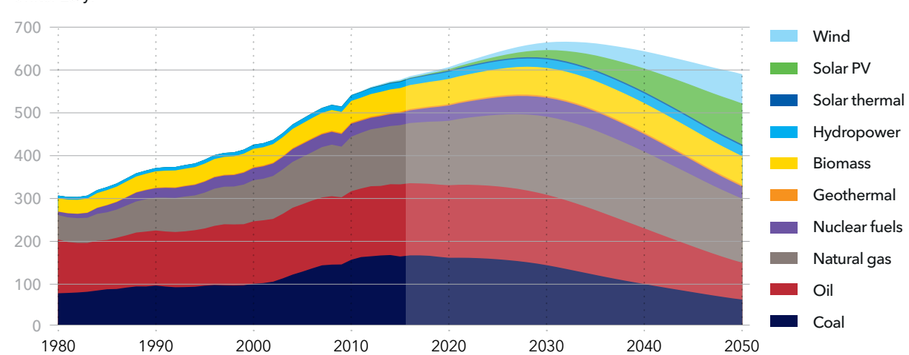
We foresee large shifts in the supply of primary energy. Oil and coal currently supply 29% and 28% respectively of global energy supply. By 2023, gas will overtake coal and will then surpass oil in 2027 to become the largest energy source.

We predict peak oil in 2023, with gas to follow in 2036. Coal has already peaked. The forecasted gas supply of 150 EJ/yr in 2050 is essentially flat compared with today. Fossil fuels' share of the primary energy mix will decline from 81% currently to about 50% in mid-century.

FIGURE 2.4

World primary energy supply by source

Units: EJ/yr



The percentage shares of biomass, hydropower, and nuclear in the energy mix will remain practically flat over the study period. Solar photovoltaic (PV) and wind will grow rapidly to each represent about 16% and 12% of world primary energy supply in 2050, respectively.

ELECTRICITY

Figure 2.5 shows solar photovoltaic (PV) and wind growing rapidly and dominating the mix by 2050. Solar PV has a 40% share and wind 29% by 2050. Onshore wind dominates, but offshore wind's contribution will grow more appreciably closer to mid-century, reaching about 20% of total wind production.

The renewables increase at the expense of coal, and later gas and nuclear[9]. Despite electricity generation growing by a factor of around 2.5 over the period, generation from fossil fuels drops to about 60% of its 2017 total.

Figure 2.6 shows the model's predictions for electricity generation capacity. With this high fraction of variable renewables, power network system stability and adequacy will become critical issues.

> "Solar photovoltaic (PV) and wind will grow rapidly to each represent about 16% and 12% of world primary energy supply in 2050, respectively.

9 Note that in the ETO model, the prospects for nuclear are assumed to be driven largely by political and public issues rather than costs.

FIGURE 2.5

World electricity generation by power station type

CHP = Combined heat and power

Units: PWh/yr

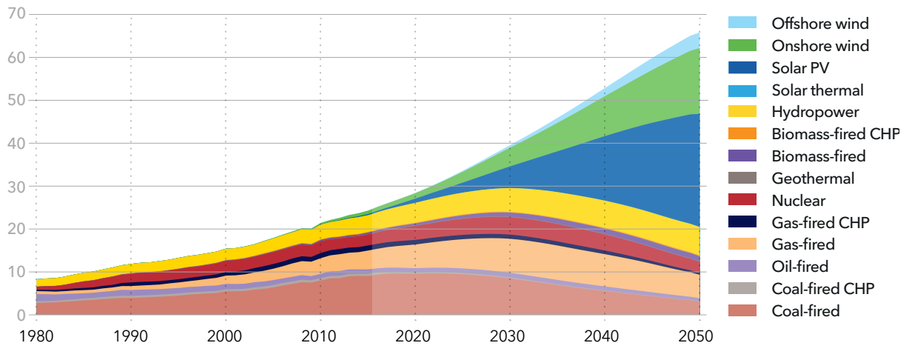
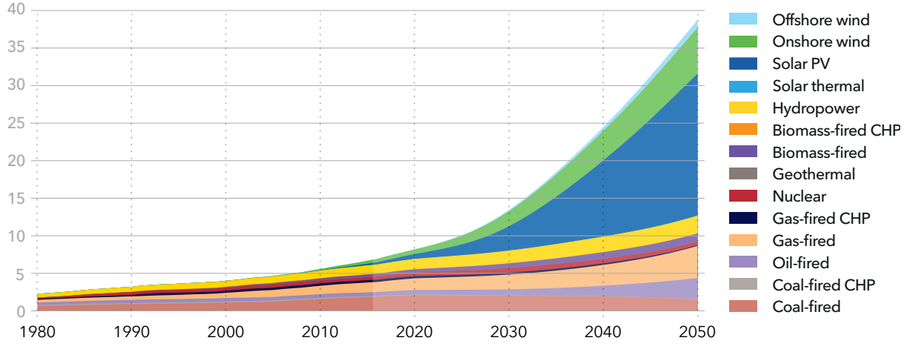


FIGURE 2.6

World electricity capacity by power station type

CHP = Combined heat and power

Units: PW



2.5 ADDITIONAL INFRASTRUCTURE REQUIREMENTS

To recap, we forecast that electricity will take an increasingly large share of energy used, and that gas will become a dominant energy carrier. Consequently, the main ETO report attempts to understand the infrastructure required to connect supply and demand for electricity and gas.

We recognize there will be continued need for new pipelines connecting new gas fields to existing gas grids, and that some large trunk pipelines connecting regions will be built. However, in this year's ETO we focus on the rapidly expanding liquefied natural gas (LNG) trade, which will be driven largely by North American shale gas exports and Middle East oil producers' strategic shift to increased emphasis on gas exports. Consequently, we see a tenfold increase in gas liquefaction capacity in North America and a near doubling in the Middle East and North Africa. Greater China and the Indian Subcontinent will see the largest expansion in regasification facilities to receive this gas, and there will be significant uptake in Sub-Saharan Africa.

Our forecast for growth in electricity demand and the number of power station connections required signals the need for a massive increase in the capacity of electricity grids. The Indian Subcontinent and Greater China lead the way in power-grid development, their geographic scale also driving the need for more extreme and ultra-high voltage grid systems for long distance transmission. Section 3.2 considers this in detail.

Our forecast of an increased volume of variable renewables also requires greater energy-storage capacity, and new technologies to address grid stability. Section 3.3 discusses these issues in greater detail.

"Our forecast for growth in electricity demand and the number of power station connections required signals the need for a massive increase in the capacity of electricity grids.

2.6 COMPARISON WITH ETO 2017 RESULTS

The ETO model has been refined for 2018, with more detail as well as updated input data and assumptions. The main conclusions from 2017 are unchanged, however.

The world will undoubtedly experience a rapid energy transition. This will be driven by electrification boosted by strong growth of wind and solar power generation, and by further decarbonization of the energy system, including a decline in the use of coal, oil, and gas, in that order.

We now expect global energy demand to be 6% higher in 2050 than previously estimated, principally due to increased demand from manufacturing in some regions. Electricity makes a greater contribution to energy supply than estimated in 2017.

The energy transition we describe is still affordable, because energy's share of global GDP will decrease.

However, the updated forecast still does not predict fast enough decarbonization to meet global climate-change mitigation targets.

Hydrogen is included in our model for the first time. With the assumptions made, the results show demand of only 2.5 PJ of hydrogen in 2050, of which 1.4 PJ is predominantly for road transport and a little for maritime fuel. This is well under 2% of all transport demand, which is instead dominated by electricity and oil. These estimates are very uncertain: they depend greatly on estimates of future costs, and on policy developments. Hence, section 3 discusses H_2 in relation to power-to-gas technology options.

CHAPTER 3

TECHNOLOGIES AND SYSTEMS

3.1 ENERGY USE AND EFFICIENCY

ELECTRIFICATION OF ENERGY USE

BUILDINGS

Carbon reduction in advanced economies calls for both decarbonization of electricity supply, and electrification of energy end uses that are currently provided for by fossil fuels. Improvements in the performance and costs of building energy controls and information technology are supporting these developments by facilitating reduced consumption, demand response, and use of distributed renewable energy.

Low-temperature space and water heating in residential and commercial buildings are ripe for electrification given recent advances in commercialized technologies, particularly heat pumps. These technologies are discussed further in the section on energy demand and energy efficiency.

MANUFACTURING INDUSTRY

Transitioning to low-carbon manufacturing will require electrification of many processes that were previously powered by the combustion of fossil fuels. Providing heat for industrial processes is one example.

Several technologies and innovation opportunities for electrification are available. Most published studies show that towards 2030, industrial electricity prices in industrialized countries are expected to rise relative to gas. This means that policies, tax regimes and/or pricing trends will need to change in favour of using electricity rather than gas. Price volatility will increase, creating the possibility for flexible electrification strategies to develop[10].

A significant share of energy use in the industrial sector is demand for heat: high-temperature process heat, low-temperature process heat, space heating, drying, and separation[11]. As electricity is increasingly provided by renewables, the carbon emissions associated with renewable-supplied electric heat will be significantly lower than that provided by fossil fuels. For this reason, many manufacturers will seek to power their processes using electricity rather than gas or coal. To encourage electrification, industry will need assurance from network operators that the decarbonization of the network will not negatively impact security or cause significant price increases. Alternatively, some industrial companies will increasingly develop their own behind-the-meter renewable energy supplies, though industry will in most cases remain grid-connected.

Electric melting for glass manufacturing, electric kilns in the ceramic sector, and steel production with electric arc furnaces are significant electrification technologies currently available, but not always at large scale. When compared to other sectors, food and drink, as well as pulp and paper, have significant low-temperature process heat demand, which could allow them to shift further towards electrification.

For other sectors, electrification is possible at higher temperatures but equipment, such as electric kilns, is not developed at scale.

This will be a key area for development if industry is to move away from fossil fuel use. Projecting electricity prices compared with gas will be a key factor in any investment decision.

TRANSPORT

The ETO model results in section 2.2 show the very significant results of our assumptions about the electrification of transport, particularly but not exclusively the light vehicle fleet, which show a substantial transfer of energy demand from oil to electricity, with accompanying reduction in total energy required, and emissions. These assumptions are driven by our understanding of policy issues, particularly on air quality, likely cost reductions, and the very large investments now going into electric vehicles (EVs), battery production capacity, the battery supply chain, and charging networks. These large investments are a noticeable difference from the situation when we produced the ETO 2017 reports.

Though other aspects are important, batteries are the EV technology area offering the greatest promise of improvement, and therefore support the greatest research and development efforts. Lithium-ion chemistries are the frontrunner technologies, but others could still emerge. In particular, there is strong interest in solid-state electrolytes, offering reduced fire risk, possibly longer life, and other benefits.

There are also substantial investments in H_2 fuel cell technology, particularly for heavy vehicles.

10 For example: http://www.ispt.eu/media/Electrification-in-the-Dutch-process-industry-final-report-DEF_LR.pdf
11 Industrial separation processes are technical procedures used in industry to separate a product from impurities or other products. Examples include clarification, crystallization, evaporation, extraction, filtration, pressing, and washing.

ENERGY EFFICIENCY IN BUILDINGS

Regional patterns and trends in energy use in homes and commercial spaces are shaped by many drivers. They include climate, local materials, construction practices used for the existing building stock, and current levels of economic development. Any short discussion of the topic therefore needs to remain very general in nature. Here, we identify and summarize high-level trends and technical developments that were accounted for in our model.

TRENDS IN ENERGY CONSUMPTION PER UNIT

In some developed countries, energy consumption per housing unit has been decreasing slowly since the late 1990s. In Europe, the decrease has averaged about 0.8% per year; in the US, about 0.5% per year.

The most recent residential energy use surveys in Europe and the US suggest that the pace of decrease in unit energy consumption has slowed or even reversed, however. The main reason appears to be the addition of consumer electronics and other household appliances, which has offset efficiency gains in heating and cooling. In OECD Pacific nations, such as Japan and Korea, consumption per housing unit has increased slightly over two decades, again reflecting increased penetration of household appliances.

Most world energy models, including our own, forecast that residential energy use per unit in advanced countries will begin to decrease more consistently by 2020. This will be driven by slower population growth, full saturation of appliances and electronics, and increases in efficiency in lighting and space conditioning.

Developing economies present a mixed picture on residential energy consumption. Use of local biomass is generally reducing. It will continue to do so, but remains high, and is in some cases of concern from climate change and environmental perspectives. Greater China and the Indian Subcontinent have progressed considerably since 1990 in shifting away from local biomass to fossil fuels and electricity. Using local biomass greatly inhibits energy-efficiency gains since conversion devices are inherently inefficient. More importantly, burning biomass such as wood and charcoal yields extremely high carbon and particulate emissions, and contributes to other environmental problems such as deforestation, flooding, and soil erosion.

TECHNOLOGY ADVANCES: LED LIGHTING

In advanced economies, lighting accounts for 9–15% of total residential electricity use, and 30–40% in the commercial sector. Light-emitting diodes (LED) offer energy savings of 10–70%, depending on the application and baseline technology they replace. Other consumer benefits including longer life and reduced maintenance costs are driving rapid increases in market share. Strong competition among suppliers to improve performance, reduce price, and expand distribution channels is very likely to ensure continued growth of LED lighting. Most market analysts forecast that LED technology's share of the lighting market will rise to 70% by 2020. This is even though lower-quality LED lighting can distort the alternating current waveform, causing 'grid pollution' and increasing the need for reactive power.

TECHNOLOGY ADVANCES: ENERGY INFORMATION SYSTEMS

Engineering case studies have long demonstrated that total energy use in most existing commercial buildings can be reduced by 10–15% through best practices in energy management. Rapidly decreasing costs of buildings' energy-system sensors and data communication infrastructure, and advances in wireless data communication, have allowed building operators and managers to optimize operations for the greatest savings.

The emerging practice of Strategic Energy Management (SEM) is becoming codified through international standards such as ISO 50001. Its value is being demonstrated through third-party verification. Major international property managers are adopting SEM in their leased portfolios to ensure high levels of tenant satisfaction and reduce tenant turnover. We anticipate that adoption of SEM will increase over the forecast period.

TECHNOLOGY ADVANCES: SMART HOMES

Home automation is receiving much media attention. Broad-based surveys find consumers interested in such systems primarily for additional security and convenience: energy saving is a secondary consideration. Energy savings achieved from 'connected devices' such as appliances and electronics are minimal, due to their relatively small total consumption and the effectiveness of existing manual controls. Adoption of home automation technology has so far been slow in advanced developed countries.

'Smart thermostats' that gather and integrate temperature and occupancy data from multiple sensors in the home are an exception to these trends. In the US, they accounted for 40–50% of the thermostat market in 2017. Independent evaluations of energy savings have found that the devices do reduce energy use, though the range of performance is very wide. Estimates of energy consumption savings from using smart thermostats in heating range from 1–15%, and from 1–17% in the case of cooling.

ZERO NET ENERGY APPROACHES

Building officials and regulators in advanced developing economies are applying more stringent building codes governing energy use in new buildings. In some cases, they are setting goals to reach zero net energy (ZNE) operation. This means that the amount of energy a building or cluster of buildings uses during the year will roughly equal the amount of energy produced on site through renewable sources. In the US, California requires all new residential developments to meet ZNE requirements. Many other US states are considering similar regulations.

Combinations of academic, government, and industry organizations in nearly every European Union member state are pursuing efforts to develop ZNE standards. Recent studies have found that the incremental cost of constructing a ZNE building, compared with a similar one that meets current building codes, is declining. This is being driven by reductions in costs for components such as solar photovoltaic (PV) panels and inverters, and by architects and builders gaining growing experience with ZNE techniques.

One study of 19 residential ZNE projects found that the incremental cost added by energy-efficient construction elements other than solar PV systems ranged from EUR45-185 per square metre (/m^2). The cost of solar PV systems for these homes was EUR12,000-18,000 per house, excluding tax credits and other incentives.

For commercial buildings, estimates of incremental costs for energy-efficient construction elements range from EUR82-165/m^2 higher than for comparable code-compliant buildings, before accounting for the costs of solar PV systems.

In addition to the high costs of design and construction, early experience in developing and selling ZNE homes has flagged up other barriers to energy savings. They include the need to train occupants in the proper operation of ZNE features and controls, and to educate mortgage lenders on the economics and risks of ZNE building ownership and sales.

As ZNE principles apply almost exclusively to new construction, the initial volume of such projects will be relatively low compared to energy-efficiency strategies aimed at existing buildings. However, given the long useful life of buildings, those energy savings will persist. In addition, the learning and experience gained through implementation of ZNE principles in new buildings may facilitate their broader application in existing buildings.

RESIDENTIAL SPACE HEAT

Heating domestic residential space accounts for 20–30% of total energy use in buildings in developed economies, mainly provided by fossil fuels. Recent advances in heat-pump technology have lowered the capital cost of purchase and installation, and increased operating efficiency. These changes have vastly improved the economics of converting fossil-fuel, residential space-heating systems to electricity, though significant barriers remain to rapid uptake of heat pumps.

The value of conversion to customers varies greatly with local climate and energy prices. A recent US study found that conversion from fossil-fuel systems to electric heat pumps reduced lifecycle costs of ownership only in warmer climate zones, and in instances where the pump replaces both central heating and cooling equipment. Further, reductions in lifecycle cost averaged only USD25–200/yr, which does not present a compelling case for investment in replacing a major home energy system.

Experience with similar issues also shows that due to the 'hassle factor', households do not often respond well to policy signals even when the economic case is clear. Millions of individual decisions are required to produce a significant impact, unless households are incentivized, or regulation drives change. An example of strong policy direction is the Netherlands, where it is intended that gas supplies to domestic properties will cease. In contrast, policymakers in the UK note that householders are likely to prefer less disruptive options, such as conversion of existing gas-fired wet central heating systems to 'green' hydrogen (H_2).

In developing countries, space heat is provided primarily by local bio-fuels. Here, electric space heat will likely leapfrog fossil-fuel systems due to relatively low initial costs and the high cost of natural gas delivery infrastructure. Electric ductless heat pumps are already prevalent in urban areas in developing regions.

Few electricity system operators have attempted to control electric heating end use as part of demand response efforts, due primarily to health, safety, and customer satisfaction concerns. Major exceptions such as Germany, New Zealand, and UK show that significant effects can be achieved with relatively simple control and communications. Introduction of combined heating/cooling/hot water heat-pump products, and advancements in internet-enabled thermostats, may provide new opportunities to bring space heating into demand response programmes in most regions.

RESIDENTIAL HOT WATER

Residential hot-water heating accounts for 4–10% of total energy consumption in buildings in advanced developed economies. In European and North American countries, the share of homes and apartments with free-standing, hot-water heaters is 55–80%. The tanks on these units represent a large opportunity for thermal energy storage on the grid: they need only to run for a total of two to three hours per day to remain fully charged. The share of water heaters powered by electricity is already relatively high at 40–60%.

Recent technical advances provide opportunities to reduce energy consumption and emissions in this end use. The latest heat-pump water heaters consume 50–60% less electricity than comparably-sized, conventional, resistance-heating models. The average energy saving is around 2,000 kilowatt hours per year per home. At current levels of installed equipment costs and electricity prices in the US, payback time on the investment to replace a resistance water heater with a heat-pump model ranges from three to six years.

The economics of converting from gas to electric hot-water heating are less straightforward. They depend on many conditions related to the individual home and its local gas and electric markets. Even under the most favourable assumptions, the difference in lifecycle costs between gas and electric heat pumps is negligible. Without subsidies and regulations to drive change, most customers would be unwilling to undertake the perceived risk and inconvenience of substituting a new technology for one that is well established.

ENERGY DEMAND AND ENERGY EFFICIENCY IN INDUSTRY

In the ETO model, the manufacturing sector aggregated all related activities in the extraction of raw materials – excluding coal, gas, and oil – and their conversion into finished goods. We analyse the sector as two categories:

- Base materials such as chemicals and petro-chemicals; iron and steel; non-ferrous materials, including aluminium; non-metallic minerals, including cement; paper, pulp, and print; and, wood and its products
- Manufactured goods including construction equipment; food and tobacco; machinery; textiles and leather; and transport equipment.

Energy is a fundamental need and a significant cost for manufacturing companies. The energy supply for manufacturing is likely to see continued pressure to lower carbon emissions. This will mean more renewable energy and lower-carbon grid-supplied electricity. Electrification of some industrial processes will also increase electricity demand. The overall energy demand will be subject to conflicting pressures. Population growth will drive it upwards while greater efficiency in energy and resource use will act to reduce demand. The manufacturing sector's energy demand will grow 7%/yr to peak slightly below 160 EJ in 2035 and then decline slightly towards 2050. Due to improved energy efficiency and increased recycling, energy demand for mining and processing of base materials remains almost constant from 2016 through to 2050 despite increased economic output in the sector.

The main options for lowering carbon emissions in the industrial sector are:

- Developing measures to reduce demand for products; examples include longer-life products or circular-economy initiatives
- Changes to energy supply, such as greater use of renewables for electricity, or converting renewable power to hydrogen as discussed in section 3.5
- Process changes
- Energy efficiency.

Capturing carbon for storage or use could also be an important option for certain high-emission sectors such as cement, iron and steel, refining and chemicals.

Renewable energy can be used directly in conjunction with the electrification of heat to reduce carbon emissions, or to produce hydrogen-rich chemicals for feedstocks or fuels. Locations with abundant renewable energy potential (hydro, solar, wind) could see the price of renewable electricity drop below USD0.03/kWh. At this low level, H_2 production may have costs on par with that of traditional gas refining, but with significantly lower carbon emissions. This is especially true for feedstocks and can significantly reduce the carbon footprint of the chemicals industry.

THE FUTURE OF MANUFACTURING

The monetary value of manufactured goods will continue to grow but at a slower rate than gross world product, as more economies transition to domination by service sectors. The practice of continually improving material efficiency in manufacturing is already well-established. It charts in our model as a steady decline in the amount of base materials needed for each kilogramme of manufactured goods. We predict that this trend will continue uninterrupted, partly because of additive manufacturing, otherwise known as 3D printing, reducing demand for base materials. This means global production of materials will increase at a slower rate than manufactured goods. We see the Greater China region remaining the largest manufacturer and net exporter. Regions such as the Indian Subcontinent, Latin America, Middle East and North Africa, and Sub-Saharan Africa will also increase manufacturing output between 2030–2050.

> “ The monetary value of manufactured goods will continue to grow but at a slower rate than gross world product, as more economies transition to domination by service sectors.

Further disruptive changes in supply chains could change demand for product, materials, and energy. This is a possibility by 2050, though subject to much uncertainty. Work is underway to deliver circular and sustainable production in key sectors such as clothing, food, packaging, plastics, and manufactured goods, for example. Accompanying business model changes can also deliver significant changes to demand for products as some sectors move from customers owning things to pay-as-you-use terms.

THE INTERNET OF THINGS

The evolution of the internet of things (IoT) will enable manufacturers to better track their production lines and consumption of materials, feedstocks and energy. It is estimated that manufacturers will invest USD70 billion in IoT solutions by 2020[12], and that the IoT could add more than USD14 trillion of value to the industrial sector[13].

IoT-enabled devices will make data sharing and analysis simpler and more easily accessible. With better data comes better control, which can mean lower energy consumption and more efficient production. IoT sensors will allow condition-based maintenance notifications that can signal small deviations from normal operation, enabling a shift from preventative to predictive maintenance. This has positive impacts on production, costs, quality control, and health and safety. More and higher-quality data will allow operators to better optimize their processes and determine exactly what ‘optimal’ looks like for every production line.

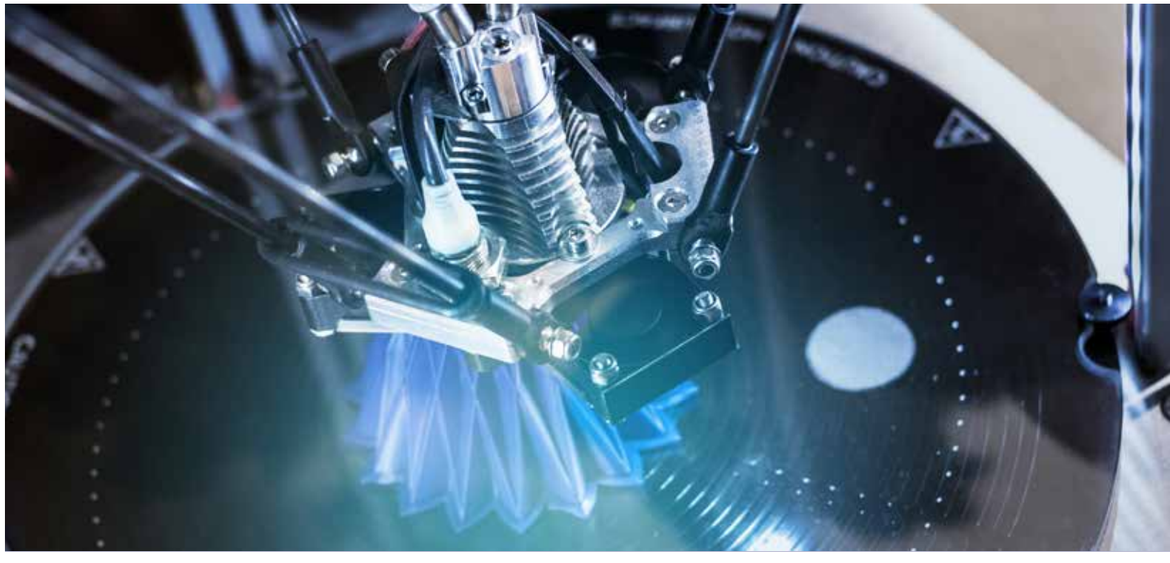
12 http://uk.businessinsider.com/internet-of-things-in-manufacturing-2016-10?r=US&IR=T
13 https://www.accenture.com/us-en/insight-industrial-internet-of-things.

MANUFACTURING SECTOR ENERGY DEMAND

Manufacturing is one of the largest users of energy. It consumed about 120 EJ of final energy in 2016, or 31% of global final energy demand. We forecast manufacturing sector energy demand will rise by nearly a third (31%) by the early-2030s then stay flat around 160 EJ/yr towards 2050. This ‘flattening out’ despite continued increases in manufacturing output results from continued improvement, averaging 0.9–1.2%/yr, in the energy-efficiency of production.

Evolution of the energy mix in manufacturing depends on technology innovation, resource availability, and policy and economic incentives. We estimate this mix through an adjusted continuation of linear trends for the various energy sources, separated out for base materials and manufactured goods in all regions.

Decarbonization of manufacturing is, and will remain, high on the agenda in OECD countries. Research and development, and investment support, for cleaner production processes will continue. Lifecycle analysis of costs and carbon footprint will become increasingly common for manufactured goods as more investors and consumers begin to demand this information, and companies seek new ways to stand out in the market. Many companies are already acting. Some, for example, are publishing science-based targets for their emissions, or making public their targets for corporate energy efficiency and carbon emissions.



ENERGY EFFICIENCY IN MANUFACTURING

Manufacturers have become more focused on energy efficiency and will continue to do so. Here, we identify and summarize high-level trends of importance to the industry.

Investing in technology for greater energy efficiency is related either to the industrial process, or to the consumption of utilities, such as power, hot water, steam, compressed air and lighting. Improving or changing processes typically reduces energy intensity[14]. When the focus is on the utilities involved, investment in technologies such as combined heat and power, variable-speed drives, and LED lighting can deliver lower energy use and hence energy cost per unit of output.

Another option is to improve heat recovery by using waste heat from one part of a process as a heat source for another.

One way of improving energy efficiency with minimal investment is to run processes differently and/or conduct a detailed energy-use study. Companies increasingly use key performance indicators to guide optimization of different processes for goals including energy efficiency. This approach can be formalized in an energy management system; evidence from companies that have done this suggests potential savings of up to 10% on annual energy costs.

Another approach involves performing a variability analysis of historic data to identify improvement opportunities from periods when processes were running optimally. Identifying the root causes of optimal and sub-optimal performance enables preventative action to ensure running at high energy efficiency. This strategy is still relatively new to industry, which has typically analysed historic data more for understanding unexpected events than examining a full year of production data for optimization opportunities.

Other options requiring minimal investment include awareness campaigns for turning off equipment during shutdowns, at times of high electricity costs or other operation stops, or changing a company's thinking around energy culture. The latter is of increasing importance to manufacturers because significant savings can be achieved by reshaping how people think about energy and energy efficiency. This applies from small to large organizations, and the benefits can extend into employees' daily lives. Improving process control and automation will also lead to increased facility efficiency. Much of this technology is already available and can be implemented without major capital investment.

DEMAND-SIDE RESPONSE

Integrating demand-side response (DSR) measures to encourage reduced energy consumption at peak times can potentially lower energy costs for industry. Any savings will depend largely on the flexibility of a facility's process, and especially on:

- How much consumption can be scheduled or rescheduled
- How much production can be fulfilled despite line stops during times of high electricity prices
- How much inventory can be stockpiled
- Electricity cost variations.

DSR will be most attractive at facilities with high electricity costs, excess capacity, and quick start-up and/or shut-down procedures. Consequently, blast furnaces, chemicals, coking, paper and pulp, and steel casting will have limited DSR potential.

Almost all regions have similar goals for implementing DSR. They are:

- To reduce electricity costs for consumers
- To reduce environmental impacts from additional electricity use and/or construction of new infrastructure to meet rising demands
- To optimize generation and grid stability, especially as more renewables are introduced.

Most DSR capacity is currently in the US, but we expect it to continue growing in all markets as renewables take a larger share in the electricity generation mix.

DEMAND-SIDE RESPONSE: OECD PACIFIC AND SOUTH EAST ASIA

Australia, Japan, and Singapore operate DSR programmes. Australia and Singapore have traditional models where end users are paid per unit of electricity for reducing power consumption. Japan provides subsidies for energy management equipment. Unlike some nations, Japan lacks a capacity market and so cannot sell DSR in this way.

Other countries are still in the development phase. The Thailand 3.0 project to transition the country into a 'first-world nation' includes provision for smart grids and the added control, such as DSR, that they offer[15]. Expansion of smart meters and smart grids is already underway in Thailand, with a proposed completion date in 2035. Indonesia has no DSR programmes, but there have been studies[16] into the possible effects of changing electricity subsidies there.

DEMAND-SIDE RESPONSE: EUROPE

Within the context of improving energy efficiency and the efficiency of infrastructure, Article 15 of the European Union's (EU) longstanding Energy Efficiency Directive (EED) require EU member states to encourage use of demand response[17]. Network companies are encouraged to include demand response in balancing markets and their ancillary services portfolios. National regulatory authorities are required to encourage demand response in wholesale and retail markets. In addition, the European Commission presented a package of legislative proposals (COM/2016/0860 final) in November 2016, which further encourage the remuneration of DSR programmes[18]. Although Article 15 of the EED is not mandatory, most countries have developed DSR programmes, which can generate significant revenue for the customer and act as an important incentive.

DEMAND-SIDE RESPONSE: MIDDLE EAST

The United Arab Emirates neighbours Abu Dhabi[19] and Dubai[20] have DSR programmes. Both focus heavily on an overall reduction of energy and water use. Dubai says DSR and energy efficiency constitute the 'most important single source of future energy'. Its programme includes a multi-pronged approach including time-of-use tariffs, curtailable load management, and direct load control.

Saudi Arabia has explored a DSR programme with a goal of 3–4 GW capacity by 2030, to be delivered by third-party aggregators. This programme is now on hold and it is unclear when it will resume.

14 Energy intensity: the energy used per unit of output.
15 http://thaiembdc.org/thailand-4-0-2/
16 https://acde.crawford.anu.edu.au/sites/default/files/publication/acde_crawford_anu_edu_au/2018-01/2018-01_burke_and_kurniawati_wp_0.pdf
17 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52013SC0450
18 http://www.ipex.eu/IPEXL-WEB/dossier/document/COM20160860.do
19 http://www.tarsheedad.com/en/media-zone/press-clippings/adwea-launches-demand-side-management-(dsm)-program-%E2%80%9Ctarsheed%E2%80%9D
20 Dubai Demand Side Management Strategy: 2015 Annual Report

3.2 ELECTRICITY GRIDS

TRANSMISSION GRIDS AND SYSTEM OPERATION

CHANGES IN ELECTRICITY SYSTEM STRUCTURE

Electricity grids transfer energy from generators to consumers. Traditionally, generators were large and their power output was interconnected by a 'transmission' system at high voltages (HV and EHV). This was the best solution for long-distance transmission, robustness against failures, and for the most economic operation of generators. Only the very largest consumers are connected to the transmission system; most are supplied by distribution systems at relatively lower voltage levels. This simple model of power flowing in one direction is being overtaken (Figure 3.1). Smaller generators connected to distribution systems or supplying electricity direct to consumers are increasing in number. The role of the transmission system operator (TSO) is becoming much more complex.

For 2018, the ETO model includes more detailed estimates for the expansion of transmission and distribution systems, as the section on grid costs describes in detail. The important conclusions for transmission systems and their operation are:

- There is massive expansion of transmission lines, cables and substations: it occurs mainly at the extra high voltage (EHV) level (345 kilovolt and above)
- This expansion occurs both in length of transmission lines, and in their capacity in gigawatts (GW)
- At the highest possible voltage level, Direct Current (DC) transmission technology becomes important in the later years of the ETO forecasting period, but does not dominate
- The clear majority of this growth occurs in Greater China and the Indian Subcontinent, though all global regions in our model show substantial growth.
- Significantly, a different picture emerges for investment in transformers and substations: most of this substantial growth occurs at lower, distribution-level voltages. This forecast indicates the impact of increased electrification of energy demand.

Figure 3.2 shows an important result of the ETO model. Major expansion in transmission and distribution systems is driven principally by demand growth. The costs attributable to connecting variable renewable energy source (VRES) plants grow very rapidly from around 2030, but still are no more than around half the costs attributable to dealing with growth in electricity demand.

ENERGY STORAGE

The ETO model adds energy storage capacity as a function of the amount of variable renewables. The costs of this are included in the economic decisions made by the model when adding electricity generating capacity.

Based on current industry experience, the model assumes that batteries provide all new storage capacity. The Hornsdale Power Reserve lithium-ion battery installation in Australia is a real example. It was installed in 2017 to address concerns about stability of the South Australian electricity system amid increasing penetration of wind and solar.

Current preferences for batteries are not entirely driven by cost, however. Competing energy storage technologies, which may offer lower costs,

FIGURE 3.1

Traditional and new electricity system architecture

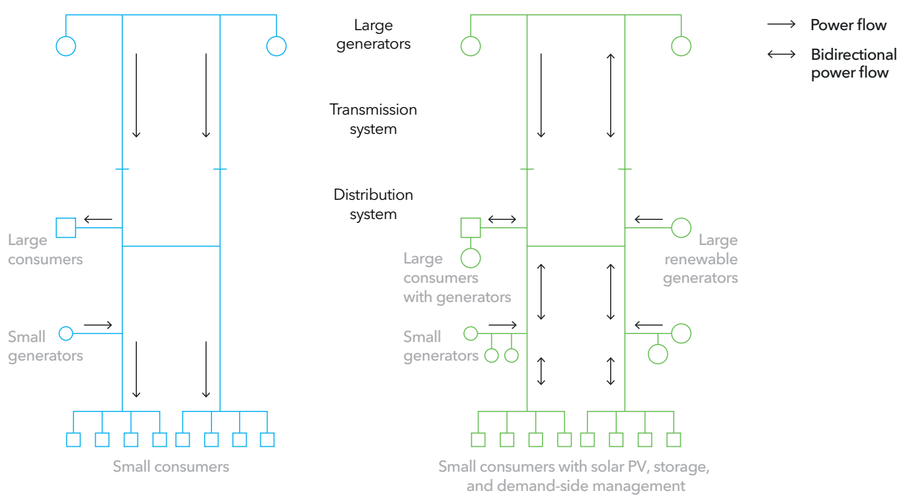
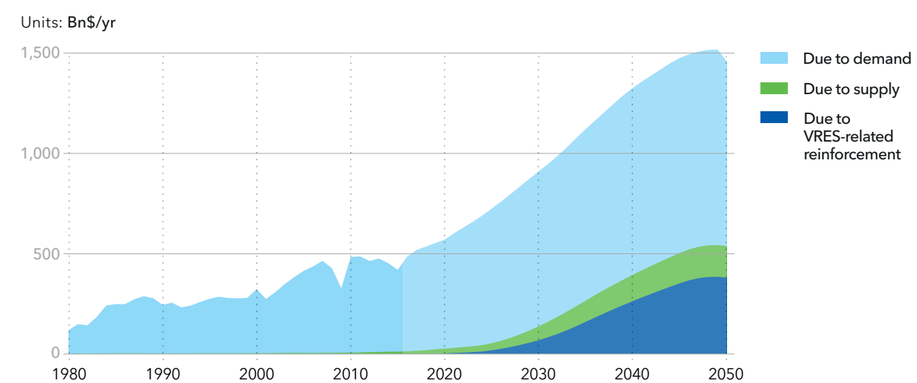


FIGURE 3.2

Global grid cost by driver



generally have larger unit sizes and substantially longer and riskier permitting and construction times. They include pumped-hydro energy storage and compressed-air energy storage.

These and other technologies could become major contributors in the future once it becomes clearer what a given system's storage requirements may be, and when planning and financing horizons lengthen.

The ETO model also assumes that 10% of total EV battery capacity is available at any time to provide storage services to the electricity network. This reduces the need to add stationary batteries.

Figure 3.3 illustrates the additional battery storage capacity which the ETO model determines is required to address the variability of solar and wind; it does not show the contribution from EV batteries. Figure 3.4 combines this additional capacity requirement with the assumed contribution of the EV fleet batteries.

The figures show:

- Very significant growth in battery capacity installed specifically to cope with variable renewables: around 50 TWh by 2050. For comparison, the ETO model predicts that global EV battery capacity will be around twice that come mid-century
- More than half of the dedicated, non-EV, battery capacity will be installed in Greater China, and about a quarter in the Indian Subcontinent
- The additional battery capacity which will be needed to deal with variable renewables is very sensitive to how much of the capacity from EV batteries can or will be made available.

This global picture masks a significant result in one region. Figures 3.5 and 3.6 show the same parameters as above, but solely for Europe. Here 10% of available EV battery capacity rapidly becomes greater than is needed to maintain a reliable electricity system with a high fraction of wind and solar.

This result is not found for any other region. It is due to the very rapid growth in EVs which the ETO model forecasts for Europe, and because wind and solar capacity in the region grows relatively slowly compared with other regions.

Some implications of these forecasts are:

- The interplays of EVs and electricity systems dominated by wind and solar are complex
- The results presented here are sensitive to assumptions about growth of EVs[21], wind, and solar
- The figures are also sensitive to the willingness and ability of EV owners to participate.

SYSTEM OPERATION

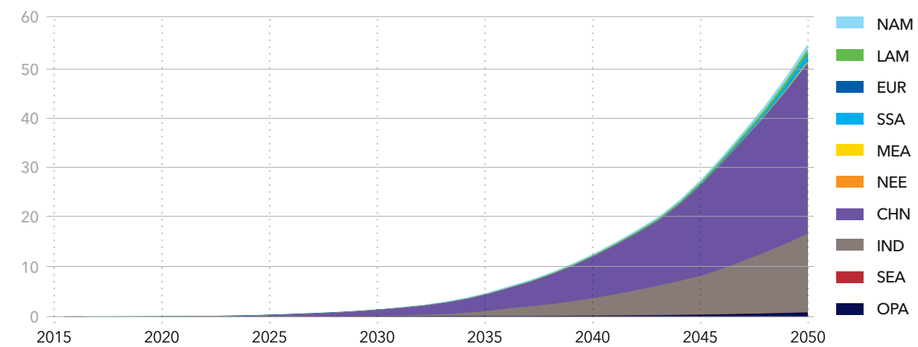
Amid the increasing complexity of managing transmission systems, growth of renewables has several effects. They include greater uncertainty for system operators over both short and long timescales. Encouragingly in the former case, forecasting for operational timescales of 24 or 48 hours ahead is already quite accurate and is improving.

21 Note that the regular bell shape of Fig 3.5 indicates no more than that the ETO model assumes an S-shaped curve for EV adoption.

FIGURE 3.3

Battery storage dedicated to power sector by region*

Units: GWh

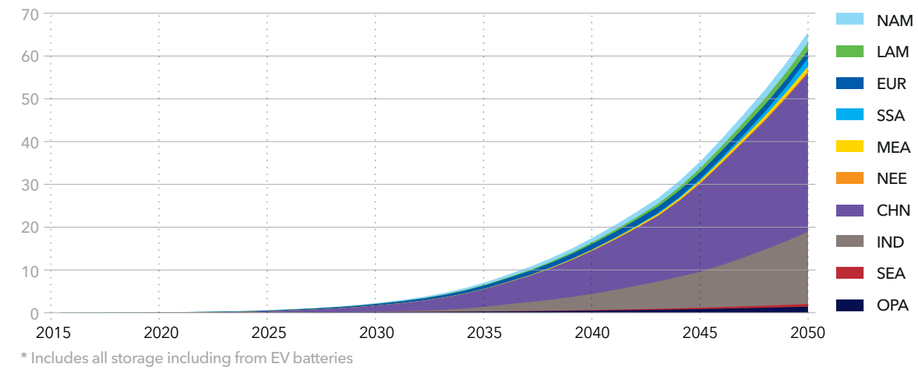


* Excludes storage from EV batteries

FIGURE 3.4

Total available battery storage by region*

Units: GWh



* Includes all storage including from EV batteries

FIGURE 3.5

Battery storage dedicated to power sector in Europe

Units: GWh

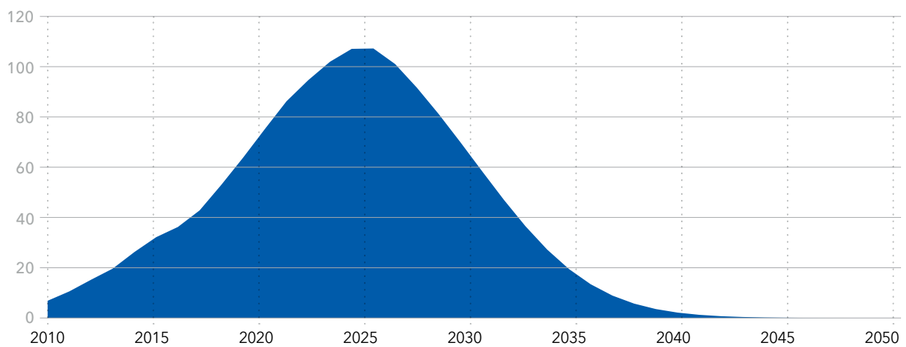
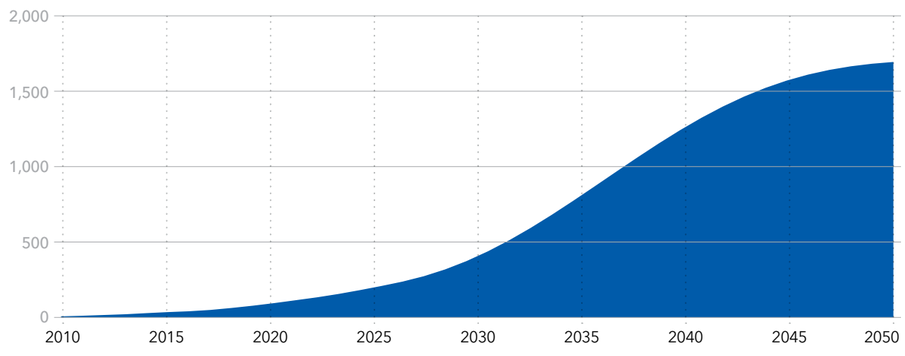


FIGURE 3.6

Total available battery storage in Europe

Units: GWh



Uncertainties over long timescales include where and when new generation sources may emerge, and existing ones shut down.

The reduction in the total capacity of conventional thermal plant also creates challenges on the very shortest timescales. Such plant universally uses synchronous generators, which rotate in synchrony with the grid frequency of 50 or 60 Hertz (Hz) and therefore with each other. Sudden imbalances in supply and demand due for example to the sudden failure of a major generator are mitigated by the significant amount of energy stored in the inertia of these spinning masses and in motor-driven loads. There is also substantial stored energy available within seconds from steam stored in the boilers. While hydropower also uses synchronous generators, wind and solar benefit from neither of these effects. Consequently, transmission system operators and regulators are already working on actions to ensure that in future with a lower proportion of synchronous generators, they can keep frequency within limits and maintain operational security.

Energy storage can contribute to resolving this issue as discussed above, but other 'flexibility options' are also available, as section 3.4 explains more fully.

Design of electricity markets is an important issue; for example, markets for balancing power and reserves. These markets may not always be entirely within the control of the TSO; regulators and governments will also have objectives to meet. For example, governments may wish to encourage certain technologies in order to establish or preserve an industrial base, such as existing coal- or gas-fired power stations. Or they may favour small-scale decentralized storage, renewables, and demand response to increase local participation, avoid negative public opinion, or weaken the position of powerful vertically-integrated utilities.

Solar and wind are not the only new issue facing TSOs. Governments are becoming increasingly interested in 'resilience', the ability of the electricity system to recover after major events. Traditionally, the main threat has been failure of major assets. To this must now be added threats from more severe weather in an increasing number of locations, and terrorist attacks, both physical and cyber.

DIGITALIZATION

Section 3.6 discusses digitalization issues in general. For transmission systems, future impacts are perhaps not as great as in other parts of energy or electricity systems. TSOs have always operated with large amounts of data from widespread sources. They use sophisticated communications technology, devices, and sensors, and many benefit from regulatory encouragement to adopt new technology.

However, digitalization is having major impacts. It enables the use of more and smarter sensors to generate more useful information. Machine learning makes greater and better sense of data, particularly during sudden events or where some sensors may be defective. Digitalization and data analytics bring better understanding of the power system state and its capability. Benefits include enhanced computational ability to determine dynamic (short-term) capability of major elements such as transformers, overhead lines, and cables, for example in response to weather conditions.

Digitalization is enabling a rapid increase in the number of power-electronic converters.

For example, all solar PV generation and most wind turbines are connected through converters. This introduces issues with harmonics, but also creates potential for rapid, precise control of power and reactive power at multiple points on the system to provide improved performance.

More useful data can also improve understanding of end-user behaviour. One potential downside of digitalization allied to greater connectivity is that it can introduce or raise cyber threats: a nation's power transmission system is an obvious target for terrorism and others with malicious intent.

DISTRIBUTION GRIDS

TECHNICAL FUNCTIONS OF DISTRIBUTION GRIDS

Distribution grids are the key infrastructure for distributing energy to final customers. They also connect smaller, decentralized generation facilities to customers and the transmission system. Distribution grids operated by Distribution System Operators[22] (DSOs) supply electricity to residential and commercial customers, and to all but the largest industrial consumers.

These grids play an important role in enabling flexible power-supply options from decentralized sources of generation, storage, and demand. In the future, many renewable generation sources will be connected to distribution systems, either as generating plants or 'behind-the-meter' sources owned by electricity consumers. Further, EV charging (including from public fleets) will have greatest impacts on the distribution networks.

The ETO model predicts a major expansion of distribution grids to address the growth in electrification of energy demand; the section on grid costs estimates the cost implications.

A CHANGE IN THE ROLE OF DSOs AND IMPACT ON SYSTEM OPERATION

DSOs are responsible for the secure operation of their networks, with increasing emphasis on distribution congestion and voltage management. They play a key role in providing data on the behaviour of consumers and distributed generation, information which is becoming of greater importance to TSOs. Aided by smart meters, this information can be provided closer to real time to increase the possibility of controlling demand better.

The energy transition will drive much closer cooperation between TSOs and prosumers, consumers who actively participate in energy, capacity, and ancillary services markets. This will in turn require DSOs to take on some responsibility for managing relations between prosumers, embedded generators, and TSOs.

Providing ancillary services such as frequency response is one possible example of such a role. DSOs will also need to confirm that all connected loads and sources of generation comply with technical and security rules for protecting distribution and transmission networks. To do this, they will require detailed information of the current generation or demand connected to their networks.

Similarly, DSOs may have a key role in enabling storage and other flexibility options (section 3.4) to provide services not just for the distribution system, but for the wider transmission system.

Digitalization will allow smart distribution substations of the future, which will play a key role through their ability to manage and control local low-voltage (LV) grids and to serve as an intelligent, medium-voltage (MV) layer interface, perhaps between prosumers and the TSO.

THE ROLE OF PROSUMERS

The vision of consumers transforming into prosumers is focused on the distribution level. Prosumers may range from households to highly engaged professional energy managers. Their rising participation may lead to a range of improved forecasting and asset-management tools.

Examples of likely engagement by prosumers include:

- Allowing EVs (private, fleet, or as part of workplace or destination charging) to be charged, and possibly discharged, to provide energy, capacity and ancillary services benefits
- Scheduling use of behind-the-meter residential loads and residential battery storage as part of 'solar with storage' installations
- Allowing behind-the-meter standby generators and uninterruptible power supply (UPS) batteries in commercial and public buildings to provide energy, capacity and ancillary services benefits.

MODERNIZATION OF THE DISTRIBUTION GRID

At transmission level, power flows, voltages and current are measured everywhere in 'near real-time'. Moving down through MV and to LV distribution, operational information is less available. In many places, measurements are made only once or twice per year at end-user level: annual electricity consumption, for example. Information about the status of the distribution grid at a given point in time is limited or unavailable.

Given the future that we predict, the quantity and complexity of grid equipment needs to increase significantly at distribution level, and we believe it will. Digitalization will be key, particularly through vastly increased data collection and communication, and distributed control. The latter benefit will allow automated control functions in even the lowest-level substations to take decisions which previously would have been implemented manually in a control centre.

One trend that will have a very large impact in the future is that grids will become 'inverter-rich' due to solar, wind, and battery systems being connected and requiring conversion of types of current. This will enable more automatic switching ('reconfiguring') and active control of generation, load, power flow and voltage. It will also change network behaviour with respect to faults and short-circuit current. Understanding the behaviour of the network with increased contributions of harmonic currents will also become more important.

The increased complexity involved will require major overhaul of protection systems, monitoring and control. New skills, tools and procedures to validate correct operation, robustness, and security will be needed.

STORAGE TECHNOLOGIES VERSUS GRID INVESTMENTS

In the decades ahead, DSOs in many countries will have to invest heavily in MV grids and associated MV/LV distribution substations –

22 The term 'Distribution System Operator' is becoming more widespread in place of 'Network Operator', and similar descriptions, as the operators move from mainly passive 'predict and provide' or 'fit and forget' roles to much more active ones in minute-to-minute operation, and running markets or auctions to procure services. This is more like a TSO.

sometimes called underlay grids – to cope with the increased share of dispersed and distributed renewable generation.

Demand response, distributed energy storage, and greater availability of operational data will contribute to delaying or avoiding grid investments. Some networks already designed for high energy flows to consumers – where direct electric heating is prevalent, for example – will be less affected.

Storage technologies suitable for DSOs[23] are currently restricted to batteries, including flow batteries. This is likely to continue. Compared with grid investments, battery-storage options have the advantage that they can in principle be moved. Batteries can be, and have been, installed in substations to avoid actual or forecast overloads of transformers; for example, to delay the need for reinforcement. This is particularly attractive for city-centre locations where land costs are high, space is restricted, and permitting processes may be prone to substantial delays. When the reinforcement is eventually implemented, the battery can then be removed relatively easily and used in another location. One UK DSO has pointed out that a significant benefit of this approach is that the need for an expensive reinforcement can then be clearly demonstrated to a sceptical regulator by using recorded demand data.

A further advantage of battery storage in comparison to grid investments is that it can often be installed much faster.

There is a fundamental issue with DSOs owning storage, however. The actions of network operators can influence electricity markets, including ancillary services markets. This is why they are usually not allowed to own or operate electricity generators and suppliers who may trade in those markets. Storage can be seen as 'infrastructure', just like network reinforcement; but it can also be operated as a generator or electricity supplier, trading energy, and services. The emerging solution for this issue appears to be that DSOs can obtain all the services that storage devices can provide, through competitive market mechanisms, but cannot own the storage devices directly. This approach is being adopted across the EU.

NEW BUSINESS MODELS

As prosumers become more prevalent, the volume of electricity transported by the distribution system may decrease markedly. However, the cost of providing a secure and stable system will remain constant or increase. This presents difficulties for methods of charging for these costs. New charging methods and business models will be required to ensure a sustainable electricity market.

In the past, the distribution grid was a system which took the energy from source to customer; in the future, its major contribution will probably be through guaranteeing a secure supply.

23 Note, however, that if DSOs also own and operate heat or cooling networks, it is feasible for thermal storage to be used. This is most likely to be considered as 'demand response' rather than energy storage.

TRANSMISSION AND DISTRIBUTION GRID COSTS

The ETO model for 2018 includes an improved method of estimating transmission and distribution grid costs. This is considered to be an important improvement, because electrification of demand and the growth of distributed generation is likely to change previous patterns of network reinforcement. This could have a significant impact on costs attributable to renewables.

For 2018, the grid cost model is based on regionally applied investment cost assumptions for typical transmission and distribution (T&D) structures in the relevant voltage levels[24]: UHV, 800 kV; EHV, 350 kV; HV, 130 kV; MV, 20 kV; and LV, 0.4 kV. It determines capital expenditure (capex) from the investments (considering equipment lifetime and specific capital interest rates), and operational expenditure (opex), as percentages of the investments. The model calculates the cost of investment needed to replace the grid (lifetime consumption), and to extend the grid as required by the forecast economic development, mainly to connect a given generation mix to the grid. This is a function of peak demand. Costs are determined separately for power lines (overhead lines, underground cables, undersea cables), transformers, and substations (excluding transformers).

The regional peak load determines the number of transformers and substations in the highest voltage level based on specific typical rated power of transformers. A generic scheme is applied to calculate the number of transformers and substations in the lower voltage ranges, based on typical short-circuit levels, targeting safe and reliable system operation[25].

Furthermore, a model for typical power lines delivers the line lengths in each level, which is important to understand how investments in the future will be distributed between grid types. This model has been calibrated with third-party information and references. The traditional overhead line is the cheapest route to grid extension. For multiple reasons, there is a clear tendency globally to use more underground HV cables, which will make future grid investments more expensive than in the past.

Investment costs for the 10 different regions in the ETO model are established by applying a regional cost matrix which is based on experience of practical T&D investment projects. For simplicity, this matrix depends on an economic weighting factor ranging from 0.75 in the Indian Subcontinent to 1.00 in Europe.

It is also clear that many other influencing factors on detailed investment cost elements (geographic conditions, installation specifics, civil works, project management, authorizations, rights of way, regulatory regimes, etc.) must remain neglected in this model.

As an example, Figure 3.7 shows the growth of power lines (all voltages) by region. The global total increases by a factor of more than three, dominated by Greater China and the Indian

24 These voltage levels represent average values from a global perspective, and differ slightly from region to region. UHV is ultra-high voltage; EHV, extra-high voltage; HV, high voltage; MV, medium voltage; and LV, low voltage.
25 Based generally on assumptions of robustness for a single contingency (N-1).

Subcontinent; but even in the mature economies, there is still substantial growth. A similar result (not shown) was obtained when only circuit length was considered.

Figures 3.8 and 3.9 show that most of the growth occurs in the extra-high voltage class, i.e. transmission, using conventional AC. However, from around 2030, high-voltage DC grows rapidly to become a significant market, predominantly in Greater China and the Indian Subcontinent.

Significant expansion is also predicted for transformers (Figure 3.10). However, the clear majority of future transformer installations are at low- and mid-voltage levels, i.e. distribution. This matches the conclusion that the expansion is driven mainly by increasing electricity demand.

Considering annual additions to the global transformer fleet (not shown), the ETO model predicts a doubling of the annual installation rate compared with the present pace.

The model also estimates growth in the number of substations by voltage level and region: this is not shown here, but supports the conclusions drawn from Figure 3.10.

FIGURE 3.7

Power line capacity by region

Units: PW-km

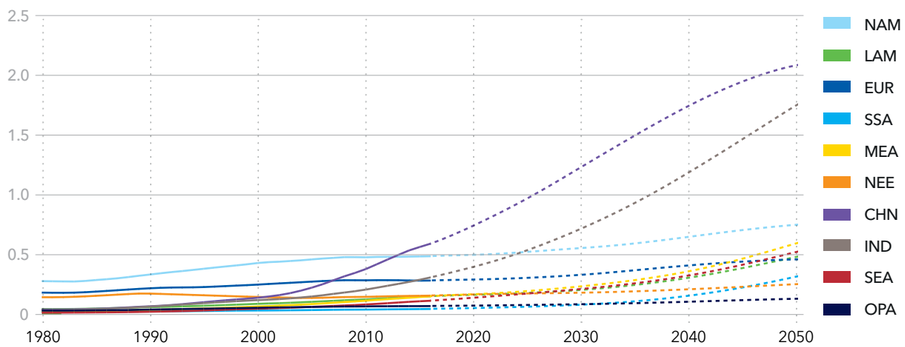


FIGURE 3.8

World power line capacity by voltage

Units: PW-km

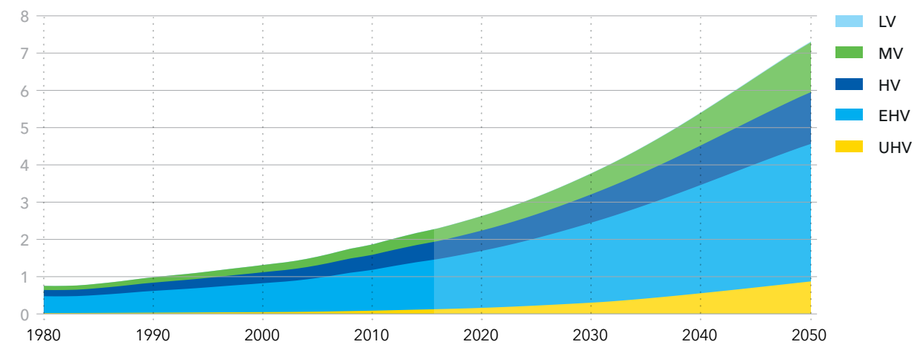
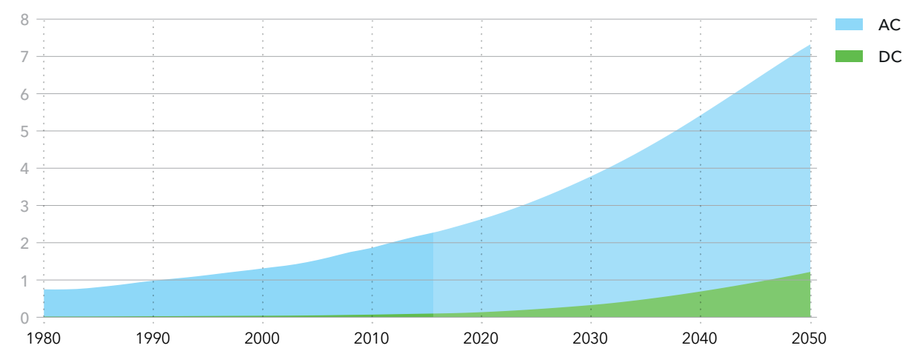


FIGURE 3.9

World power line capacity by technology

Units: PW-km



From these projections, total costs can be estimated (Figure 3.11). Capex in this figure is annualized, converted to an annual equivalent over the lifetime of the asset. This matches the way regulators and network operators assess investments, and allows a more useful comparison with opex. The chart shows that substantial costs are incurred, particularly from 2030 onwards.

The total annualized cost in 2050 is approximately three times today's level. Opex is seen to be minor in comparison with annualized capex. Total costs are dominated by annualized capex for overhead power lines.

Figure 3.12 shows that in the context of total electricity system costs, these increased grid costs are not dominant. Although capex costs for power lines and for non-fossil generation (primarily renewables) each increase considerably by 2050, this is compensated by reductions in other areas.

Further, global GDP is forecast to increase considerably by 2050. The main ETO report establishes that total energy-system expenditures decrease from around 6% of global GDP today to around 3%.

FIGURE 3.10

World number of transformers by voltage

Units: Millions

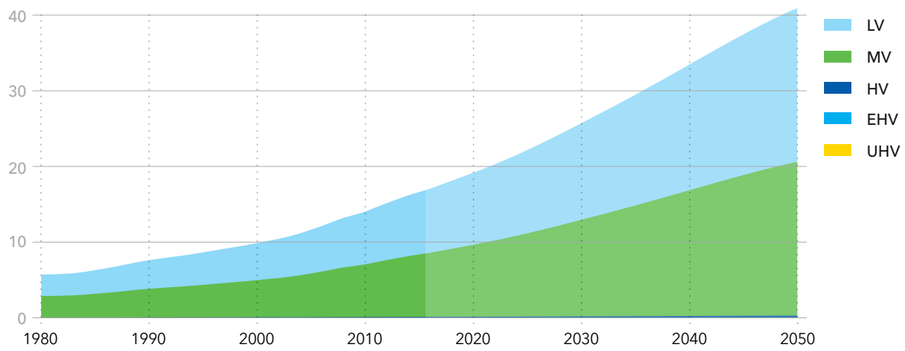


FIGURE 3.11

Annualized grid capex/opex

Units: Bn$/yr

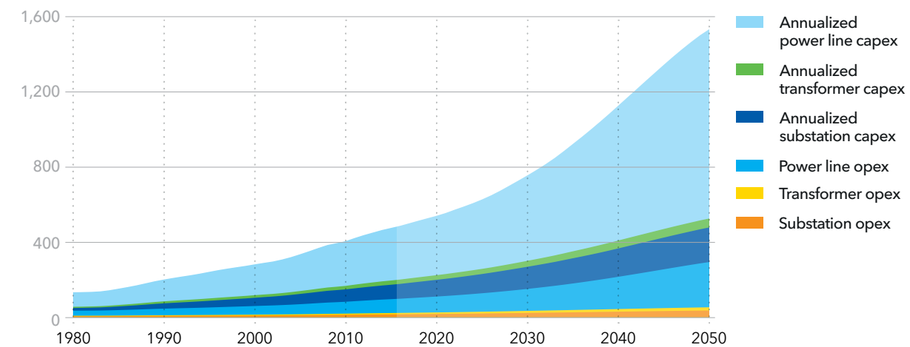
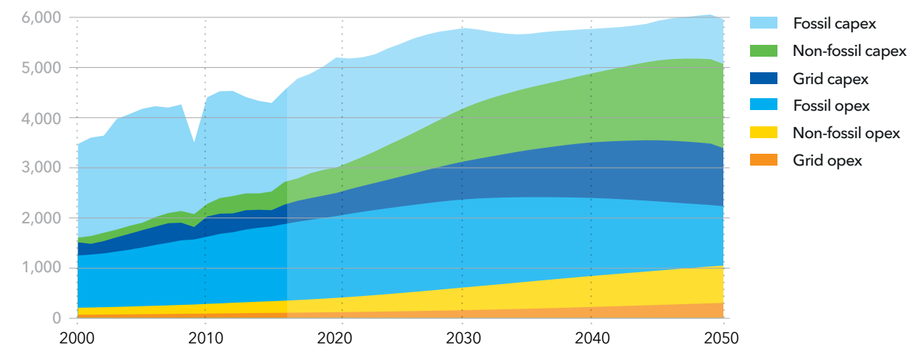


FIGURE 3.12

World energy expenditures

Units: Bn$/yr



OFF-GRID AND MICROGRIDS

The ETO model forecasts major expansion of transmission and distribution grids. However, some of the increasing electricity demand can instead be met by 'microgrids', a term which unfortunately has multiple conflicting meanings:

- Isolated very small electricity grids, e.g. for islands or remote villages, usually because low population density or low economic activity makes traditional network extension unaffordable
- Isolated very small electricity grids, driven by economics of fuel supply, such as for military use, mines, offshore oil installations, remote telecommunications, or scientific installations
- Commercial, industrial or residential electricity systems which have a connection to a larger network, but which, for reasons of reliability, are intended to be run disconnected if necessary
- Commercial, industrial or residential electricity systems never intended to be autonomous, but managing their own 'behind-the-meter' generation, storage, and demand to minimize costs and/or manage grid-connection limitations.

The future evolution of each of these is expected to be very different. For islands and remote villages, solar or wind generation with battery storage is often already seen as the cheapest option and, importantly, is becoming more affordable. There is rapid growth, particularly in Sub-Saharan Africa, in suppliers of household-to village-scale systems, using sale, lease, energy-supply or energy-service business models. Payment can be by mobile phone. This trend will continue, providing major economic benefits to some of the world's poorest people; though the volumes of electricity supplied will not be visible on the scale of the ETO model results.

As economic activity and electricity demand increase, it is not at all clear whether such microgrids will eventually join together into conventional distribution systems, or whether further expected reductions in solar and storage costs will remove the incentive. Indeed, it is seen already that in some rural areas with existing conventional distribution systems, if they are unreliable or expensive, electricity consumers may prefer to go 'off-grid', i.e. reversing the process.

For commercial, industrial, or residential microgrids with connections to larger networks, the main drivers of development will be financial and regulatory. As costs of behind-the-meter renewables, storage, and demand management reduce, the justification for grid-connection changes from its value for energy supply to its value for reliability. Going completely 'off-grid' requires substantial capital investment in redundant equipment to achieve the same security of supply as an urban distribution network. Regulatory barriers will be crucial: most electricity regulation regimes were not written with these situations in mind. Consequently, significant divergence between countries can be expected in the short term as regulators seek to resolve emerging problems with the minimum changes to established regulatory regimes.

INTERNATIONAL AND INTER-CONTINENTAL TRANSMISSION

The ETO model covers trade in coal, oil, and gas between 10 regions, but does not allow trade in electricity across regions as there is currently little of such trade. However, the ETO model projects very substantial expansion of transmission systems within regions; so, there may also be strong drivers in future for inter-regional or inter-continental transmission. The prime current example of this is the 'Belt and Road' strategy and initiative promoted by China, and in particular its State Grid Corporation. The initiative's declared aim is to 'build a strong and smart grid with a UHV power grid as the backbone, clean energy transmission, and global connectivity'.

Regional examples are the North-East-Asian-Supergrid, interconnections in the Baltic and North Sea, and plans to build large scale offshore wind DC grids.

Power interconnection at this scale is still in its infancy and faces many practical barriers including, among others, existing grids, national policies, and required investment levels.

BARRIER 1: EXISTING GRIDS

In some countries, the level of existing grid interconnections is relatively low. The distribution of energy resources along the line is extremely uneven, and there is a marked mismatch between energy production centres and load centres. It is necessary to systematically plan the construction of long-distance, large-capacity and high-efficiency power transmission channels from energy bases to load centres. However, many developing countries along potential routes suffer from weak power infrastructure, ageing backbone transmission lines, small transmission capacity, and high transmission and distribution network losses. They still lack the conditions for large-scale interconnection and interoperability.

BARRIER 2: NATIONAL POLICIES SUPPORT CONSTRAINTS

Due to large differences in their stages of development and national conditions, the understanding of power interconnection and interoperability among countries along the route of any proposed cross-border network system tends not to be uniform. There are different views on technical feasibility and safety, and it is difficult to promote power interconnection and interoperability.

BARRIER 3: CONSTRAINTS ON THE MASSIVE INVESTMENT REQUIRED

Large-capacity and long-distance power transmission requires huge capital investment. Against a background of weak infrastructure, and limited financing channels of countries along a route, large-scale promotion of transnational power interconnection can inevitably face constraints on capital investment.

3.3 ELECTRICITY GENERATING TECHNOLOGIES

CONVENTIONAL THERMAL GENERATION

PRODUCTION AND CAPACITY

Section 2.3 discussed the ETO model's forecasts for electricity production and generation capacity. There are substantial reductions in electricity production from the 'conventional' thermal generating technologies, including nuclear. Most also show declines in total capacity, except for gas. This indicates gas moving from a 'baseload' role to a 'peaking' role. The term 'baseload' starts to lose meaning in the new paradigm, but gas plant is forecast to operate with a substantially lower capacity factor. This will change the gas plant mix, in order to increase flexibility of operation.

Gas plant is therefore used as a 'flexibility' option (see Section 3.4) competing with other options such as energy storage and demand management.

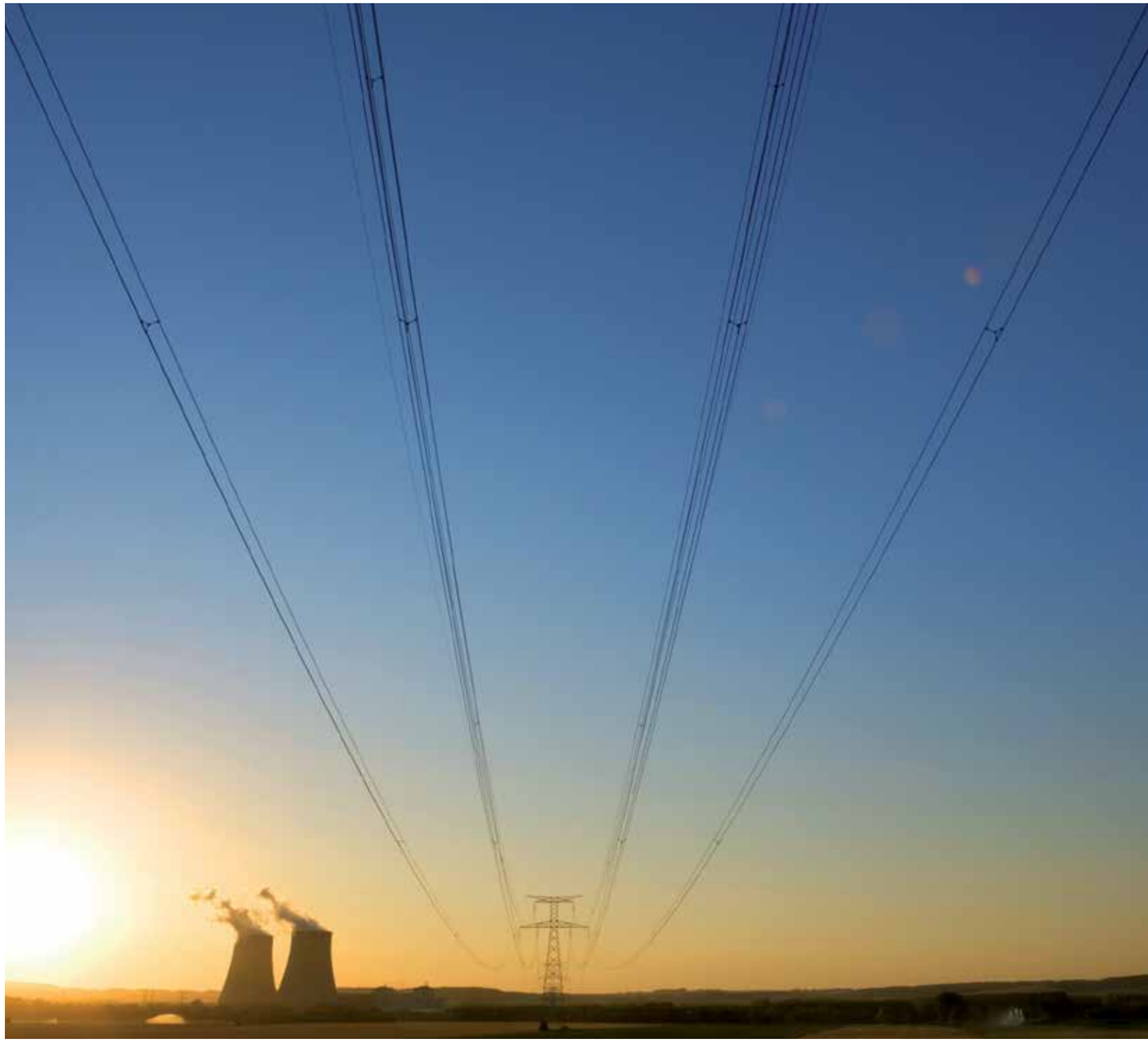
For the other thermal technologies, the reduction in use creates a risk of stranded assets.

Although H_2 was included in the ETO model for 2018, the main potential use assigned to it is transport, as studies internal to DNV GL indicate that H_2 is an expensive option for electricity generation.

CARBON CAPTURE AND STORAGE

Although power generation with carbon capture and storage is included as an option in the ETO model, the costs assumed, including 'learning curve' effects, are sufficient to ensure that the algorithm chooses other options in preference.

"Although H_2 was included in the ETO model for 2018, the main potential use assigned to it is transport, as studies internal to DNV GL indicate that H_2 is an expensive option for electricity generation.



VARIABLE RENEWABLES

PRODUCTION AND CAPACITY

Section 2.3 shows massive increase in both production and capacity for solar PV, onshore wind, and offshore wind. This makes a substantial contribution at acceptable cost to decarbonization.

The ETO model includes some constraints on growth due to supply-chain issues: these do not appear to place fundamental constraints on this growth.

The space required for these quantities of renewables were evaluated. For solar PV, the total land area required by 2050 (excluding rooftop solar) is around 300,000 square kilometres, equivalent to 0.6% of the world's agricultural land. The greatest land use occurs in the Indian Subcontinent region, where solar PV requires around 2.3% of agricultural land.

The land area required for onshore wind is greater. The most critical region is Greater China, where wind farms would be installed on 14% of agricultural land in 2050. Of course, agriculture can continue within the area occupied by wind farms: only around 1% of the area is actually lost to turbine foundations, roads and other structures.

For offshore wind, the most critical region is again Greater China, where around 37% of the coastline would be used, though alternative array configurations could reduce this impact.

For biomass (liquids), Greater China is once again the most critical region, where around 4.6% of agricultural land would be used.

Offshore wind, including floating wind, appears to be the resource where competing claims for space could produce the most significant constraints on generation capacity by 2050.

DELAYS AND CURTAILMENTS IN RENEWABLES

The ETO model assumes that grid infrastructure can be built as needed in time to match growth in generation. Rapid growth in both wind and solar has taken policymakers and electricity network operators by surprise in many countries in recent years. The results have been either moratoria or other means to delay new projects, or curtailment of wind and solar when in operation[26]. The costs of curtailments may be borne by the project owners, or socialized across all electricity consumers.

THE ISSUE OF VARIABILITY

A major impact of this very high penetration of wind and solar is the weather-dependent variation in power output. Because of the strong averaging effects of geographical separation, for both wind and solar, very short-term variability of the order of seconds and minutes is not an issue for power systems, though it may have local effects. The main issues are variability on timescales of hours and days, and seasonality.

The ETO model attempts to address both these issues, within the confines of the yearly timescale, by adding storage and gas or oil-fired peaking plant. The costs for this are included in the model's decisions. Peaking plant is electricity generating plant with low capex and opex (specifically fuel costs) and which is intended to run infrequently.

Section 3.4 discusses storage and other flexibility options in more detail.

WIND AND SOLAR IMPACT ON ELECTRICITY PRICE

It is important to understand the economic aspects of electricity systems with very high fractions of variable renewables. Other work by DNV GL, issued in September 2018[27], analyses an important issue: 'cannibalization' of the business case for variable renewables because of a decreasing capture price. Periods of high renewables generation, such as mid-day for solar, affect the electricity price under most electricity markets. As solar production in individual plants is well-correlated across an area, the majority will produce most of their output simultaneously, lowering the electricity price. The average price obtained by solar or wind, the 'capture price', will therefore be lower than the average across all generators. This effect increases as the fraction of solar or wind rises.

The same report also illustrates that current forms of electricity market based on marginal costs of generation struggle to support the economics of large-scale thermal plant.

> "Rapid growth in both wind and solar has taken policymakers and electricity network operators by surprise in many countries in recent years

26 For example, official figures for China in 2017 show 12% curtailment of wind generation and 6% curtailment of solar.
27 'Future-proof renewables: Implications of a high percentage of solar and wind in the power system', DNV GL, September 2018

OTHER RENEWABLES

As a mature renewable technology, hydropower is well understood. Long lead-times, high capex, and concern over potential environmental and social impacts limit its growth.

Hydropower with reservoirs store enormous amounts of energy, and are key for seasonal balancing of electricity systems. The ability to support power quality and balance on different time scales may become increasingly appreciated by system operators.

The ETO model predicts a gentle, continued increase in hydropower capacity, almost doubling by 2050.

The use of biomass for combined heat and power, or district heating with dual electricity and biomass boilers is part of the integration of thermal and electricity markets. Further, this supports a role for biomass as part of the flexibility required to balance the electricity system increasingly dominated by weather-driven generation, namely solar and wind.

ELECTRICITY MARKETS AND FINANCING

In the last decade and more, renewables growth has occurred under the umbrella of feed-in tariff (FIT) schemes and other subsidy or premium-price systems. Renewable energy now has claims to be both a mature technology and a mature sector, and is viewed thus by stakeholders in the energy sector. Subsidies and FIT schemes are being replaced by auction systems, or by no external support at all, examples of the latter being pure 'merchant' projects and corporate Power Purchase Agreements (PPAs).

This has caused huge turmoil among players in the renewables industries. Lenders no longer have the comfort of long-term prices guaranteed by a government.

The results of public auctions have produced surprisingly low prices for solar PV, onshore wind, and offshore wind, encouraging other governments to follow this path. Also, in some countries, the growth of renewables (particularly solar PV) under FIT schemes has been greater than governments have expected, resulting in substantial unexpected costs to be borne by the electricity consumer or taxpayer.

This has occurred in parallel with substantial capital and operational cost reductions for wind and solar. Improved design of both components and projects has produced substantial cost savings, particularly for offshore wind. For solar PV, the increase in volume has resulted in manufacturing improvements and cost reduction.

Solar and wind projects are therefore now exposed to 'merchant risk', which conventional thermal generators have always had to live with.

Electricity markets have existed for many years. The energy mix has changed, and the rules of these markets have adapted to keep pace, and to meet demands from users, consumers, and governments.

These markets now face a situation where variable renewables can achieve peak (short-term) penetration levels greater than 70%. In the future envisaged by the ETO model, there will be substantial periods of surplus renewables.

In these situations, electricity markets are driven not by fuel costs of conventional thermal plant in an economic 'merit order', but by renewables with very low marginal cost. Wholesale prices have already gone to zero, or negative under some regulatory arrangements, and very high in situations with low wind or solar generation. New market arrangements are emerging which provide income for generators for their ability to provide essential ancillary services, such as frequency response and reserve. In addition, income for capacity, a payment to 'be there', is intended to support the fixed costs of providing firm generation capacity.

Well-designed markets are 'technology blind'. They are arranged so that the service is defined, not the technology by which that service is provided. For example, the UK TSO ran an auction process in 2016 for 'enhanced frequency response', which required the ability to export or import power within one second in response to sudden frequency deviations. Generators, demand aggregators, and energy storage suppliers bid into the auction; battery projects won all the contracts.

There have also been developments in financing new generation projects, particularly for renewables. What started in 2014 as a new fashion called green bonds, has proved to be a very effective way of obtaining finance. In certain debt market operations, and for certain participants, interest rates as low as 1.875% have been obtained, significantly below those offered to project finance schemes. The green bond market is increasingly popular.

Big players continue to adapt their approaches. Projects in which the construction and early operation are handled within corporate resources reduce both the financing costs and the time to market of their projects. This is the so-called ´Build, Sell and Operate´ scheme in which the sponsor deals with the cost of the construction and operation of the initial, typically two, years. Uncertainties in the project's operation and performance are reduced. After this, the owner sells, typically, about 50% of the shares while remaining in control of the asset management and the energy produced. This way, the initial developer, though supporting a higher debt burden during the early years, can offer the market a much more certain investment prospect. This offer is highly appreciated by low risk-appetite investors such as pension funds.

> "New market arrangements are emerging which provide income for generators for their ability to provide essential ancillary services, such as frequency response and reserve.

3.4 ENERGY STORAGE AND OTHER FLEXIBILITY OPTIONS

Energy storage, and battery storage in particular, is sometimes suggested as the obvious solution to the challenge of variable renewables, and more generally for other issues of electricity system operation.

It is important to realize, however, that there are several competing options, often described together as providers of 'flexibility':

- Energy storage: Until recently, pumped-hydro storage was by far the dominant source of energy storage on electricity systems[28]. Other technologies such as batteries, flywheels and compressed-air storage in caverns were insignificant in comparison. However, developments in new battery chemistries and other technologies such as liquid air energy storage have changed this picture.
- Greater interconnection: Providing stronger interconnections between different parts of the electricity system, particularly between nations, provides significant benefits in 'smoothing' the variability of solar or wind over a larger geographical area. It also smoothes variability of demand considerably, and improves robustness to failures.
- Flexible generation: Electricity systems already make substantial use of generators with the ability to start quickly and vary their output rapidly. Examples are hydro generators, open-cycle gas turbines, and diesel generators.
- Flexible demand: Demand-side response (DSR) is already provided by industrial or commercial consumers with loads they can avoid or defer for a short time, such as air-conditioning, or refrigeration in distribution centres. Domestic water heating is already a significant provider in some countries. Digitalization and the Internet of Things are lowering the costs of providing DSR from a wide range of loads. EV charging is a major new source of DSR. There is substantial competition in some countries to establish new business models and gain a customer base of residential EV owners. EV charging complicates the picture if discharging is also considered. This encompasses vehicle-to-grid services, where the EV battery can be discharged while connected to the charging system, providing that it is satisfactorily charged when the owner next needs it.
- Flexible markets and regulation: This 'flexibility option' is often overlooked but is important. There are many examples of cases where traditional market rules or regulatory requirements have unintended consequences which have been barriers to flexible operation of power systems. An example arose in Germany, where each of the four TSOs was required to balance generation and demand across its own service area. This produced higher costs than if the net imbalance across all Germany had been the only target: the impact was small until wind capacity in the north of Germany became significant.

28 There are alternative ways of defining what constitutes 'energy storage'. Clearly, coal stockpiles at a power station are a form of energy storage, and could contain substantially more energy than pumped hydro storage. However, in the context of electricity systems, energy storage is commonly defined to cover conversion of electricity into some form of stored energy, available for reconversion back to electricity.

Figure 3.13 shows that, for all flexibility issues, it is important to understand the issue of timescales.

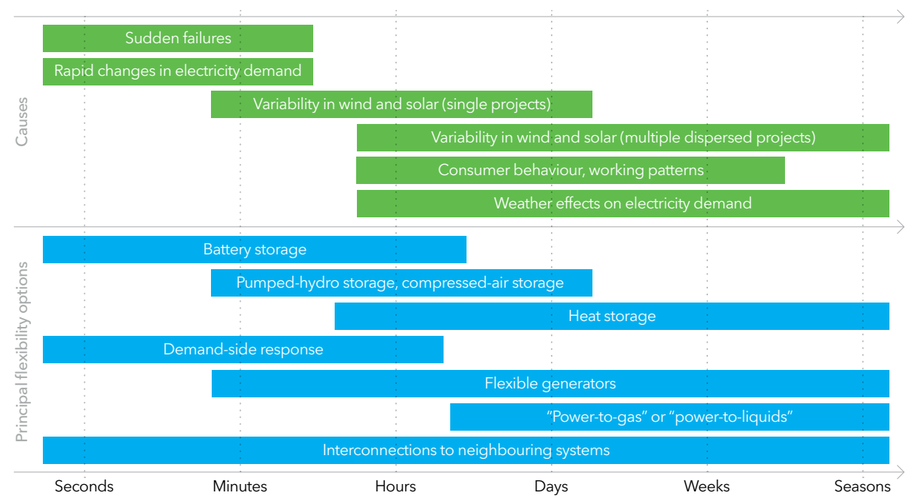
DSR, interconnections and storage, particularly batteries, are good for the very shortest timescales of sub-seconds and seconds. All options are useful on timescales up to minutes and hours. For example, we are now seeing significant growth in batteries being used in conjunction with solar PV to smooth the mid-day peak in solar production into the evenings.

The greatest challenge to flexibility providers is seasonal variability in demand, and in wind and solar production. Storing surplus solar production in summer for use in winter is unfeasible by battery. In addition to hydro reservoirs, credible options presently include power-to-gas or liquid fuels, as discussed below, and long-term heat storage for use as heat, such as in district heating systems.

Both options can be regarded as examples of 'sector coupling', connecting electricity markets to gas, fuel, and heat markets.

FIGURE 3.13

Flexibility issues by timescale



3.5 POWER-TO-GAS

Power-to-gas covers the conversion of electricity to gas, principally H_2, with a possible further conversion to methane (CH_4) or other gases (Figure 3.14). Hydrogen has the potential to be a major energy carrier, and an option for decarbonization of transport and high-temperature industrial heat. It can also be combined with carbon dioxide (CO_2) and nitrogen to produce sustainable products such as ammonia, ethylene, and methanol, which can be used in the chemical industry.

Production by electrolysis from 'surplus' or low-cost electricity from renewables is an option for producing 'green' H_2 with no related carbon emissions. In this respect, it is in competition with biogas.

Electrolysis is a well-understood industrial process for production of H_2, with prospects of significant cost reductions at scale. It is presently more expensive than producing H_2 from natural gas by Steam Methane Reforming (SMR), or via other processes from fossil fuels, even when costs of carbon capture are included.

Injection of H_2 into existing natural gas grids is feasible up to fractions of a few percent, by energy value. This is limited by specifics of the gas grid, such as the materials used, and by the burners on existing appliances such as central-heating boilers and cookers. 100% H_2 networks are feasible with some modifications. An alternative for existing gas networks is conversion to CH_4 using a source of CO_2, with substantial energy-conversion losses.

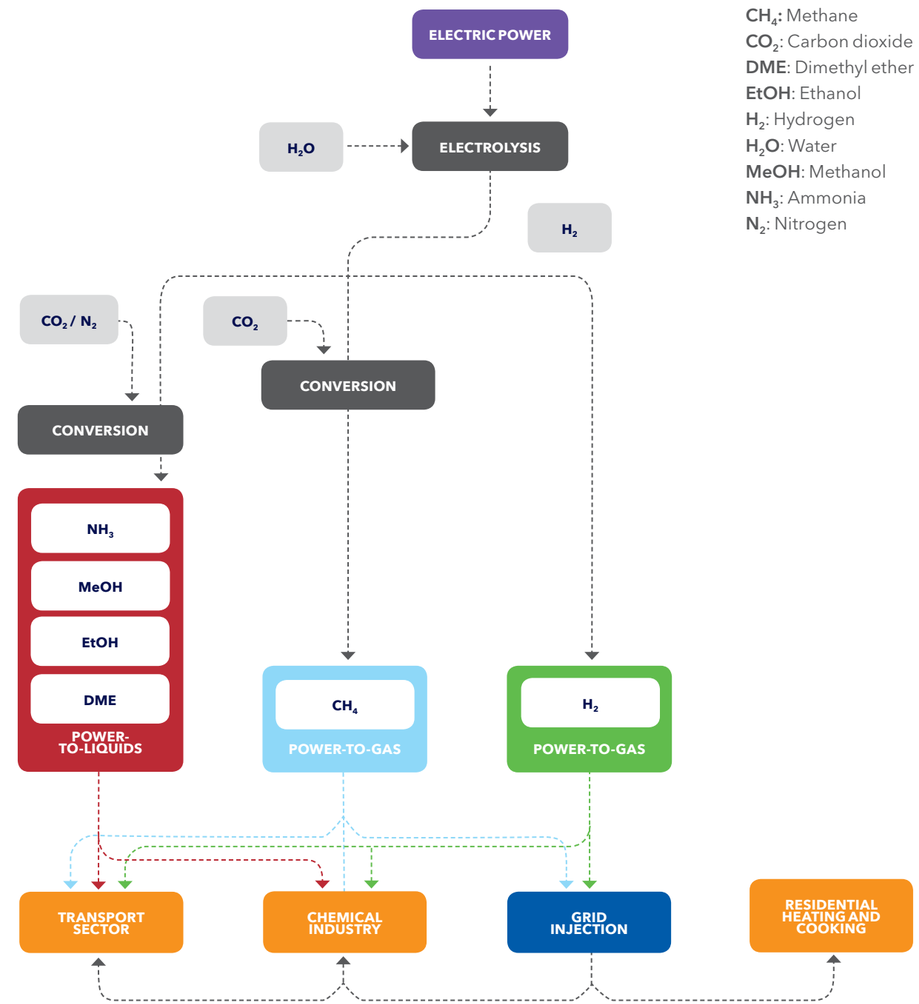
The benefits offered by power-to-gas options are as follows:

- A possible low-cost route to decarbonizing residential and commercial heat, using much of existing gas networks with little public disruption
- A possible low-cost route to decarbonizing high-temperature industrial heat, particularly reduction processes such as in brickworks and in the steel industry by replacing blast furnaces
- A possible route for decarbonizing several modes of transport, including aviation
- A provider of very large energy-storage capacity within gas networks or caverns, at little cost, thereby providing a flexibility option for variable renewables. Europe's underground gas storage capacity is, in stored energy terms, an order of magnitude greater than its pumped-hydro storage capacity.

> "Production by electrolysis from 'surplus' or low-cost electricity from renewables is an option for producing 'green' H_2 with no related carbon emissions. In this respect, it is in competition with biogas.

FIGURE 3.14

Power-to-gas options



CH_4: Methane
CO_2: Carbon dioxide
DME: Dimethyl ether
EtOH: Ethanol
H_2: Hydrogen
H_2O: Water
MeOH: Methanol
NH_3: Ammonia
N_2: Nitrogen

3.6 DIGITALIZATION

'Digitalization' can be a poorly-defined term. In the context of this work, the important facets of this group of related concepts are:

- improved communications, allowing large numbers of devices to communicate seamlessly and robustly even if mobile, with multiple protocols
- large numbers of sensors, some with substantial built-in intelligence and processing power
- large amounts of data, easily accessible by multiple parties
- tools for understanding and making use of these large amounts of data, including machine learning and artificial intelligence
- complex control systems.

These factors apply across the entire energy system from generation through transmission and distribution and in end-users' plant and machinery. They are critical to enabling the energy transition as we envision it. Such digitalization allows for higher asset utilization, improved energy efficiency, and the ability to implement new business models, such as demand response, which along with greater customer engagement can impact energy requirements.

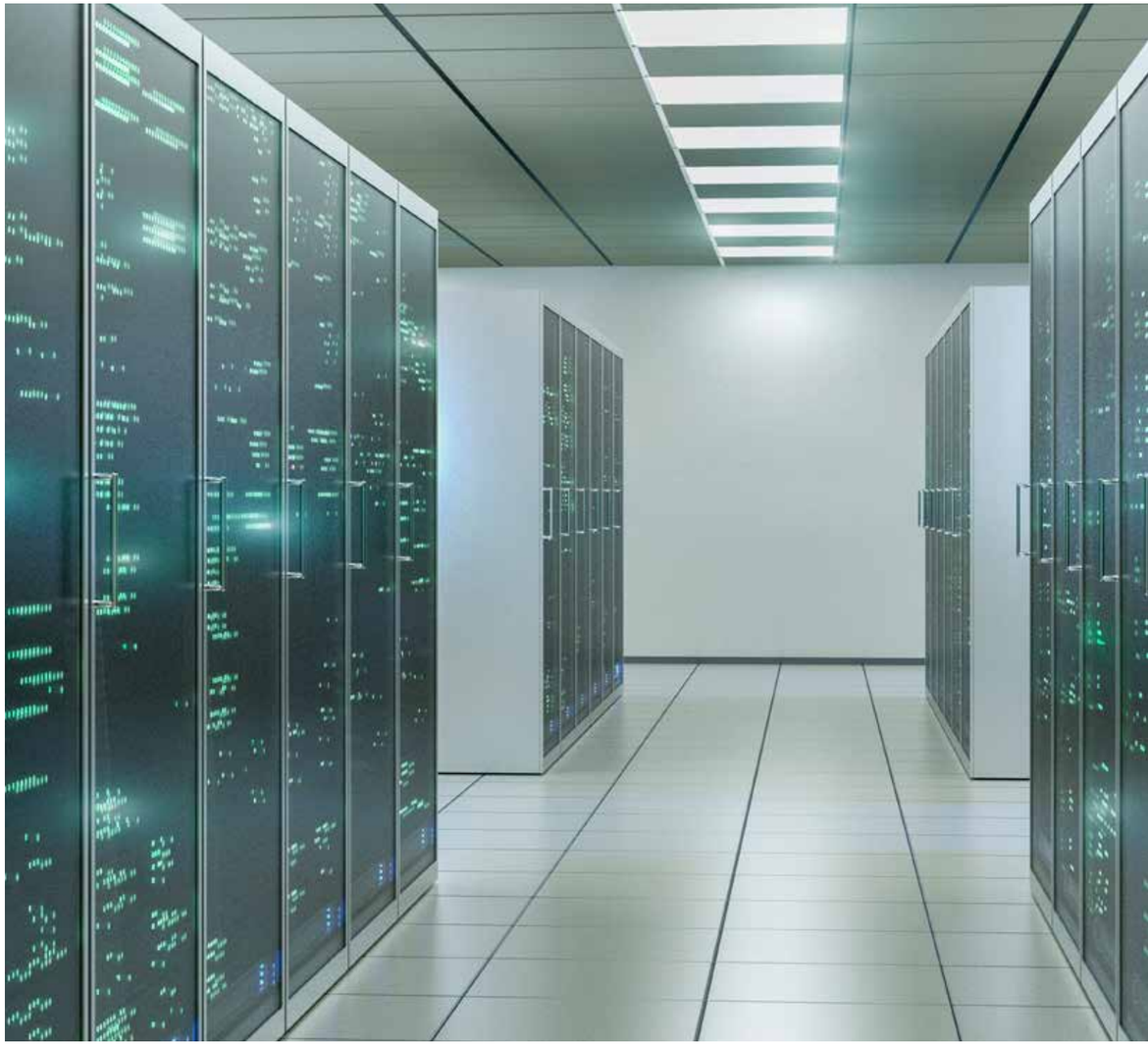
Sensitivity studies conducted with the ETO model show that assumptions about improved data and communications could have visible though not radical impacts on the results.

New business models also threaten disruptive change to well-established industries.

All the concepts listed above are also vulnerable to misuse; and the importance of energy systems to society is such that they are attractive targets for criminals and terrorists. Cyber security is therefore a high priority.

Digitalization's total impact is hard to quantify as it is widely spread throughout the energy system, but its influence will continue to grow. Implications of aspects of digitalization are discussed in Section 4.

"Such digitalization allows for higher asset utilization, improved energy efficiency, and the ability to implement new business models, such as demand response, which along with greater customer engagement can impact energy requirements.



CHAPTER 4

TAKEAWAYS FOR STAKEHOLDER GROUPS

4.1 POLICYMAKERS

The rapid decline in the cost of solar and wind power shifts the nature of the development of renewables from being policy-driven to market-driven. A similar process may be expected as electric-vehicle (EV) costs reduce. Public policy-makers need to respond to fast-paced techno-logy and market changes by developing regulations and market design to support the energy transition and avoid inefficiencies. With policies moving from setting the agenda to trailing development, the normal political decision processes can be put under stress. In this landscape, it is important that policymakers support efficient markets and further technology developments, and avoid locking in technology choices.

> Our results imply that the energy trilemma is changing. The low emission technologies are to an increasing degree also low-cost technology and utilize local resources.

Our results imply that the energy trilemma[29] is changing. The low emission technologies are to an increasing degree also low-cost technology and utilize local resources. Energy security with respect to electricity will shift from a question of access to internal or imported reasonably priced fossil fuels to a question of ensuring stable supply of power from renewables at the required quality for modern appliances. However, the energy transition is capital-cost intensive with large investments in generation and in grids, and it is important to develop clever market design and pricing strategies (electricity tariffs) to properly incentivize low carbon investments.

The costs are significant for investments in networks and in measures to mitigate the variability of renewable power generation and new types of load. The model for recouping these costs in the system, often through regulated grid and system operators, will have to be guided by policy and regulations that ensure acceptance.

The transition requires wise use of methods and markets to avoid unnecessary infrastructure investments. New tools such as increased deploy-ment of batteries, digitalization, and flexibility markets require new regulation.

The energy transition is creating stranded assets. Older fossil electricity generation capacity is increasingly seen as stranded assets, and the policymakers are challenged on how they manage this. Equally, electrification of energy use renders some gas and petroleum infrastructure redundant and stranded.

State, county, and municipal ownership has traditionally been strong in the power and utilities sector, making the impact of stranded assets directly visible in the budget at different authority levels. This challenge is stronger in OECD nations, with ageing infrastructure, than in emerging markets with relatively newer infrastructure and stronger demand growth to carry the cost of new investments.

While the energy transition has positive climate effects, the shift requires new areas to be covered by wind farms and solar parks. The spatial footprint will evoke the same 'not-in-my-back-yard' discussions as other types of large-scale infrastructure. Again, the role of government will be to balance the gains and pains to ensure the necessary level of acceptance to the changes.

Our results indicate a 'most likely' energy future that does not meet the COP21 Paris Agreement's climate-change mitigation goals. Additional measures should be taken to put the world on a pathway to avoid severe climate problems. Policy-makers can put in place measures to incentivize a demand shift towards clean energy, to stimulate innovation in new efficient and clean technolo-gies, and to drive standards for energy efficiency and lower emissions.

Transitioning to low-carbon manufacturing will require electrification of many processes previ-ously powered by combusting fossil fuels. Several technologies and innovation opportunities for electrification are available.

However, most published studies show that towards 2030, industrial electricity prices in industrialized countries are expected to rise relative to gas. This means that policies, tax regimes and/or pricing trends will need to change in favour of using electricity instead of gas, unless carbon capture is implemented.

The ETO model foresees very limited develop-ments in carbon capture and storage (CCS). Current understanding is that a technology breakthrough for CCS is required to spur more rapid decarbonization. Carbon emission costs are quite far from driving CCS. Government investments are required to advance deployment of this technology.

> Our results indicate a 'most likely' energy future that does not meet the COP21 Paris Agreement's climate-change mitigation goals.

29 The need to compromise between the competing aims of low cost, reliability of energy supply, and sustainability.

4.2 REGULATORS

Regulators are faced with ensuring a secure, reliable and affordable electricity supply, fair electricity markets, and implementing policymakers' environmental, social, and economic aims. The fundamental challenge facing regulators through the energy transition is how to reconcile the 'infrastructure' model (long asset lifetimes, low risk, low financing costs, monopoly structures) with the new environment of rapid change and uncertainty.

Some of the uncertainties will reduce in future, as the costs and benefits of the multiple technical options become clearer; electrification options for heat or transport, for example. Rapid change remains a challenge to the monopoly infrastructure model, however. Regulators will have to make decisions about where the risks of major decisions should lie. Should consumers, governments, or network operators bear the costs of stranded assets made in good faith using the best available information at the time, but which 10 years later prove unnecessary?

Regulators will also have to deal with 'sector coupling'. To cope with variable renewables and driven by decarbonization, electricity, gas, heat, and electric transport systems will likely become more closely inter-related. The consequences may be revolutionary in some cases. It is possible for example that EVs, low-cost solar photovoltaic, battery storage and zero-emission buildings could within a decade lead to entirely different usage patterns for distribution networks. Such a trend could bring new business models for residential and small commercial customers within the same timeframe. In particular, the ETO model results show that the interaction of EV charging and variable renewables has complex effects on electricity networks.

4.3 TRANSMISSION SYSTEM OPERATORS

Transmission system operators (TSOs) face the same uncertainties as regulators, and some issues specific to their element of the electricity value chain.

MASSIVE EXPANSION OF TRANSMISSION

Our results indicate a major expansion of transmission systems, especially overhead high-voltage AC lines, to cope with electrification and the growth of renewables. The majority of this is in Greater China and the Indian Subcontinent, though all regions are affected. This will require major investments, perhaps in advance of a clear demonstration of need. An expansion of skilled staff within TSOs and their contractors will be required.

In some regions, this expansion will mostly be 'new-build' or 'green field'. In others, it will involve reinforcement or replacement of existing assets; particularly within cities, the costs can be very high and the timescales long.

COMPLEXITY OF SYSTEM OPERATION

Electricity transmission systems will experience much greater variations in power flows, and more extremes of high usage and low usage. Climate change may also produce a greater range of weather conditions in some regions.

Much of both the electricity demand and generation will become converter-connected, resulting in new problems from harmonic currents, requiring improved tools and understanding, and new infrastructure investments.

NEW TECHNOLOGIES

High-voltage DC will become an essential component of transmission systems in some regions, though only at the longer and higher-capacity end of the spectrum.

Digitalization and new business models will allow greater interactions with electricity consumers, potentially providing new tools for balancing the system in normal and abnormal operating conditions.

Energy storage, particularly batteries, offers new solutions for deferring network reinforcement and perhaps also for temporary supplies.

CYBER SECURITY

Transmission systems are obvious targets for malicious cyber attacks. They are also physically widespread, with very many devices from different suppliers using different principles, and are modified almost daily. Managing all the interfaces is therefore a major cyber-security problem.

4.4 DISTRIBUTION SYSTEM OPERATORS

Distribution systems face some of the same challenges as transmission systems, though costs of individual projects are generally lower and timescales shorter. The digitalization and cyber risks are similar. Some specific issues are described here.

UNCERTAINTY

Uncertainty impacts most strongly at distribution level, at least for the next few years. Growth of solar PV in all customer classes, with and without storage and EV charging, presents a major issue for network operators. The 'cluster effect' seen in solar PV in relatively affluent neighbourhoods[30] may also be occurring with EVs. Both can grow much faster than the distribution system can be reinforced. This also occurs for large-scale solar PV: there are current examples in Europe where grid constraints are limiting expansion.

ELECTRIFICATION

The ETO model results forecast massive electrification of demand, which drives major expansion of distribution networks. For example, new additions of transformers and associated plant are expected to occur at double the recent rate. This introduces risks of supply-chain constraints, and shortage of skilled staff.

EV CHARGING MODELS

There are several models for EV charging. The control they provide over the timing of charging is a critical differentiator between them.

Four parties whose objectives may conflict with each other are:

- The EV owner
- The energy supplier, who wishes to buy the energy at the cheapest rate, and perhaps also use the EV battery to sell energy at high-price periods or to provide ancillary services
- The TSO, who may wish to use EV charging to mitigate network constraints and for balancing
- The distribution system operator (DSO), who may wish to avoid network constraints.

Of these, the DSO is least able to participate under current arrangements.

BATTERY STORAGE

More so than at transmission scale, transportable battery storage offers new options to DSOs. For temporary, unexpected situations, they may replace diesel generators. We are already seeing signs of this in developed economies, where the noise and air-quality benefits are significant. However, there is potentially a larger market for longer-term installations, to avoid or defer network reinforcement. This is particularly so in urban areas, where costs and timescales for new overhead or underground cables are a greater problem.

30 Where one house in a street installs rooftop solar PV, there is a greater chance of others doing so, leading to a rapid growth in specific locations. Both solar PV and EVs are highly visible to neighbours, in a way that, for example, heat pumps or improved insulation are not.

4.5 ENERGY SUPPLIERS AND AGGREGATORS

In liberalized markets, complex arrangements may emerge, involving both energy suppliers and aggregators. A supplier is the contracting party for the end user of electricity and gas. In the same part of the value chain, aggregators contract with end users to provide flexibility services; they aggregate these and sell in ancillary-services markets. Frequency response is an example. Very often, it is suppliers who take the role of aggregators, and it becomes difficult to distinguish the impacts of energy transition on the two business models.

The increased numbers of distributed generation and prosumers are both challenges and opportunities for electricity suppliers. The challenge is from reduced direct sales of energy. The opportunity comes as new markets emerge within liberalized electricity systems and new transactions must be handled.

Suppliers and aggregators alike should reap the benefit of increasing digitalization and improved data from smart meters.

Both may be threatened by the emergence of peer-to-peer trading platforms, however. For example, this allows residential householders with behind-the-meter solar PV and storage to trade energy between each other. The trading can be set up and facilitated by the provider of the solar PV and storage systems, with no involvement of an energy supplier or aggregator[31]. Peer-to-peer trading of ancillary services is harder to envisage; but for example, a platform could allow a TSO to buy frequency-response or demand-response services direct from residential customers.

As noted for other stakeholders, the emergence of a large EV charging load with potential for vehicle-to-grid discharging is very significant. It is relatively dependable once purchased, large relative to other consumer loads, and has in-built standardized interfaces, good communications, and local intelligence.

> "Suppliers and aggregators alike should reap the benefit of increasing digitalization and improved data from smart meters.

31 Though the electricity network owner will also need to be paid for use of the network between the parties: again, this can in principle be handled by the trading platform.

4.6 UTILITIES

'Utility' is commonly used in North America and elsewhere to describe private or publicly-owned entities, publicly-regulated, that own electricity transmission or distribution infrastructure and may also generate and supply energy. They may also provide other services such as irrigation. They cover some or all of the functions of a generator, TSO, DSO, supplier, or aggregator, which are discussed in other sections. Two issues specific to utilities are discussed below.

REDUCED RISK OF STRANDED ASSETS

If the owner of the infrastructure assets is also in control of most of the generation and the energy supply to consumers, then the complete system can be managed so that the whole-system costs of strategic decisions are considered. One example of such a decision would be the closure of a major generator. There is still no protection against decisions by consumers, however.

'SYSTEM ARCHITECT' ROLE

Utilities may have greater ability to implement major decarbonization initiatives. One example might be a programme to promote adoption of EVs by encouraging EV charging at locations and times that avoid the need for distribution and transmission reinforcement, and which optimize use of generation capacity.

4.7 GENERATORS

DECLINE OF FOSSIL GENERATION AND THE NEED FOR CAPACITY

Existing fossil generators face reducing demand, though the picture is very different across the 10 regions included in this report. The ETO model assumes that, once built, all plant operates to the end of its design life. In reality, closure decisions are based on many factors, including random failures, expectations of future carbon costs, and local political implications. As solar and wind reach subsidy-free cost parity with existing fossil plant, the ability of policymakers to control the rate of growth reduces greatly.

However, the model's results also show a continuing need for fossil plant to cope with the variability of solar and wind. This is particularly important for seasonal variability, for example in northern latitudes or in monsoon belts. There is a challenge for fossil generators, and of course for policy- makers and regulators, to find a way to finance existing or new generation in these different and uncertain conditions. Capacity markets have already emerged in countries with high penetration of renewables.

VARIABLE RENEWABLES AND GENERATION-WEIGHTED AVERAGE PRICES

Wind and solar generators that rely on wholesale electricity prices each face the problem of all such plants in a particular area generating the most power at the same times, thereby reducing the wholesale price. This effect is not yet great, but analysis by DNV GL indicates that it will become so in future with a very high share of renewables in the generation mix.

Most large-scale renewables projects are financed based on long asset lives coupled with known costs and income streams; uncertainty in future revenue creates a new risk for long-term investors.

SECTOR COUPLING

The variability of solar and wind, particularly on a seasonal basis, can be mitigated by coupling electricity systems with heat storage in district heating, or by generating low-carbon gas through power-to-gas.

The use of biomass for combined heat and power, or for district heating with dual electricity and biomass boilers, is part of the integration of thermal and electricity markets.

SOLAR AND STORAGE

For small electricity systems in locations with good solar conditions, it is already acknowledged that there are strong reasons for solar plants to include battery storage with several hours' capacity. Recent auctions in Hawaii have resulted in long-term power purchase agreements (PPAs) at low prices. This is likely to spread as solar PV and battery costs continue to reduce and investors and purchasers gain confidence. Closer integration of power-electronic inverters for solar PV panels and batteries is already happening. It is likely that in a few years, in good solar locations, the default position will be to include some level of battery storage.

The same drivers apply for wind plus storage, though less strongly.

4.8 ENERGY CONSUMERS

MAJOR PLAYERS

Energy consumers will be major drivers of the energy transition for several reasons:

- Their purchasing strength, individually or through aggregators
- Greater empowerment due to digitalization
- As providers of flexibility and demand response, through digitalization and new, enabling business models
- Their willingness and ability to procure their own behind-the-meter generation and storage
- Societal and governmental preferences for emissions reduction and improved air quality.

ELECTRIC VEHICLES

For residential consumers, the purchase of an EV is likely to come with greater opportunities to engage in demand response and provision of ancillary services. It is possible that most will choose to delegate this to aggregators.

RESIDENTIAL AND COMMERCIAL SPACE AND WATER HEATING

There are no painless routes to decarbonization of space and water heating in industrialized economies. In addition, consumers may be faced with unpalatable options that entail higher costs, disruption within buildings or in the street, and changes in habits.

MANUFACTURING

Business model changes may deliver significant shifts in demand for products as some sectors of the economy move from ownership to 'pay-as-you-use' service models.

Major industries using high-temperature heat in processes may face difficulties in decarbonizing their heat demand. This will likely become a high priority for policymakers.

> "Business model changes may deliver significant shifts in demand for products as some sectors of the economy move from ownership to 'pay-as-you-use' service models.

4.9 INVESTORS

ELECTRICITY MARKET ISSUES

New stakeholders for the energy sector have emerged in the finance community. Investment and pension funds are new incumbents attracted by stable revenues and the stability that the portfolio effect provides to global investments. New products are coming into the market for financing projects, particularly renewables. Green bonds have proved to be a very profitable source of financing for several players.

As described in detail in Section 3, the growth of the variable renewables, principally solar and wind, creates problems for the financing of electricity generating capacity. The two principal issues are how to finance variable renewables and conventional generation.

Wind and solar cost reductions and the maturing technologies and supply chains have encouraged governments and regulators to move from providing financial support via subsidies, to premium prices and feed-in tariffs, and then to auction systems. Electricity market reform and policy development in the European Union has driven this move. Positive results in the form of low auction prices have encouraged other countries to do the same. This trend is likely to spread further. As solar and wind prices drop, the trend will in turn be replaced by direct participation in electricity wholesale markets ('merchant' projects) and direct sales to large electricity consumers through corporate PPAs.

This means that solar and wind are exposed to wholesale market prices: either in the short-term, for merchant projects, or in the long-term pricing structure defined in a PPA. Current experience and expectations for further cost reductions indicate that, in many countries, solar and wind will be able to compete satisfactorily under current wholesale prices. However, the strong correlation in solar or wind production over geographical areas that are the size of electricity systems and markets means that periods of high production from a solar or wind project will correlate with low, very low, or even negative wholesale prices. This is occasionally described as the 'price cannibalization' effect for renewables.

As investigated in the DNV GL work described in Section 3, this effect and accompanying uncertainties can have strongly negative impacts, and investors in renewables projects will need to understand and forecast the effects. Possible mitigating factors will also need to be considered; principally, the flexibility options allowing time-shifting of energy, such as demand response and storage.

Financing of conventional generation assets faces a different problem. Although production can be scheduled to meet electricity demand including during high-price periods, and this can be forecasted accurately for 24 or 48 hours ahead, the production and income in any year becomes much more variable. This uncertainty will lead to high financing costs.

Regulators and governments recognize this problem and are moving to include capacity markets, i.e. to provide income to firm generators for the capacity they provide, not just the energy. Experience so far is that capacity market auctions produce quite volatile results: they are difficult to forecast well, and hard to design to achieve the desired effects. Capacity markets are also subject to political risk. Investors in conventional thermal plants will need to understand these new risks.

INTERCONNECTORS

Interconnectors between electricity systems are one of the flexibility options discussed earlier. Under some regulatory frameworks, these could be treated as regulated investments by TSOs. Under others, they are treated as 'merchant' projects, not subject to regulation. These face the same 'stranded assets' risks as network reinforcements by TSOs and DSOs, but without the benefits of spreading risk across all a network operator's assets. Investors in interconnectors therefore need to understand the risks inherent in their projections of future use and income. These risks will be strongly influenced by assumptions about growth of variable renewables and other factors, at both ends of the interconnector.

As merchant interconnector projects are effectively 'infrastructure' investments with long lifetimes, and with security benefits for both the connected electricity systems, there is an argument for socializing some of the most extreme risks[32] to increase the pool of potential investors and reduce the cost of finance.

32 For example, regulators may transfer some of the risk to electricity consumers through a 'cap and floor' agreement to recompense a merchant interconnector project should its revenues fall below a (very low) floor value. If, on the other hand, circumstances prove to be substantially better than forecast and revenues rise above a 'cap' level, the interconnector project returns some income to electricity consumers.

CHAPTER 5

KEY ISSUES TO MONITOR

5 KEY ISSUES TO MONITOR

The ETO model makes forecasts based on long-term trends. This section identifies issues which are nevertheless important to monitor in the near term, particularly to identify trends which confirm or refute assumptions made in the model.

Many assumptions in the model would, if changed, result in significant variations to the conclusions presented in this report. That said, a few issues stand out as being of prime importance based on probability, some sensitivity studies, and likely impacts.

ELECTRIC VEHICLES

The predictions for uptake of electric vehicles (EVs) are based on early experiences in only a few countries, and also depend on assumptions about cost reductions, development of charging points, public acceptance, safety, and ownership models. For example, very rapid growth of autonomous vehicles could change the assumed adoption rates significantly.

Either different adoption rates or usage patterns would affect the forecasts for electricity demand growth, thus impacting on the estimated requirements for new renewable generation. In addition, availability of EV batteries appears to be a significant tool for dealing with short-term variability of renewables. Consequently, varying our assumptions for the rate and extent of EV uptake would affect our assessments of the costs of integrating renewables.

The willingness of owners to allow their EVs to be used to provide grid services is also important, and this may well be a function of the business models which emerge.

The EV industry is driving technology development and cost reductions for batteries; so, it also influences the costs and performance of grid-connected storage batteries from utility-scale to residential.

RURAL ELECTRIFICATION

The ETO model results predict massive electrification of demand, requiring huge expansion of distribution networks, mainly outside the OECD countries. Much of this increase in demand will be in cities, but much will also occur in rural areas and is likely to coincide with the expansion there of solar PV in particular. The next five years should see this trend become well-established, resulting in very significant social and economic benefits for some of the world's poorest people. Where it does not happen, it will be important to understand why: for example, uncertainty over the timing of network expansion; or business models which are vulnerable to high levels of defaults on payments.

There should also be evidence to show whether, in areas with very weak or non-existent electricity networks, microgrids win out over traditional distribution expansion on cost, reliability, and speed.

HEAT DEMAND, HYDROGEN, AND POWER-TO-GAS

Electrification of demand is a major element of the ETO model's results. Along with electrification of transport demand, decarbonization of heat demand is 'the next big challenge' for policymakers to resolve. There are several credible options for residential, commercial, and industrial heat demand, though the optimum choice in any country is yet unclear. Because most of these options have major infrastructure requirements, policymakers may well have to make choices before the main unknowns are resolved.

The heat question could lead to the development of substantial hydrogen (H_2) infrastructure for both residential and industrial demand. This could affect national decisions about decarbonizing heavy road vehicles, ships, and trains. Further, the ability to store large amounts of energy as H_2 could ease the problem of seasonal variability of wind and solar.

Alternatively, the difficulties of decarbonizing residential and commercial heat demand may drive governments to large-scale insulation programmes and drastic tightening of construction standards.

The next five years will not bring large-scale implementation of either heat or H_2 networks, but they should provide good evidence on the likely costs and non-financial factors that will be critical in making these big infrastructure decisions.

SOLAR WITH STORAGE

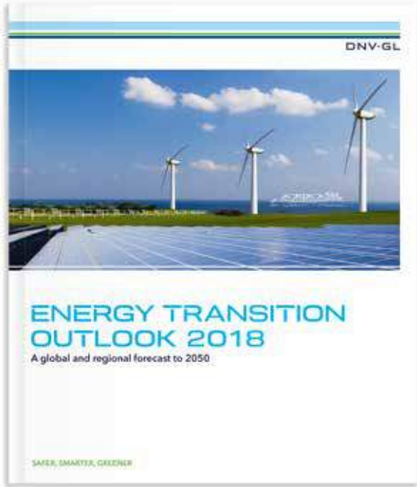
The ETO model predicts very large growth in solar PV, driven largely by economics. Even when we include some cost penalties to cope with variability, solar PV is seen to be the cheapest option for electricity in large parts of the globe well before 2050.

Part of this issue is battery storage, which from evidence of current auctions appears to be an economic way of dealing with daily variability. The model assumes that both solar PV and battery costs will follow historic learning rates[33], resulting in major cost reductions. Learning rates for technologies can appear inevitable in hindsight, particularly when plotted on logarithmic axes, but in forecasting they have the disadvantage of inherent positive feedback: an optimistic forecast for price reduction will result in an optimistic forecast for volumes installed, which will in turn increase the expectations for price reductions.

There are technical and cost advantages to battery storage co-located and closely integrated with solar PV. It is possible that within five years we will see that 'solar plus storage' becomes the default option in many parts of the globe. If this does not happen, it will be important to understand why. Would it be due to fundamental costs, or to regulatory barriers which prevent the true network costs of distributed solar PV being reflected in consumers' energy bills, or perhaps massive demand for EVs keeping battery prices high in the short term? We will be monitoring the situation closely and feeding back any appropriate data and new insights into our model.

33 Typically, percentage price reduction per doubling of installed capacity.

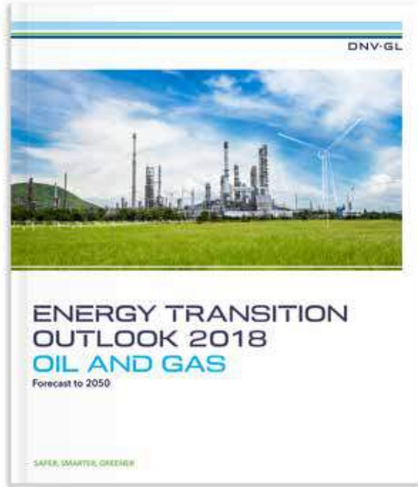
ENERGY TRANSITION OUTLOOK 2018 REPORTS OVERVIEW



ENERGY TRANSITION OUTLOOK

Our main publication deals with our model-based forecast of the world's energy system through to 2050. It gives our independent view of what we consider 'our best estimate' for the coming energy transition. The report covers:

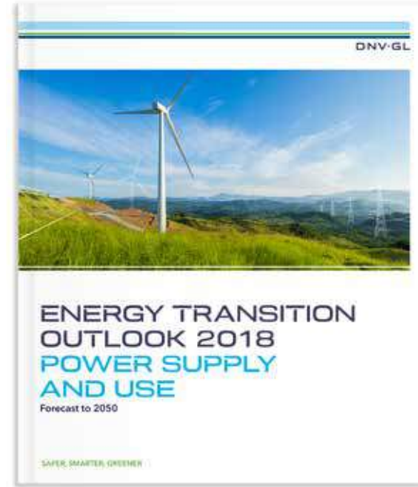
- The DNV GL Model and our main assumptions on population, productivity, technology, costs and the role of policy and governments
- Our outlook for global energy demand for transport, buildings and manufacturing, energy supply for each energy carrier, energy efficiency and expenditures
- Regional energy outlooks for each of our 10 regions
- The climate implications of our outlook and an assessment of how to close the gap to 2°C.



OIL AND GAS

Our oil and gas report underlines the continued importance of these hydrocarbons for the world's energy future. It forecasts several trends:

- Gas will overtake oil to become the largest energy source in 2026, and industry efforts will be directed accordingly
- Production is likely to come from a greater number of smaller, more technically-challenging reservoirs, with shorter lifespans
- Investment in pipeline and LNG infrastructure will increase to connect new sources of supply with changing demand centres
- New gases will enter distribution networks, and lifecycle performance will come under increasing focus for the refining and petrochemical industries.



POWER SUPPLY AND USE

This report presents implications of our energy forecast for key stakeholders in the power industry, including electricity generation, which includes renewables; electricity transmission and distribution; and energy use. Amidst electricity consumption increasing rapidly and production becoming dominated by renewables, the report details important industry implications.
These include:

- Deep and widespread change involving established energy industry players
- The need for increased use of market mechanisms and changes to the electricity markets and regulation
- Massive expansion and automation of transmission and distribution network
- Rapid expansion of electric vehicles.

MARITIME

In our Maritime Forecast to 2050, we present our wider outlook for the maritime industry.
The report details:

- Outlooks for seaborne trade; for regulatory development; as well as fuels and technology
- Implications for the world fleet, including future energy mix and greenhouse gas emissions.

The report ends by presenting a significant development of the 'carbon robust ship concept'; a structured, knowledge-based approach to handling uncertainty – supported by modelling tools – which allows stakeholders to stay ahead of industry developments and remain competitive moving forward.

PROJECT TEAM: POWER SUPPLY AND USE

This report has been prepared by DNV GL as a cross-disciplinary exercise between the DNV GL Group and our Energy business area.

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HISTORICAL DATA

This work is partially based on the World Energy Balances database developed by the International Energy Agency, © OECD/IEA 2016, 2017, 2018 but the resulting work has been prepared by DNV GL and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2016) numerical data is mainly based on IEA data from World Energy Balances © OECD/IEA 2016, www.iea.org/statistics, License: www.iea.org/t&c, as modified by DNV GL.

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DNV GL delivers world-renowned testing and advisory services to the energy value chain including renewables and energy management. Our expertise spans onshore and offshore wind power, solar, conventional generation, transmission and distribution, smart grids, and sustainable energy use, as well as energy markets and regulations. Our experts support customers around the globe in delivering a safe, reliable, efficient, and sustainable energy supply.

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