The world’s energy system is changing profoundly, bringing opportunities and risks. The transition from fossil-based to zero-carbon is happening fast but not quickly enough to meet the Paris Agreement’s objectives to limit global warming to ‘well below 2°C’, let alone 1.5°C.

The third edition of our Energy Transition Outlook (ETO) confirms that available technologies and systems have the potential to close the ‘emissions gap’, the difference between the current rate of decarbonizing energy and the pace needed for global warming of 1.5°C. We believe that a combination of measures can get us there. Our checklist for the next decade includes growth of 1000% in solar power to 5 terawatts (TW), and 500% in wind power to 3 TW. Fifty million electrical vehicles (EVs) per year will be needed by 2030, requiring a 50-fold increase in batteries, and large-scale charging infrastructure. Other items on the list include more ultra-high voltage transmission networks; annual improvements in global energy intensity (the energy use per unit of output) by 3.5%; and low- and zero-carbon hydrogen to heat buildings and industry, fuel transport and capture value from surplus renewables.

However, time is against us and we are moving in the wrong direction. Higher energy demand in 2018 drove a 1.7% rise in global energy-related carbon dioxide (CO₂) to a record 33.1 gigatonnes (Gt), according to the International Energy Agency. This was the fastest growth since 2013. Emissions from all fossil fuels increased, with the power sector accounting for nearly two thirds of this growth.

We forecast that CO₂ emissions will not fall sufficiently by mid-century: the 2°C carbon budget will be exhausted in 2049, and energy-related emissions in 2050 are still 19 Gt CO₂/year. Alarmingly, for a 1.5°C warming limit, the remaining carbon budget will be exhausted as early as 2028, with an overshoot of 770 Gt CO₂ in 2050.

Our modelling is based on the lowest cost of the technologies and systems that we cover. Despite this, our forecast indicates a world that will be 2.4°C warmer at the end of this century than in the immediate pre-industrial period. We must act now to prevent climate change bringing even stronger storms; more frequent floods and droughts; ever-higher sea levels; and disruption to food supply.

We need extraordinary policy action: policies that advance renewables, new decarbonization technologies and systems, EVs and energy efficiency. Beyond this, we need to change the prevailing mindset from ‘business-as-usual’ to ‘business-as-unusual’. Only by challenging how businesses and societies operate and behave can...
we start to close the emissions gap between where we are headed on global warming and where humanity has agreed through the Paris Agreement and the Sustainable Development Goals.

All parties to the Paris Agreement must raise and realize increased ambitions for their updated Nationally Determined Contributions (NDCs) and move to faster implementation of these. In a snapshot of the first NDCs submitted to the United Nations Framework Convention on Climate Change secretariat, 75% currently refer to renewable energy, and 58% to energy efficiency. Our view is that both these percentages need to be 100% in the second NDCs.

Government and business leaders need to make immediate and concerted efforts to accelerate action. They must determine which energy sources need to be scaled up and down, and how fast. IEA et al. (2019) estimate that an annual average investment of about USD 1.4 trillion is required between 2018 and 2030 to achieve all related UN Sustainable Development Goal 7 targets: i.e. ensuring access to affordable, reliable, sustainable and modern energy for all.1 Yet this is nothing compared with the expected price of dealing with the impacts of climate change: the cost of doing nothing. Private sector capital is central to meeting this investment challenge.

Our ETO, based on DNV GL’s independent model of the world energy system, can help nations create and implement their NDC plans. It also aids energy-sector analysts and decision makers to develop strategic options to speed up the transition.

This year’s edition of the ETO again confirms that the transition is affordable. The world will spend an ever-smaller share of GDP on energy, allowing for greater investment to accelerate the transition. This is critical for mitigating climate change, and makes economic sense for all of us, even though it will change and challenge the dynamics of the current business environment.

We need extraordinary policy action: policies that advance renewables, new decarbonization technologies and systems, EVs and energy efficiency.

At DNV GL, with our 12,000 independent experts, we are optimistic about the role technologies and systems can play for a sustainable future, and about their future expected cost. We are, however, concerned about the speed of implementation of these technologies and systems. We hope that the ETO can help to steer the conversations, decisions and investment needed to ensure a transition that will meet the goals of the Paris Agreement.

Engagement and cooperation between governments, businesses and citizens is vital for fast-tracking the energy transition. DNV GL stands ready to support the power and renewables industries and other sectors.

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The energy transition is picking up pace. The world is starting to wean itself off fossil fuels and move towards a net-zero carbon future. There will be a profound shift towards electrification and to generating that electricity from renewable sources, with significant implications for power supply and use. DNV GL’s main Energy Transition Outlook (ETO) covers all aspects of this extensive and rapid change. In this companion report to the main ETO, we provide more detailed analysis and insight on the implications for power generation, transmission and distribution, and electricity use.

Our ETO is based on our own independent energy model, which tracks and forecasts regional energy demand and supply, as well as energy transport between regions. The model divides the world into 10 geographical regions with the inputs and results being the weighted average of the countries within them. The model is enhanced by our own experts to provide our ‘best estimate’ of energy systems out to 2050.

**MAIN OUTCOMES**

Three main outcomes stand out from our projection of the future.

1. **PRIMARY ENERGY SUPPLY PEAKS**
   Applying more efficient technologies for energy use – such as substantial electrification in buildings, manufacturing and, significantly, road transport – sees final energy demand level off in the 2030s at some 460 exajoules per year (EJ/yr). It then slowly declines to 446 EJ/yr in 2050 (down 3% from peak). Combined with more efficient electrical generation from renewables, this leads to primary energy supply peaking in 2030 at around 640 EJ, followed by a more pronounced decline than demand to reach 577 EJ in 2050 (down 10% from peak).

The transition to declining energy supply is achieved despite continued population and GDP growth. This shows that applying advances in technology is essential to help the world’s population to prosper while reducing energy supply and, importantly, reducing emissions.

2. **SOLAR AND WIND WILL DOMINATE ELECTRICAL GENERATION**
   By 2050, generation from solar photovoltaic (PV) and wind will be 36,000 terawatt hours per year, more than 20 times today’s output. Together with hydropower, and a smaller contribution from biomass generation, renewables will provide almost 80% of the electricity mix. This generation will be much more geographically dispersed than today’s largely centralized power plants.

The significant growth in generation from renewables will require more production facilities, new power plant locations, and significant investment in grid infrastructure. It will also need the application of storage and other ‘flexibility’ options. Energy users will have increasing opportunities to create additional value through services to the grid, such as demand-side response (DSR) and vehicle-to-grid (V2G), much of it enabled by connected digital solutions, and close to real-time more flexible markets.
3. THE TRANSITION IS FAST; BUT NOT FAST ENOUGH

Despite primary energy supply peaking alongside massive growth in power from renewables, we estimate a rise in average global temperatures of 2.4°C above pre-industrial levels by the end of the century; well short of the 2°C Paris Agreement goal. The additional effort to achieve the 2-degree future, or stretch target of 1.5°C, may appear trivial, however as last year's Intergovernmental Panel on Climate Change (IPCC) report highlighted, every tenth of a degree matters in avoiding dramatic and consequential impacts such as severe environmental degradation and massive movements of populations.

The rates of technology development and cost reduction suggest it is still possible to achieve the 1.5°C target; but advancing and deploying them swiftly enough is a tremendous challenge. Only extraordinary steps combining the efforts of governments, the private sector and broader society will get us there if we take action now.

KEY TAKEAWAYS

Key takeaways for our sector relate to generation, the grid, and use of power.

GENERATION

There will be substantial opportunities for those parties involved in solar PV and wind generation. Renewables manufacturers will continue to invest in manufacturing facilities, and in research and development, as well as giving greater consideration to longer-life assets and products, and recycling. As renewables transitions to a subsidy-free phase, developers will need greater understanding of electricity market opportunities and risks. They will also need to assess alternative approaches to maximize the value of their developments – such as incorporating storage into projects - and, to have greater awareness of potential ‘price cannibalization’ and mitigating actions.

The investment community must capitalize on significant opportunities to continue supporting the growth of renewables. The number of projects that will be installed, and their diverse locations, will require ever-more efficient transaction processes. Power producers will have growing and changing portfolios of assets that will need to operate with increasing volumes of variable generation. This will raise the risk of coal assets potentially being stranded, and will result in increasing use of innovative and smart operations such as virtual power plants. Nevertheless, sufficient frequency containment reserves, frequency restoration and replacement reserves, currently provided by conventional generation, are important for a successful transition.

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2 A virtual power plant (VPP) is a network of decentralized, often medium-scale power generating units such as wind farms, solar parks, and combined heat and power (CHP) units, as well as flexible power consumers and storage systems. The interconnected units are dispatched through the central control room of the VPP but nonetheless remain independent in their operation and ownership.
THE GRID
Enormous renewable generation capacity and electricity’s increasing share in energy use – from 19% now to 40% in 2050 – will have significant implications for transmission and distribution systems. Challenges will include expanding, reinforcing and upgrading the grid to maintain high reliability, and swiftly determining where reinforcement is most needed to keep up with the rapid deployment of distributed generation.

To cope efficiently with much greater variations in power flows, including periods of reverse flow in distribution systems, electricity system operators will need to both upgrade the network and deploy non-wire alternatives. Using storage to handle peak power usage may delay or avoid an upgrade, for example.

Transmission system operators with high amounts of variable renewable generation will have some of the highest capex investment programmes to date. New grid structures with higher degrees of interconnection to other network control areas will be established, leading to so called overlay grids.

Digitalization will have a significant impact on power grids, from smart metering and associated technologies to the observability and controllability of lower-voltage grid levels and intelligent (digital) substations. There will be a heightened need for new security functions to manage distribution-connected generation, storage and DSR.

USE OF POWER
Our ETO highlights the continued need for energy users to strive for more energy efficient and low-carbon options. Energy efficiency is a low-cost, readily available way to cut carbon emissions, but is implemented far less than available financial returns merit.

Greater electrification will be one solution to achieving net-zero carbon targets for buildings and manufacturing. An increasing number of technical solutions are becoming available, such as heat pumps for low temperature heating and electric arc furnaces for manufacturing. Greater electrical demand from energy users, combined with growing variable generation from renewables, creates opportunities to provide greater value to power markets through DSR, local generation and storage.

In the next five years, the electric vehicle (EV) revolution will see its fastest rate of change, particularly for light vehicles and city buses. This will have a significant impact on the broader energy transition as society moves away from reliance on fossil fuels to a cleaner, sustainable energy system. Importantly for the power sector, it will be one of the main drivers behind increased demand for electricity. In our ETO Model, the EV sector also plays an important role in the integration of variable renewable generation due to the flexibility that will be available from smart charging and V2G services.
Solar plants, such as this one in Altai Republic in Southern Siberia, will benefit from artificial intelligence including drones for remote inspection.
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 2019 ETO, which also considers the implications for industries involved in electricity generation, transmission and distribution.

Alongside the company’s main Outlook report3, the suite includes three others discussing implications for separate industries: oil and gas4; power supply and use (this report)5; and maritime6.

Our core ETO Model (Figure 1.1) 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-end use treatment of the entire energy system
- focus on technology trends and needs for the future
- focus on the ongoing transition rather than on the status quo of the energy system.

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3 ‘Energy Transition Outlook 2019: A global and regional forecast to 2050’, DNV GL, September 2019
4 ‘Energy Transition Outlook 2019: Oil and gas, Forecast to 2050’, DNV GL, September 2019
5 ‘Energy Transition Outlook 2019: Power supply and use, Forecast to 2050’, DNV GL, September 2019
6 ‘Energy Transition Outlook 2019: Maritime, Forecast to 2050’, DNV GL, September 2019
Figure 1.1 above presents the framework of our model. The arrows in the diagram show information flows, starting with population and GDP per person, while physical flows are in the opposite direction. Policy owing influences all aspects of the energy system. Energy efficiency improvements in extraction, conversion and end-use are a cornerstone of the transition.
In this report for the power and renewables industries, we review the implications of our ETO forecasts for key stakeholders in several industries that DNV GL advises and assists: electricity generation, including renewables; electricity transmission and distribution; and energy use.\(^7\)

Among other changes from the 2018 approach, we have conducted the power system modelling with greater granularity. Rather than modelling annual averages, the model has been extensively improved to capture hourly variations in demand and generation, better reflecting the behaviour of the power systems with increasing levels of solar PV and wind generation.

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

This Outlook divides the world into 10 geographical regions as shown in the map below (Figure 1.2). 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 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. The data behind each chart is available for download on our open industry platform, Veracity.\(^8\)

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; 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.

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\(^7\) 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.

\(^8\) www.veracity.com
Rising population and standards of living drive up building sector energy consumption and associated emissions in the Indian Subcontinent.
CHAPTER 2

KEY CONCLUSIONS FROM OUR 2019 MODEL
2 KEY CONCLUSIONS FROM OUR 2019 MODEL

This chapter describes the principles on which our modelling is based, then summarizes the main results of relevance to 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. For example, our modelling of final energy demand accounts for how much fuel is used by vehicles but does not calculate the ‘mechanical work’ (the energy provided by the engine to the wheels) that they do. Population and economic growth are the two main drivers of the energy system’s demand side in the model.

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 we consider learning-curve effects.

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, we treat demand categories critical to the energy transition, such as road transport, more thoroughly than more marginal ones.

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

The ETO Model makes economic decisions to build new assets such as electricity generating plants and gas import plants. It normally ‘retires’ assets at the end of their technical lifetimes, but high operating costs and lower utilization lead to early retirements.

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 currently very low levels of such flows, though this may change in future. For instance, projects such as the Northeast Asian supergrid will form intercontinental ultra-high-voltage direct-current (UHVDC) transmission systems.

We do not incorporate political instability or disruptive actions that may revolutionize energy demand or supply, accepting that what constitutes ‘disruption’ is subjective.

The main report also contains analyses of uncertainties, i.e. the effects on the results of changing the most important or most uncertain assumptions; but this companion report does not include sensitivity analysis.
WHAT IS NOT COVERED BY THE DNV GL OUTLOOK?

- This Outlook’s focus on long-term transition means short-term changes receive less attention, and it generally does not cover them. They include both cyclical and one-off impacts; for example, from policies, conflicts, and strategic moves by industry players.

- We build up this Outlook by considering energy demand and supply, focusing on yearly averages. The exception is our modelling of the electricity grid, which is at hourly granularity.

- We typically do not include technologies that we view as marginal, but do include new technologies which we expect to scale. We discuss breakthrough emerging technologies, but do not include them in the model forecast. The exception is hydrogen, which we model and discuss.

- We discuss changes in consumer behaviour, evolving travel and work patterns, social media and other sociological trends; but we include and quantify them in only a few areas in our forecast.

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:

- $1 \text{ EJ} = 23.88 \text{ Mtoe}$
- $1 \text{ EJ} = 277.8 \text{ TWh}$
2.2 ENERGY DEMAND

In our 2019 forecast, we see a world where energy demand will peak in 2033, slightly earlier than our 2018 forecast. This reaffirms a conclusion from last year’s report that we are approaching a period where technology and energy efficiency will be advancing faster than the global population and economy are growing. We forecast that final energy demand of 420 exajoules per year (EJ/yr) in 2018 will grow at a fairly consistent rate until the mid-2020s, at which point growth slows to a peak of 462 EJ/yr in 2033, then declines to 446 EJ/yr by 2050 (Figure 2.1). By mid-century, global GDP will have grown by 120% from today’s levels, but energy demand will have risen by only 6% and, importantly, will be on a declining path.

The accelerated decline in energy intensity\(^9\) is in part due to increasing electrification of energy use. Despite declining total energy demand in the 2030s and 2040s, there is a very significant increase in the use of electricity as an energy carrier (Figure 2.2). In 2018, electricity demand of 79 EJ/yr represented 19% of world final energy demand; by 2050, its share will be 40% at more than 177 EJ/yr. Electricity displaces both coal and oil in the final energy demand mix.

\(^9\) Energy intensity: the energy use per unit of output.

FIGURE 2.1

World final energy demand by sector

Units: EJ/yr

Historical data source: IEA WEB (2018)
In 2018, electricity demand of 79 EJ/yr represented 19% of world final energy demand; by 2050, its share will be 40% at more than 177 EJ/yr.
2.2.1 TRANSPORT
In 2018, transport energy demand of 119 EJ/yr accounts for 28% of world total energy demand. We see some growth in the sector’s energy demand up to 2026. It then declines to 112 EJ/yr in 2050, when its share in the world total is approximately 25%. Electrification of road transport, most significantly from the mid-2020s when electric vehicles (EVs) achieve cost parity with internal combustion engine vehicles, is the major reason for this reduction in energy demand.

The electrification of road transport has a significant impact on the broader energy transition, contributing to greater electrical demand, oil’s decline, and enabling integration of variable renewables. All of this significantly lowers carbon emissions and helps to combat climate change. The results of the ETO Model in Figure 2.3 show that two- and three-wheeler vehicles will transition first (dominated by the Indian Subcontinent, Greater China and South East Asia), followed by passenger and then commercial vehicles. The figures for non-combustion alternatives include battery-electric and hydrogen fuel-cell vehicles; however, we predict that non-combustion light vehicles will be almost entirely battery-electric.

The EV revolution is predicted to occur most rapidly in Greater China, followed by Europe, then North America and OECD Pacific, with other regions following five to 10 years after Greater China. The trend for commercial vehicles will be led by city buses and municipal fleets, where already there are more than four hundred thousand electric buses operating in Greater China.

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 our maritime companion report.10 Where rail can be electrified, it will be by 2050. We expect electrification of air travel to still be in its infancy by 2050.11

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10 ‘Energy Transition Outlook 2019: Maritime, Forecast to 2050’, DNV GL, September 2019

11 ‘Energy Transition Outlook 2019: Forecast to 2050’, DNV GL, September 2019

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**FIGURE 2.3**

**World number of road vehicles by type and drivetrain**

Units: Billion vehicles

Combustion vehicles include ICEVs and PHEVs. Electric vehicles include BEVs and FCEVs. Historical data source: OICA (2016), IEA GEVO (2018)
In China, growth in the market for combustion engine cars has already stalled, while demand for electric cars is accelerating. In the first 10 months of this year, petrol car sales in China fell to less than 18m from 18.7m in the same period a year ago, according to Jato, global supplier of automotive business intelligence.
2.2.2 BUILDINGS
Global energy demand for buildings will grow by around 0.9% annually to 2030. It will then slow to 0.4%, reaching 145 EJ/yr by 2050, when it will be almost a third of total demand compared with 29% today. This growth is driven by rising population and standard of living, particularly in countries such as Greater China, India and Mexico, whose economies are growing rapidly. The resulting rise in energy consumption is mitigated somewhat by:

- Government regulation and incentives driving increases in energy efficiency
- Increased efficiency of energy-using equipment and systems
- Increased control over energy-using equipment and systems
- Electrification of end uses, such as space and water heating.

2.2.3 MANUFACTURING
Manufacturing is one of the three largest users of energy. It consumed some 127 EJ of final energy in 2018, nearly a third (30%) of global final energy demand. We forecast that its share of total energy demand will remain relatively constant. Its growth in line with population and GDP growth will be restrained by improved efficiency, circular economy trends, and by electricity displacing coal and gas as energy carriers. Electricity’s 25% share of manufacturing energy demand in 2018 is set to grow to 45% in 2050. Electrification of heat in manufacturing will involve heat pumps and direct electrical heating.

Outside the three big sectors of buildings, manufacturing and transport, the remaining 12% of energy demand is split between agriculture, forestry and other smaller categories, and by non-energy uses of fossil fuel; for example, as feedstock for asphalt, lubricants and petrochemicals.

2.3 ELECTRICITY DEMAND
We forecast that world electricity demand (excluding the energy industry’s own use) will more than double (+125%) from 22 petawatt hours per year (PWh/yr) in 2018 to 49 PWh/yr in 2050. This is due to greater standards of living for much of the world’s population, combined with electrification of energy use. Taking into account self-consumption by generators and storage, and power to hydrogen, global electricity demand is expected to increase from 24 PWh/yr to 53 PWh/yr over that period (Figure 2.4).

Transport sector demand for electricity is negligible today and still does not match that of either buildings or manufacturing in 2050. However, it will have an 18% share in global demand for electricity by then, growth that will be a significant driver of the broader trend towards increasing electrical demand.

2.4 ENERGY SUPPLY
The peak in primary energy supply is more marked than that of final energy demand. This is because of increasingly efficient methods of meeting society’s energy needs (Figure 2.5).

GLOBAL PRIMARY ENERGY SUPPLY TO PEAK
Global primary energy supply peaks in 2030, three years earlier than energy demand. It then drops more steeply than demand, decreasing by 61 EJ/yr (10%) from between its peak and 2050 compared with a drop from its peak of only 16 EJ/yr (4%) in energy demand. The major contributor to this effect is 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.
**FIGURE 2.4**

World electricity demand by sector

Units: PWh/yr

**FIGURE 2.5**

World primary energy supply by source

Units: EJ/yr
HYDROCARBONS TO PEAK
We foresee large shifts in the supply of primary energy. Oil and coal currently account for 27% and 29% respectively of global energy supply. By 2021, gas will overtake coal and will then surpass oil in 2026 to become the largest energy source. This is two years earlier than predicted in our 2018 ETO, highlighting our finding that the energy transition is progressing faster than we previously anticipated.

We predict peak oil in 2022, with gas to follow in 2033. Coal has already peaked. From 2033 gas supply remains virtually constant out to 2050. Fossil fuels’ share of the primary energy mix will significantly decline from more than 80% now, but will still be more than half (56%) at mid-century.

ELECTRICITY
Figure 2.6 shows solar PV and wind growing rapidly, dominating the electricity mix by 2050, when they have a 33% and 30% share respectively.

Wind generation is largely onshore, but offshore wind’s contribution will grow more appreciably closer to mid-century, reaching about 40% of total wind production.

The ramping up of renewables displaces coal, most notably from 2030, with other sectors remaining relatively constant. As total electricity generation rises significantly, and coal declines, the contribution from fossil fuels to the electricity mix drops to 18% by 2050.

The combination of rising total electricity generation and the high penetration of variable renewables will require investment, development and deployment of grid infrastructure and flexibility options to efficiently deliver the robust power systems of the future.
2.5 ADDITIONAL INFRASTRUCTURE REQUIREMENTS

To recap on what our ETO is forecasting: electricity will meet an increasingly large share of final demand for energy, and will become the dominant energy carrier in 2036, with gas in second place.

Consequently, the main ETO report attempts to understand the infrastructure required to connect supply and demand for electricity and gas as the energy landscape is transformed in the transition.

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, there will also be an expanding liquefied natural gas (LNG) trade, leading global liquefaction capacity to more than triple to 2050 to enable shipments.

Our forecast for growth in electricity demand and the massive expansion in renewable generation signals the need for a huge increase in the capacity of electricity grids. System operation will become more complex with new technologies including HVDC and hybrid (AC and DC) grids. It will also face having to operate the network closer to its thermal limits. In Greater China, the India Subcontinent and Europe, expansion of grids to cover larger market areas will move from interconnection to supergrids, extreme and ultra-high-voltage systems for long distance transmission. Section 3.3 considers this in detail.

There will be increased variability in generation profiles from increasing proportions of wind and solar PV, resulting in tough challenges to ensure that the grid is operated reliably and efficiently. As discussed in Section 3.2, storage and other flexibility options will play a key role in meeting this challenge.

2.6 COMPARISON WITH ETO 2018 RESULTS

The ETO Model has been refined for 2019, with more detail as well as updated input data and assumptions. The main conclusions from 2018 are unchanged, however. The world will undoubtedly experience a rapid energy transition, with this year’s results indicating that its pace will likely be slightly faster than previously anticipated.

— In this report, total energy demand in 2050 is a little lower than in our 2018 report.
— The peaks for both final energy demand and primary energy supply are forecast to be two years earlier than we predicted in 2018.
— Gas will overtake coal, and then oil, a little sooner than previously predicted to become the largest energy source.

Modelling of the power system has been conducted at hourly granularity this year compared with the previous modelling of annual averages. This has led to more accurate capture of the interactions between variable renewable generation, power price, and flexibility options. The results show ‘price cannibalization’ (defined on page 34) for renewable generation when penetration levels are high. Consequently, there is slightly less electrical generation from solar PV than predicted in 2018. The enhanced modelling also highlights the benefit of storage, demand-side response and more flexible markets to mitigate the impacts of ‘price cannibalization; Section 3.1.1 has further details.

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 Paris Agreement targets for mitigating global climate change.
CHAPTER 3

TECHNOLOGIES AND SYSTEMS
3 TECHNOLOGIES AND SYSTEMS

This chapter focuses on the key technologies and systems of power generation, transmission and distribution and use. We discuss the results from the ETO Model, as well as the expected key developments which may follow.

3.1 ELECTRICITY GENERATION TECHNOLOGIES

Sections 2.3 and 2.4 discussed the ETO Model’s forecasts for electricity demand, production and generation capacity. We forecast that annual global electricity generation will more than double from almost 26 PWh in 2018 to more than 58 PWh in 2050, a rise of approximately 125%. The vast majority of this growth stems from increased solar PV and wind generation, with ‘conventional’ thermal generation declining (Figure 2.6).

3.1.1 VARIABLE RENEWABLES

Production and capacity

Our model forecasts global annual solar PV generation will be 36 times current levels by 2050, increasing from 0.5 PWh in 2018 to 19 PWh at mid-century. We see over a 15-fold escalation in wind-powered generation from 1.1 PWh in 2018 to 17 PWh in 2050. Together, solar PV and wind, cover nearly two thirds of all electricity generation at mid-century. In terms of installed capacity, the share of solar PV and wind is even more dramatic at nearly three quarters by 2050 (Figure 3.1).

FIGURE 3.1

World installed electricity generation capacity by power station type

Units: TW

In North America and Europe, growth of solar PV and wind generation is most marked in the period 2020–2040, after which growth slows. This slowing reflects the model’s results being impacted by the anticipated reduction in ‘capture price’ on power markets as penetration of renewables increases. Further information on this is provided on page 34 in our commentary on wholesale power price cannibalization. The growth of solar PV and wind in Greater China and the Indian Subcontinent continues strongly throughout the ETO forecasting period as demand for electricity continues to grow. The massive growth in generation from solar PV in our model is driven by these technologies being the most attractive economic choices. This judgment takes into account current government policies and support mechanisms (including phasing out of subsidies); continued reduction in project costs as production levels increase; and, technological advances. Many countries have reduced or removed renewables subsidies, and subsidy-free solar PV and wind projects are starting to become the most attractive economic option for new electricity generation. This tends to be in places where renewable resources are sufficient, wholesale power market prices are attractive enough, and project costs are low enough. Over the coming years, these criteria will be met in an increasing number of markets. It will accelerate development of renewable energy, lower carbon emissions, and provide access to clean energy for more of the world’s population.

As well as the anticipated huge growth in capacity and generation being driven by the sheer volume of solar PV and wind projects being installed over the coming decades, technological improvements are also a key factor. They will lower the levelized cost of energy from solar PV and wind, leading to even more subsidy-free opportunities. Some major technology trends that we see in the industry are:

**COMING OF AGE: AN END TO SUBSIDIES FOR WIND AND SOLAR**

- The 175 MW, 265-hectare Don Rodrigo solar PV project in Sevilla, Spain, is one of the first solar projects of its size in Europe to be built without subsidies or state support. It was recently acquired by a German asset management group.\(^a\)

- All new wind power in Norway and Finland after 2021 (including projects now going into construction) is subsidy free. In Finland, OX2 will build four onshore wind farms with a total capacity of 107 MW by 2020, the largest subsidy-free wind power development in the Nordic region.\(^b\) The farms will be financed and owned by Swedish furniture retailing giant IKEA.

- In the US, the Production Tax Credit (PTC) for wind farms is being phased out, with wind farms starting construction after the end of 2019 no longer being eligible.\(^c\)

- China is moving to a substantial subsidy-free model for solar PV this year and will be phasing out subsidies entirely over the next two-three years.\(^d\)

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\(a\): MEAG, ‘MEAG acquires solar park in the south of Spain’ press release, 3 January 2019, viewed at meag.com

\(b\): Viewed at ox2.com

\(c\): https://www.eia.gov/todayinenergy/detail.php?id=39472

— Solar PV
- Advances in solar module technology such as bifacial solar cells, which generate power from both sides of the panel, while traditional opaque-back-sheeted panels are monofacial. When bifacial modules are installed on a highly reflective surface (e.g. a white Thermoplastic Polyolefin (TPO) roof or on light-coloured stones on the ground), some bifacial module manufacturers claim significant (up to 30%) increase in production just from the extra power generated from the rear. We are seeing some 25% of pre-construction energy yield assessments in North America include bifacial modules for projects that will start construction in 2021–2022.
- Other module improvements are:
  - Higher efficiency modules through the application of a Passivated Emitter and Rear Cell (PERC), which will dominate the market this year.
  - Reduced degradation. Improvements to module structure to mitigate Light Induced Degradation and elevated Temperature Induced Degradation.
  - A shift in wafer production from multi-crystalline to mono-crystalline silicon and eventually from p-type to n-type wafers, thus achieving higher efficiencies and better power-to-cost ratios.
  - The main trend in mounting mechanisms is toward greater use of single-axis tracking, which will dramatically increase the capacity factor.

— Wind
- Larger turbines and ‘supersized’ blades.
- Over the past decade, the wind energy industry has significantly improved energy production and cost efficiency, driven in part by increased turbine, blade, and tower size. Further advancements in turbine technology are likely to include supersized blades (Figure 3.2). For onshore use, these will require innovative transportation solutions, blade segmentation or onsite manufacturing.
- Operators will increasingly take account of power prices to optimize operations for maximum revenue rather than just maximum generation. Digitalization will be a key enabler for more flexible operations.
- There will be an increasing trend towards a more detailed data- and model-driven approach to assessing life extension of wind projects or repowering.
- Floating wind is in its infancy; but the next decade will likely bring greater consolidation in the market, with full-scale demonstration projects progressing to commercial-scale deployments.

All of the above trends result in improved energy capture per project or lower cost per MWh.

**The issue of variability**
The huge growth in capacity and power production from solar PV and wind is essential to reduce global carbon dioxide (CO₂) emissions. Nevertheless, both technologies are by their nature at the mercy of variable, if often predictable, weather patterns. Modelling of the power systems in the 2019 ETO has been at a much more granular level than in previous years. This has been done to account for the anticipated hourly fluctuations in generation and demand – which in turn impact on projected power prices – and use of flexibility options such as DSR and storage.

Figure 3.3 overleaf shows the fluctuation in electricity demand for Europe in our ETO Model for an example week in 2040 including the demand from storage. The corresponding supply is in Figure 3.4. These illustrate the likely variable, flexible and dynamic power systems of the future.
In many parts of the world, rare but possible winter weather events in which periods of limited wind generation coincide with low temperatures will become the design case for the grid. One example of these is when stable high-pressure weather systems sit over Northwest Europe in the winter. In a scenario like this, with high demand for energy for heating, but less wind generation for potentially a week, the power systems of the future will need to operate very differently from today. They will need to continue providing the very high reliability that we all expect, but from the much cleaner generation mix that we all want.

A combination of solutions is needed, including better prediction of renewable power generation levels, and demand response to react to excess renewables and shift electricity usage from peak periods to those of lower demand. Continued investment is required in the interconnectors between physical transmission systems, and in the links between generation and load centres. One good example is the Nemo Project, which will see a transmission cable from Belgium to the UK grid built to deliver 1 GW of power. It is among many plans for interconnecting systems, in Europe and elsewhere.

Energy storage will also play an increasingly important role in future power systems with high penetration of variable renewables generation; Section 3.2 discusses storage and other flexibility options in more detail.

**Wholesale power price cannibalization**

While the ETO Model predicts huge benefits to society from a considerable increase in the percentage of electricity generated from solar PV and wind, there is also some bad news for operators. As the definition in the text box explains, they will start to ‘cannibalize their own business case’.

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**FIGURE 3.2**

In comparison: A supersized wind turbine blade

![Diagram](https://via.placeholder.com/150)
**FIGURE 3.3**

Europe hourly electricity demand by segment in 2040, example week

Units: GW

**FIGURE 3.4**

Europe hourly electricity supply by technology in 2040, example week

Units: GW

**WHOLESALE POWER PRICE CANNIBALIZATION**

This term describes the depressive influence on the wholesale electricity price at times of high output from intermittent, weather-driven generation such as solar, onshore and offshore wind. This is described in more detail in our report, ‘Future-proof renewables’. It is downloadable at dnvgl.com
High volumes of simultaneously generated electricity combined with lower demand will lead to a greater number of hours in which there is potential for oversupply. The outcome is low, zero or even negative electricity prices that could erode the business case of renewable generation.

The results of the higher granularity of modelling in this year’s ETO indicate that wholesale power price cannibalization starts to slow growth of renewables generation in some regions with higher penetration. This is seen in the forecasted growth rates of wind and solar PV slowing a little in Europe and North America after 2040. The impact is slightly higher for solar PV due to a stronger correlation with daily production.

Solutions to this include flexibility options. Section 3.2 describes them in more detail, but it is worth mentioning here that increasingly cheaper battery storage will be one key to mitigating the impact of price cannibalization.

Figure 3.5 shows DNV GL’s day-ahead wind power forecasts for Great Britain (GB) compared with actual generation, with the corresponding electrical demand plotted on the same chart. Figure 3.6 shows both the day-ahead market (DAM) price and the continuous power price.

**FIGURE 3.5**

Comparison of day-ahead GB wind power forecasts, actual generation, and demand

Units: GW

**FIGURE 3.6**

GB power price fluctuations over 20 days in winter 2018

Units: GBP/MWh
Two things stand out. First, although renewable generation is variable, it is currently possible to forecast the power output highly accurately a day in advance. Second, fluctuations in half-hourly power prices tend to be higher when there is either low wind and high demand, or high wind power and low demand, including some periods of negative power price.

We predict that events such as the peaks and troughs in power price seen above will become more frequent in energy markets with large volumes of renewable generation. This will be a key element in driving increased provision of flexibility services such as DSR and storage, which in turn will dampen price fluctuations so that the true value of renewable generation and grid services will be recognized. In a number of markets, we see many renewables developers evaluating the colocation of storage with new solar plants, or operators creating virtual power plants to maximize the benefit of hybrid systems. To facilitate the provision of flexibility services, many markets will shift to focusing on shorter horizons and settlement periods.

3.1.2 OTHER RENEWABLES

Hydropower is predicted to grow slowly out to 2050 as its share in electrical generation declines from approximately 17% to 14%. As a mature renewable technology, it is well understood. Long lead-times, high capex, limited geographical locations and concern over potential environmental and social impacts limit its growth.

Reservoirs for hydropower 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.

Generation from biomass is predicted to grow steadily out to 2050, making a relatively consistent contribution of slightly more than 2% to electrical generation during the ETO forecasting period. The use of biomass for CHP, or for 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.

3.1.3 CONVENTIONAL THERMAL GENERATION

Production and capacity

Although total electricity production grows significantly, ‘conventional’ thermal generation declines during the ETO period (Figure 2.6). Globally, we see electricity generation from coal remaining relatively constant out to 2030, then declining to less than a third of today’s levels. Natural gas remains relatively constant out to 2050, and nuclear sees a moderate increase for the next decade before declining to approximately 75% of today’s levels by mid-century.

These global trends vary considerably between regions. In Europe and North America, electricity generated from coal will drop significantly over the coming five years, with demand being met increasingly by a mix of renewable and gas generation. No electricity was produced from coal for two weeks of May 2019 in the UK, the longest period of ‘coal-free’ power in the country since the 1880s. Fintan Slye, director of the UK’s National Grid Electricity System Operator (ESO) commented that ‘things progress at an astonishing rate’ as more and more renewables come onto the system. The ESO has also predicted that 2019 will be the first year since the Industrial Revolution when more of Britain’s electricity production will come from zero-carbon energy sources than fossil fuels. The UK government plans to phase out coal-fired plants by 2025. In Greater China and India electricity from coal is set to grow, peaking in 2024 and 2031 respectively, before also starting to decline.
We predict that the global installed capacity of ‘conventional’ thermal generation will rise through to the mid-2020s, mostly due to coal installations. In our model, it then remains relatively constant through to 2050, but coal gives way almost entirely to gas installations. We foresee the annual capacity factor for coal-fired generation falling significantly by 2050, highlighting the risk of stranded assets. Nuclear capacity factors remain relatively constant over our forecasting period, and gas increases. Although we see the capacity factor for gas rising out to 2050 on an annual basis, operation of many plants will fluctuate over days, weeks and seasons. This is because gas-fired power plants will likely be a ‘flexibility’ option to help manage the variability of increasing levels of solar PV and wind (see the end of the week in Figure 3.4).

The model includes the use of hydrogen to meet overall energy demand. However, the results show it playing a limited role as an energy carrier for only 1.7% of total global energy demand by 2050, when it is seen as being used for some road and maritime transport. Our studies show that over the period of this ETO, hydrogen remains an expensive option for electricity generation.

Carbon capture and storage
We do not see carbon capture and storage (CCS) playing a significant role in the future generation of electricity, at least until mid-century. The ETO Model indicates increased use of CCS from 2035 out to 2050; but even by 2050, it impacts on only 5% of total emissions. This is due to the cost assumptions, including ‘learning curve’ effects resulting in other options being more favourable. However, this result is from our model’s forecast of the most probable future, based on existing knowledge and predicted policy, market and technological trends. It should be noted, as is done in Chapter 8 of our main report, that our model also predicts a failure to meet the Paris Agreement’s 2°C limit for global warming; in which case, increasing levels of CCS could be part of the solution to combating climate change.

3.1.4 ELECTRICITY MARKETS AND POLICIES
As we transition to an energy system with a substantially larger mix of electrical generation from variable renewable energy sources (vRES), electricity markets will shift and adapt to facilitate the transition. Markets are in principle designed and regulated to provide mechanisms for efficiently meeting the needs of society, but are clearly impacted by political concerns.

The ‘new’ complexity of the electricity sector calls for increased use of market mechanisms and less use of traditional planning-based decision making. There are three essential reasons to rely on market mechanisms and distributed decision making on both investment and dispatch decisions, where prices serve as the key coordination mechanism among stakeholders:

1. The need to forecast ‘physical’ factors will grow with deep decarbonization. In electricity systems based solely on coal and gas, it is largely enough to forecast demand to come up with a reasonably efficient production plan for the following day. With a huge variety of energy resources, there is a lot more forecasting to be done, so that there is time to ensure plans are compatible with available network capacity. This is achieved efficiently via markets.

2. To ensure efficient utilization of scarce network capacity, market mechanisms play a fundamental role in simultaneously informing network operators about the immediate (short-term, up to day-ahead) demands from producers and end users. These mechanisms also signal to market participants how they can optimize their short-term operations.

3. Markets also play a vital role in ensuring efficient allocation of financial risks. Long-term markets allow for a separation of who takes the financial risks and who takes the more operational risks in maintaining and operating power plants. Long-term markets tend to be more efficient if they can work in parallel with short-term markets.
To facilitate the energy transition, most modern and developed markets will have a greater focus on shorter horizons and settlement periods to facilitate flexibility, including further development of balancing markets. In many regions, markets were structured to work efficiently with large centralized thermal generation. Wind and solar PV generation behaves, and is controlled, very differently; so, as the energy transition progresses, market rules and regulations will continue to change to ensure that the value of distributed generation and flexibility options can be truly recognized. For example, it might be better to produce ammonia locally, based on available generation profiles, rather than producing it centrally and transporting it to where it is needed. The value chain will also be more granular. With locally distributed energy resources, larger consumers will have greater options for influencing local generation.

New renewable generation will also have a big impact in less-developed regions by bringing electrification to new areas and improving power supply in others. As new microgrids and mesogrids are developed, markets will be structured differently for the distributed generation on these, to recognize the value that power is providing to people’s lives.

Effective markets are technology agnostic, but certain technologies can visibly perform well under particular market conditions. For example, markets for ancillary services can be open for anyone able to comply with the requirements of the system operation rather than focusing on a limited group of suppliers like large thermal generators. Trends such as this are considered in our ETO Model, resulting in the substantial projected growth in battery storage, discussed further in Section 3.2.

Increasing digitalization of power systems is enabling change from more rigid mechanisms to direct markets, such as flexibility markets and the growing role of aggregators. This also drives market focus towards shorter horizons and provides closer to real-time flexibility. The ability to efficiently process increasing volumes of data from distribution systems will also help markets to operate effectively, through aspects such as optimization of markets based on the specific location of smaller generation and load, and enabling improved short-term forecasting of renewable generation and power prices.

Over the next decade, climate change and pollution control policies will continue to drive the energy transition. They will vary between regions but will have common themes. The Government of India’s policy goal is to reach 175 GW of renewable generating capacity by 2022 and 275 GW by 2027, compared with the current installed capacity of 75 GW. In Greater China, the 2018–2020 Three-Year Action Plan for clean air indicates the coming together of the nation’s management of air pollution and climate change. The plan calls explicitly for ‘large reductions in total emissions of major pollutants in coordination with reduction in emissions of greenhouse gases. It mandates reductions of at least 18% in levels (compared with a baseline in 2015) of particulate matter with a diameter of 2.5 micrometres or less in more than 300 cities.

Policies will also continue to consider energy security and opportunities for local job creation, all of which will have an impact on the energy transition. In many regions, the technologies often advance faster than policy development, which must adapt to keep up. Historically, policies would drive technology development, but many of today’s policies would not be possible without technologies being demonstrated as viable options. The bans on new petrol and diesel cars in several locations around the world would be unlikely without industry having first proved the capability of EVs and the infrastructure to support them.

Rapid technological advances and ramping up of production in the solar PV industry led to solar generation growing faster than many
policymakers had anticipated. This resulted in support mechanisms such as feed-in tariffs being reduced or withdrawn more abruptly than planned. The ETO Model considers the anticipated technological and financial trends which lead to the point where, in many regions, subsidy-free renewable generation will be the optimal choice. At that stage, policies will have a decreasing impact on the energy transition; market economics will be the driving force.

3.2 ENERGY STORAGE AND OTHER FLEXIBILITY OPTIONS

As we highlight in Section 3.3, limited control over the growing share of wind and solar PV in generation creates a tougher challenge to ensure that the grid is operated reliably and efficiently. Storage and other flexibility options will play key roles in meeting this challenge.

A range of flexibility options are summarized below:

- **Energy storage**: Technologies include pumped-hydro, batteries, flywheels and compressed-air storage in caverns. Pumped-hydro and batteries are the only technologies considered to have any significant impact in the ETO.

- **Greater interconnection**: Improving connections between neighbouring grids enables balancing of supply and demand over larger geographies, ‘smoothing’ variability and improving robustness to failures. Such as the approved 1.4 GW NorthConnect interconnector between the UK and Norway, which will be 665 km of high-voltage direct current cable, due to be operational in 2023/24.

- **Flexible generation**: Electricity systems already make substantial use of generators with the ability to start quickly and vary their output rapidly. Examples are hydro and diesel generators, and open-cycle gas turbines. It should be noted that output from solar PV and wind generation can also be adjusted rapidly; but while power can be easily reduced, any increase is limited by weather conditions at the time. This limitation is removed where storage is integrated into hybrid systems so that output can correspond more closely to demand.

- **Flexible demand**: Integrating DSR measures to encourage reduced power consumption at peak times reduces strain on the grid and lowers costs for the consumer. We predict the DSR market to grow both in industry, where it is more established, and in commercial and residential buildings. The lower cost of sensors, greater data processing capacity, and advancements in artificial intelligence (AI) will enable DSR to be applied in a more automated and specific manner, providing a more granular level of control. EV charging is also a major new source of DSR both for fleets and domestic use.

- **Flexible markets and regulation**: With more distributed generation and DSR, greater flexibility in markets will evolve to enable power systems to operate efficiently (see Section 3.1.4). The increased number of sites to manage will lead to greater devolution of responsibility; this may result in TSOs being responsible for frequency management and black start, with DSOs and other market participants taking larger responsibility for voltage and reactive power flow. Flexible and interconnected markets and regulation will be important in facilitating closer cooperation and coordination between market participants, such as cooperation within each synchronous area\(^\text{12}\) for efficient frequency control.

**STORAGE**

Of the options summarized above, energy storage is the area where the ETO Model predicts the most significant growth (Figure 3.7). Pumped-hydro is a mature storage technology predicted to grow noticeably over the coming decades but is limited by the number of places where it can be used. With recent advances in battery storage technology and, importantly, lower costs due

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12 Synchronous area: an area where the frequencies of the electrical grids are synchronized
to greater production volumes, its use is predicted to grow significantly throughout the ETO forecasting period.

Lithium ion (Li-ion) is currently the most cost-effective battery chemistry for most battery storage uses, including large-scale applications for the grid and in EVs. We predict it to dominate the battery storage market over the coming five years. Approximately 95% of storage projects that we are currently involved in through feasibility assessment, development and construction, are Li-ion. Further refinement in Li-ion batteries will improve their performance, increase energy density, and reduce the use of key raw materials such as cobalt. Newer battery technologies such as solid-state also offer better energy density, reduced fire risk, longer life and faster charging/discharging capability; these are likely to be mass produced in the next five to 10 years. Redox flow batteries are currently very limited in use, but do offer a potential solution for longer storage periods, and as such may see increased use beyond 2030 as variable renewables penetration increases.

Battery storage also offers flexibility through modular construction easily adapted for: residential use, typically sub-15 kWh; smaller behind-the-meter projects, typically sub-1 MWh; or for combining multiple battery containers to provide hundreds of MWh of storage. The first GWh-scale projects will be built in 2020 with more to come over the next five years. We anticipate that although large scale in-front-of-the-meter battery storage projects will offer the lowest cost option for power system batteries, there will be a large market for residential and behind-the-meter storage where they can maximize the value of local generation and minimize peak power costs for consumers.

EVs providing flexibility in the grid is also an important trend in our ETO modelling. They can be viewed as smart, connected batteries on wheels. As range increases, charging infrastructure improves, and the uptake of EVs accelerates, the option of using spare capacity in EV batteries for vehicle-to-grid (V2G) services becomes increasingly valuable. If you were told you may never have to pay for the energy going into your vehicle, just by making your spare battery capacity available to the grid, you might well say ‘yes’. In future decades, as new...

**FIGURE 3.7**

**World storage capacity available to the grid**

Units: TWh
Figure 3.8 shows the importance of understanding timescales when considering flexibility issues. DSR, interconnections and storage, particularly batteries, are good for the short timescales. For example, we are beginning to see significant growth in batteries being used along 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 with conventional batteries. Long-duration technologies that decouple power and energy to take advantage of low-cost storage materials are required. Such technologies could use pressure, gravimetric or electrochemical conversion processes, but many are not in widespread commercial use today. In addition to hydro reservoirs which are in use, credible options presently include power-to-gas or liquid fuels, as discussed in Section 3.5, and long-term heat storage for use as heat, such as in district heating systems. These options are examples of ‘sector coupling’, connecting electricity markets to gas, fuel, and heat markets.

DEMAND-SIDE RESPONSE
Demand-side response (DSR) has been available to industrial companies for decades. However, increasing penetration from onsite renewables will create opportunity for manufacturing to provide further flexibility through DSR, supporting and benefitting from the broader energy transition.

DSR can be implemented through time-based electricity tariffs encouraging consumers to reduce consumption during high tariff periods; it can also be implemented in reserve markets through tendered contracts between utilities,

FIGURE 3.8
Flexibility issues by timescale
TSOs or DSOs and end consumers, mostly industry. For example, companies that have daily pumping requirements have a certain electricity demand, but the exact time in the day (or week) of this demand could be changed according to flexibility requirements in the market without disturbing the company’s primary processes.

DSR can be used to control demand profiles in various ways, such as peak shaving (to reduce peak load on the system) or by increasing demand (e.g. to help with frequency control or to absorb local surplus renewable energy). In manufacturing, decreasing or switching off non-time-critical processes could provide demand-based flexibility. Examples include short-time batch processes, municipal water pumping and wastewater treatment.

Additionally, local microgrids or smart grids could provide larger, aggregated demand-side flexibility from clusters of end consumers (homes, small industries and businesses). Within these future systems, sophisticated communication and controls could be integrated to coordinate flexible resources across consumer-based supply and demand, both for local purposes and as a service to the central level.

3.3 ELECTRICITY GRIDS

3.3.1 STRUCTURAL CHANGE IN THE ELECTRICITY SYSTEM

For electricity grids, the energy transition means moving away from traditional systems with their centralized conventional generation and unidirectional power flows. Systems will become much more complex to handle multidirectional power flows and a high amount of decentralized, weather-dependent, fluctuating generation from variable renewable energy sources (vRES).

The process of integrating solar PV and wind accelerates rapidly to 2030 amid global efforts to decarbonize the world energy system. Allied major trends are the nuclear and coal phase-out in Germany, Switzerland and Sweden, and the shift away from nuclear power in Japan.

The big shift, electrification of energy – including in sectors like heat, gas, and transport – will drive growth of transmission and distribution grid infrastructure. Electricity demand will rise almost 40% by 2030 and more than double by 2050, driven by population growth in Africa, Asia and Latin America, and electrification of heat and transport.

Grid responses to technology and market trends

Grid reinforcement, extension and flexibility, with appropriate balancing schemes to maintain balance of supply and demand, are needed to adapt to these technology and market trends. Integrating vRES will require large-scale investment in network extensions. The greater complexity in system operation will include increased application of newer technologies such as high-voltage direct current (HVDC) and hybrid alternating and direct current (AC/DC) grids. Networks will have to be operated closer to their thermal and stability limits. In Europe, interconnectors between large market areas will add to this complexity. Elsewhere, such as Latin America, the increasing share of vRES allied with market coupling opportunities will lead to interconnectors between countries which have hitherto operated as ‘electrical islands’.

Figure 3.9 takes major grid extension trends into account to show how power-line capacity tracks forward by voltage class. It indicates that a strong ultra-high voltage (UHV), extra-high voltage (EHV) and high voltage (HV) transmission backbone will be required in the future to satisfy electricity transport and trading needs. Modern societies require the highest levels of reliability from their
electrical infrastructure. This can be provided by a greater number of more widely distributed elements connected via a strong backbone.

**From interconnections to supergrids**
The completion and continued development of current and new interconnector projects is needed to manage supply and demand as vRES capture an increasing share of power markets. Projects such as the Northeast Asian supergrid, interconnectors in Southern Europe, and Northern Europe’s new Hansa PowerBridge, combined with Germany’s HVDC corridors, will form overlay grids on top of the existing high-voltage alternating current (HVAC) grid topology. Such overlays will enable seamless trading of electricity, and further reductions in wholesale electricity prices, helping markets and regions to remain competitive. They will also have an impact on geopolitics, as reliance on fossil fuels (often imported) reduces and the value of renewable resources increases.

**Changes in the transmission system**
Meshed overlay networks will be established to enable transmission of bulk power over long distances. They will be based on HVDC technology, DC breakers, extensive application of HV cables and the interoperability of different converters.

As power generation decarbonizes, the contribution of ‘conventional’ generation plant will eventually become very low, reducing short-circuit levels. The specification and design of grid components will change as short-circuit currents and thermal limits vary. The varied short-circuit currents will pose challenges in detecting grid failures; new principles for protection schemes will be required.

**FIGURE 3.9**

**World power line capacity by voltage class**

Units: Million GW-km

3.3.2 THE FUTURE OF SYSTEM OPERATION
Given the trends described above, system operators will turn to innovation for grid reliability and stability. We will see rising use of markets for flexibility and ancillary services to support system operations. Capacity elements will play an increasing role in maintaining reliability. With greater variability of generation, some power plants will be needed only during particular power system extremes. For example, some high-cost thermal generation will operate only in periods of low renewables output. Though operating infrequently, they will play a role in ensuring grid reliability and stability, and will need appropriate incentives to provide the capacity to generate when required.

Decision-making tools will be automated. We expect more use of flexibility platforms for accessing decentralized flexibility; automatic optimization of several load flow-controlling assets; reactive management for operation closer to thermal limits; and dynamic weather-dependent line rating. In this new landscape, shared system operations between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) will drive a need for higher levels of regulation to define their roles and the interfaces between these players.

Better operational planning and more accurate forecasting of energy demand and supply will be needed. Efficiently integrating vRES will also require improved system services such as balancing, voltage regulation, fast frequency response (FFR), and congestion management. Wind and solar PV plants will have to assist their own integration by providing synthetic inertia in combination with storage elements. They can add further value to power systems by supporting grid restoration following black-outs.

FFR’s potential as an ancillary service is illustrated in a scenario (Figure 3.10) modelled by DNV GL GridLab. It shows the positive frequency effect of synthetic inertia contributions from wind and solar PV farms after a sudden outage of a 1,500 MW generation unit for the entire electricity system for Western Japan.

Renewable energy generators will increasingly provide ancillary services under the condition that they comply with grid codes as well as balancing market and product requirements.

In the future, state-of-the-art load-frequency control processes will be required for operating highly reliable power systems. These will include frequency containment reserves (FCR), frequency restoration reserves (FRR) and replacement reserves (RR) provided by regional balancing markets. The framework of the European Network of Transmission System Operators acknowledges the new situation with less conventional inertia, but needs refinements as further integration of vRES continues.

3.3.3 MODERNIZATION OF DISTRIBUTION NETWORKS
Distribution networks were originally designed to get electrical energy from transmission systems to consumers. Many distribution systems already operate with ‘reversed’ flow of power, a trend set to continue and spread geographically as penetration of distributed generation from vRES and the resulting regional imbalance between supply and demand increases.

As distribution system operation becomes more complex, digitalization will play a growing role and have a big impact through better monitoring and control of lower-voltage grid levels, and intelligent (digital) substations. Better and new security tools, including cyber security, will be needed to manage renewable sources connected to distribution networks. For example, 95% of vRES in Germany are connected to DSOs. We expect greater use of ‘digital twins’, data-driven virtual representations of physical assets and processes, to predict and test condition management for optimizing renewal and maintenance strategies.
A large amount of future investment in the grid will be at the distribution level to cope with distributed generation, sector coupling and deployment of electric vehicles (EVs).

3.3.4 TRANSMISSION AND DISTRIBUTION COST PREDICTIONS

We will see grid costs increase in the next decade to finance large-scale projects. At the same time, the final power price will shift from being dominated by generation costs to being influenced more by higher grid costs. HV-cable applications for subsea and underground interconnections drive costs extensively, especially in developed energy markets with offshore wind plans. TSOs in regions like Europe predict their highest investment level ever in the next 10 years to establish grid extensions and offshore wind connections.

While substantial investment in new and upgraded grid infrastructure is required, some trends—electrification, digitalization and flexibility management—will boost capacity utilization in distribution networks. These will reduce the relative unit costs for consumers; i.e. there will be more energy flowing through the network, which will help to lower the cost per kilowatt hour (kWh). There are also associated costs for the grids that stretch beyond financing infrastructure. Grid structures will generally be optimized (fewer voltage levels), leading to lower network costs in both transmission and distribution. Risk-based asset management methodologies will help to deal effectively with the cost of ageing infrastructure.

Source: ‘Integrating renewables into the Japanese power grid by 2030’, a GridLab study for Agora Energiewende and REI, December 2018

FIGURE 3.10

Frequency response after loss of 1,500 MW for western Japan based on a scenario involving varying contributions from vRES, with and without FFR from wind and solar PV plants

Units: Hz
3.3.5 NEW TECHNOLOGIES AND TRENDS

Digitalization and smart technologies

Digitalization is having a profound impact on the future of electricity grids. Smart technologies are fundamentally changing the way that electricity is transmitted, distributed and managed. In the next decade, we will see more automation of network operation, and full automation of energy billing and accounting processes. IT platforms will grant access and open the market to new distributed energy and flexibility providers.

Sensors and data analytics will mature and enable smart asset management and better utilization of main system elements. This will include new Internet of Things (IoT) sensors; new monitoring of lifetime consumption indicators; enablement of a decentralized generation structure; and, more sophisticated Supervisory Control and Data Acquisition (SCADA) and related grid-operation tools. Much of this progress will depend on adequate data sharing by grid companies to facilitate combined data harvesting and data hubs to improve performance.

The impact of storage on the grid

As the volume of vRES grows, storage will play an important role in managing supply and demand, together with other flexibility options. We will likely see increasing trade-offs between potential solutions for future power systems, such as: massive distribution grid reinforcement; flexibility, e.g. intelligent charging of EVs; storage; demand management; and sector coupling.

The European Ten-Year Network Development Plan, which provides an overview of what the electricity transmission grid should look like in 2040 to create maximum value, predicts that up to 10% of system load will be from EV battery storage and large-scale batteries.

Some US states have targets for high penetration of renewables on their grids (e.g. California, 100% renewables generation by 2045\(^{13}\); New York State, 70% by 2030\(^{14}\)). They will benefit from connections with surrounding jurisdictions to help balance the grid, but must also include substantial increases in storage to maintain a robust, reliable and efficient system.

Storage has a dual role to play in the electrification of transport; both in the deployment of batteries in the large fleet of EVs, and the need for static batteries to support weaker grid infrastructure and provide fast charging capability.

Other aspects to note are:

- Depending on how much and how quickly fossil-based power generation is phased out, the importance of storage for the provision of ancillary services increases
- Adding new storage technologies to the grid results in different fault conditions, which will require adjusted fault detection schemes
- Using flexible hydropower and pumped storage is on the agenda for large-scale storage, but the commercial viability of this option is very country-dependent.

New business models

New business models will emerge by 2025 as vRES start to provide more than a quarter of our power needs. At the heart of these models will be flexibility to include the introduction of local ancillary services, EVs and their associated demands, and behind-the-meter services.

In the looming shake-up of power generation business models, new aggregator roles will enable prosumers to benefit from wholesale price signals. Consumers transforming into prosumers will also increase direct energy transfers and shift the power balance between providers and customers as the two roles merge.

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13 https://www.pv-tech.org/news/california-senate-mandates-for-100-renewable-energy
Digitalization will give rise to new digitally-based energy demand management solutions for industries, commercial businesses and households.

**The trends for microgrids**

Microgrids will play larger roles in the future. Examples include the following:

- 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.

We will see more small-scale local microgrids in communities taking advantage of decentralized power generation opportunities, such as community solar farms. As vRES are integrated into the grid, microgrids can provide a reliable and resilient solution in times of main-grid instability or outages. Lower-cost energy storage equipment enables remote microgrids with vRES in two ways. First, in regions where delivered fuel is expensive, battery storage can reduce the amount of fuel consumed, which in turn reduces the levelized cost of electricity. Second, using less fuel reduces related greenhouse gas emissions.

### 3.4 ENERGY USE AND EFFICIENCY

#### 3.4.1 ELECTRIFICATION OF ENERGY USE

**Buildings**

Our ETO Model predicts that electricity use for heating and cooling in residential and commercial buildings will almost double between 2018 and 2050. This results most significantly in less biomass use, with natural gas usage initially rising slightly before slowly declining.

Advances in technologies such as heat pumps will result in heating (space and water) and cooling being increasingly provided by these efficient devices over the coming decades. However, at current equipment costs and energy prices, conversion of fossil-fuel heating and hot-water equipment to efficient heat-pump technologies is not yet cost effective for most home and commercial facility owners. Moreover, the thermal integrity of a large proportion of the building stock in cold climates must be improved for current versions of the technology to meet full heating requirements. These conditions further increase the technology and transaction costs of installing heat-pump space and water heating.

Given these market conditions, decarbonization of space and water heating will require continued public sector activity. In the Netherlands, for example, national agencies have proposed regulations to discontinue natural gas supplies to new residential developments. Many national governments support R&D to improve the performance and reduce the costs of heat-pump technologies, and to conduct field demonstrations of new technologies.

Newer energy conversion devices combined with continued advances in digitalization, both in terms of capability and lower costs, will result in the increasing application of digital solutions for smarter buildings. We predict that this will give residential and commercial building occupants convenient and more automated control over their
environment. We also foresee it increasingly enabling utilities and aggregators to have some control for demand response.

**Manufacturing industry**

In the ETO Model, the manufacturing sector aggregates all related activities in the extraction of raw materials (excluding coal, gas, and oil) and their conversion into finished goods.

Manufacturing is one of the three largest users of energy, consuming about 127 EJ of final energy in 2018. We forecast manufacturing sector total energy demand will rise by approximately 15% by the 2030s, and then decline steadily to 2050 (Figure 3.11). We predict manufacturing energy demand of 134 EJ in 2050 having remained at a relatively consistent 30% of final energy demand.

Energy is a fundamental need and a significant cost for manufacturing companies. Energy supply for the sector is likely to see continued pressure to reduce carbon emissions. This will mean the use of more co-located renewable energy and lower-carbon grid-supplied electricity. Electrification of some industrial processes will also increase electricity demand. The percentage of manufacturing energy demand being met by electricity was 26% in 2018 and is set to grow to 45% in 2050. Electrification of heat in manufacturing will take the form of heat pumps and direct electrical heating.

As we move towards more recycling of materials, there will be greater value in electrical heating in manufacturing because it is a more precise heating method. This will enable more effective recovery of critical raw materials or embedded rare-earth metals. The greater precision will also be valuable for high-quality steel production where greater control of the location and temperature of electrical heating (using arc furnaces) helps to improve quality. We expect more sectors to deploy electrical heating in core processes, but this will need more innovation and technology cost reduction. We envisage a timeframe of 2025 and beyond for these changes to impact.

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**FIGURE 3.11**

*World manufacturing sector energy demand by carrier*

Units: EJ/yr

Historical data source: IEA WEB (2018)
The shift towards electrification will require a clear business case for manufacturers who will have invested in fossil fuel-fired boilers with an expected life of approximately 40 years. This is likely to dampen the speed of change over the next five years, though further investment in fossil fuel boilers will likely be low for fear of stranded assets. Manufacturers will also increasingly pay closer scrutiny to future electricity prices and their fluctuations as they assess electrification options. Some sectors may be able to exploit price fluctuations to increase production during periods of cheaper power. Others will need to keep manufacturing processes operating consistently irrespective of power price. Onsite renewables can assist the business case for increased electrification and lower carbon emissions. They can provide lower-cost local electricity which, combined with storage, can create a clean power source to meet manufacturing demand and, potentially, provide grid services. We already see this trend, and it is set to continue.

**Transport**

Improved modelling in this year’s ETO of the transport sector, and most significantly road transport, has refined our projection of its electrification. It continues to show the substantial shift towards EVs, most notably the light-vehicle fleet. Almost 20% of electricity demand will be due to transportation by 2050, starting from close to zero today (Figure 2.4).

This transition shifts energy demand away from oil, improves energy efficiency, and reduces emissions. Figure 3.12 shows almost 40% of road transport final energy demand being met by electricity by 2050. More than half (54%) of the (albeit much smaller) rail demand is met by electricity by this time, with a small amount of electrification of maritime and aviation.
The accelerating EV revolution is being driven by three major factors:

- Increasing urgency to address climate change: the ‘climate emergency’
- Pollution reduction measures in cities
- Higher performance and cheaper batteries.

With transport accounting for almost 30% of energy demand (Figure 2.1), reducing its CO₂ emissions will have a major impact on global levels. Climate emergency declarations have been made in 740 jurisdictions and local governments covering 136 million citizens.¹⁵ This re-invigorated focus on the climate, combined with transport’s high share in energy demand, has led to many governments putting forward policies to support a shift to EVs. For example, the sale of new petrol and diesel cars beyond certain cut-off years is being banned by a growing number of countries (Table 3.1).

Beyond the climate change initiatives, there is also a strong drive globally for cleaner cities, in which an increasing proportion of the population lives. More than 20 cities globally are planning to ban diesel and petrol vehicles. Mexico City, Mexico, plans to ban diesel vehicles from the city in 2025¹⁶; many others propose bans in 2025 and 2030.

Alongside policies and regulations supporting the EV revolution, technological advances are a strong driver of cleaner, greener transport. Improved Li-ion battery chemistries and battery management systems are notable in this regard. They offer significantly better performance through higher energy density, faster charge/discharge rates, and lower costs. Battery cost learning rates of about 18% have recently been observed for doubling accumulated global capacity. We expect this rate to continue, resulting in passenger EVs reaching total cost of ownership parity with an ICE (Internal Combustion Engine) equivalent from 2023. This date varies considerably depending on the vehicle range (and therefore battery size) and annual usage. Although there is substantial investment in hydrogen fuel-cell technology, particularly for heavy vehicles, we expect battery technology to be more successful for the foreseeable future.

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¹⁶ https://www.theguardian.com/environment/2016/dec/02/four-of-worlds-biggest-cities-to-ban-diesel-cars-from-their-centres

### TABLE 3.1

<table>
<thead>
<tr>
<th>Date of ban</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025 (targeted ban)</td>
<td>Norway</td>
</tr>
<tr>
<td>2030</td>
<td>Denmark, Netherlands, France, Ireland, Israel, Sweden</td>
</tr>
<tr>
<td>2040</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Bans being proposed by ministers but no confirmed date yet</td>
<td>Greater China, India, Spain</td>
</tr>
</tbody>
</table>
Solid-state batteries offering reduced fire risk, longer life and faster charging/discharging will likely be mass produced in the next five to 10 years.

The significant investment being seen in EVs, battery production capacity and supply chains, and in charging networks, will continue through the coming decades. The benefits will be lower costs, better performance, ease of ownership, and greater choice for consumers. They will accelerate the transition to EVs.

We predict that by 2032, half the global sales of new passenger vehicles will be battery EVs (BEVs) (Figure 3.13). More detailed modelling of parameters influencing consumer decisions generates a relatively broad range of dates for when this transition will happen in different global regions. We predict that in Greater China, half of new passenger vehicles will be non-combustion by 2026, with Europe hitting the 50% mark a couple of years later. South East Asia and Latin America will achieve this closer to 2040. The range of adoption rates largely reflects varying infrastructure availability among regions. For example, the Netherlands has the highest ratio of public charge points to vehicles, helping to support the transition to EVs. We assume that easy access to charging stations will continue to greatly influence decisions whether to buy a BEV.

The adoption rate of non-combustion commercial vehicles is slower than for passenger vehicles but still significant (Figure 3.14), note that in this figure non-combustion includes BEVs and fuel-cell vehicles. A fraction of heavy long-haul vehicles will require driving ranges unlikely to be affordable with battery-based propulsion. Countries that can produce or import sufficient low- or zero-carbon hydrogen and have a simultaneous need to decarbonize heating, will see a fraction of road electrification become fuel-cell based. This applies to Europe, Greater China, OCED Pacific and North America. In other regions, such long-haul needs will still be covered by ICE-powered trucks and buses.

There will be a very rapid transition of some commercial vehicles to electrification based on range, regular routes and proximity to charging infrastructure. Electric buses will lead this, and the adoption rate is likely to be faster than the average for passenger vehicles. In Greater China, there are already more than 400,000 electric buses.
As mentioned above, the EV revolution will have a significant impact on increasing electrical demand, and on the demand profile. EVs will be charged at four main locations: at home, work, destinations like shops and cinemas, and on route. Most charging is currently at home, but an increasing share will be at work and destinations. All scenarios require significant investment to deploy charging infrastructure and integrate it along with new load into tomorrow’s power systems. EVs will greatly assist integration by helping to balance supply and demand through load shifting and frequency response. Increasing renewables penetration in power systems globally will likely see the symbiosis between variable renewable generation and EVs play an ever-more important role on the grid. EVs providing services to the grid enable efficient integration of increasing renewables, while a greater share of renewables generation helps to reduce CO₂ emissions associated with driving EVs.

Autonomous vehicles, a mega-trend not covered in the ETO, will increase the value of EVs to the grid. Financial incentives may not be sufficient motivation for individuals to make their EV batteries available for grid services when they are plugged in. However, assessing the benefits and costs of making millions of vehicles in autonomous fleets available for grid services will be based on a more logical business case approach.

The aviation industry will play a very minor role compared with EVs in the electrification of transport. However, some shorter flights will be electrified in the future, including selected domestic flights and transfers by autonomous air taxi. Norway intends all short-haul flights leaving its airports to be on aircraft powered by electricity by 2040.¹⁷

### 3.4.2 ENERGY EFFICIENCY IN BUILDINGS

**Introduction**

Among major pathways for the transition from fossil fuels, increasing energy efficiency in buildings remains the most widely available, least expensive, and lowest-risk.¹⁸ However, recent trends suggest that much of the economically attractive opportunity for energy and emission reductions remains untapped.

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**FIGURE 3.14**

**Market share of electric commercial vehicle sales by region**

Units: Percentages

Electric vehicles include BEVs and FCEVs. Historical data source: OICA (2016), IEA GEVO (2018)
The International Energy Agency (IEA) estimates that financially attractive investment in proven technologies could reduce energy consumption in buildings by 30%–40% in OECD and other major economies. It argues that such investments continue to be far smaller than available financial returns merit. IEA calculates that it would take a fourfold increase in the pace of investment to realize a significant portion of economically viable efficiency improvements.

Global final energy demand in buildings saw a steady compound annual growth rate (CAGR) of 0.8% between 1980 and 2018 (Figure 3.15). The ETO Model predicts the CAGR will edge up to 0.9% through 2030 on greater adoption of space cooling, home appliances and business electronics. These drivers are linked to population and GDP growth. The impact of this growth will be moderated by factors such as stricter regulation, digital control technologies, and more energy-efficient equipment in homes, businesses and factories. The model sees the CAGR slowing to 0.4% between 2031 and 2050.

Uncertainty surrounds the forecasted slowing of growth of building sector final energy demand. We have seen broad adoption since 2000 of efficient technologies. Examples include light-emitting diode (LED) lighting, variable-speed drives, and electrically commutated motors in heating, cooling, and refrigeration systems. Despite such trends reducing energy intensity in major end uses, total consumption in the building sector has risen steadily. Technological innovation and adoption of efficient technologies must speed up significantly to slow growth in energy use. The stakes are high. In our model, if the CAGR of final energy demand in the building sector turns out to be 0.7% rather than the forecasted 0.4% over the period 2031–2050, total emissions from all sources would increase by 2.2%.

Rising population and standards of living drive up building sector energy consumption and associated emissions, particularly with rapid GDP growth, such as in Greater China, the Indian Subcontinent and Mexico. This effect is partly mitigated by:

- Supply chain companies raising the efficiency of products and designs in response to competition and regulation.

- Switching to electric equipment for end uses such as space and water heating that are primarily fossil-fuelled, thus reducing related energy consumption and emissions as power generation itself decarbonizes.

- Increased control over energy-using equipment and systems. The rapid evolution in the capabilities and cost of digital sensing, control, communication, and data processing technologies provides further opportunities to reduce energy consumption and improve the integration of energy use in buildings with the broader energy system.

- Regulating building design, materials and construction, and incentivizing energy efficiency. Building codes and minimum energy performance standards for equipment have been the key policy drivers for greater energy efficiency since 1990. They now apply to a third (34%) of building energy consumption\(^2\); increasing their coverage and stringency will be required to advance energy efficiency. Public sector bodies at all levels are running innovative incentive, obligation, and financing schemes that show promise for speeding adoption of energy-efficient products and building designs.

The examples below show how developments in end use adoption and efficiencies cooling

This fastest-growing end use accounts for 22% of total building sector energy use. Energy use for cooling has near doubled from 3.3 EJ in 2000 to some 6.0 EJ today for two main reasons. First, cooling equipment uptake has rapidly reached saturation levels in Greater China, the Indian Subcontinent, Latin America, Middle East, and South East Asia. Second, ambient temperatures have risen. The ETO Model forecasts a near 300% rise in energy for cooling buildings between 2017 and 2050 (Figure 3.16). Without accounting for greater thermal efficiency of buildings (insulation) and cooling equipment (efficiency), the rise would be 600%.

Recent analyses of space-cooling technology and markets show great potential to improve efficiency. Here are some steps required to achieve it.

- **Promote the purchase of commercially available efficient models.** Even in relatively advanced markets such as Europe, Japan, Korea and North America, the median efficiency of installed cooling equipment is near the bottom of the range for commercially available models.\(^2\) Cooling energy could be reduced by 20% to 40% through broader adoption of available efficient models. However, the incremental costs of very high-efficiency air conditioning equipment remain relatively high, inhibiting their adoption outside very hot, humid climates.

- **Harmonize standards.** Most countries with high saturation of air conditioning have minimum energy performance standards; but the stringency of these varies greatly. This increases the manufacturers’ testing and compliance costs, as most makers operate globally. It also weakens the effectiveness of the standards.

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Sources of change in world energy demand for space cooling between 2017 and 2050

Units: EJ/yr

FIGURE 3.16

- **Maintain investment in research and development (R&D).** Enabling new, highly efficient space-cooling products to be advanced and deployed.

**Lighting**

Lighting accounts for only 5% of total building energy use; but it offers cost-effective opportunities for efficiency increases in the short term. LED lighting offers energy savings of 10% to 70% depending on the application and baseline technology being replaced. It also facilitates dimming and other control technologies to better match energy use to lighting needs. Other consumer benefits, including longer life and reduced maintenance costs, are driving rapid increases in market share.

The market share of LED technology rose from 0.3% in 2010 to more than 40% in 2018 in one of the most rapid transformations ever recorded for a major product category. We estimate that this share will be 80% or more by 2030 under business-as-usual conditions.22

Private and public sector organizations are working to capture the full range of economic and environmental benefits offered by LED lighting. Advances in sensor, control, and information technology (IT) have sharply reduced the price and increased the capability of networked lighting controls. Sensors and controls are now built into many lighting fixtures and IT enables sophisticated automated and user-activated controls that greatly reduce lighting energy use. A recent evaluation of networked lighting controls in 114 buildings estimated energy savings at 47% of pre-retrofit lighting energy.23 In an example of LED promotion in a hard-to-reach market, an Indian government programme had replaced 14 million street lights and distributed some 347 million LED bulbs to homes by March 2019.

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**Increased control capabilities**

**Home automation and smart thermostats:** Independent evaluations estimate that smart thermostats, such as those manufactured by Nest and EcoBee, result in savings of 10% to 15% in home heating and cooling energy, or about 3% to 5% of total home energy use.\(^{24}\) They are selling briskly despite their cost (USD 250 per unit in the US); by early 2019, over 20 million had been sold in the US. If they were all installed, these sales would represent 15% saturation of all housing units for a product category introduced only in 2011. Sales of smart thermostats grow more slowly elsewhere; for example, saturation in Europe was an estimated 2.5% of homes in 2017. Thus, there is a great deal of room for growth.\(^{25}\)

Customers interviewed for the evaluations cited above valued non-energy benefits more than the energy savings they achieved. These other benefits included improved comfort, convenience in managing temperature setbacks using occupancy sensors, and alerts of malfunctioning equipment. Industry observers think explosive growth of smart speakers such as the Amazon Echo and Google Home Hub will further accelerate smart thermostat sales. This view rests on the increasing convenience of using voice commands, and on more functional links being established between thermostat sensors and other services such as home entertainment and security. Smart speakers are already installed in 10% to 30% of homes in North America and Europe, and sales are growing rapidly in all global regions.

**Integration of building controls and demand response:** The proliferation of smart thermostats and more complex building automation systems is enabling building owners to access value streams offered by demand response. Facility owners receive payment for load reduction, which is automatically controlled by power suppliers or aggregators, in response to signals from the grid. This accelerates return on investment in control technologies that also provide energy cost savings. This is an important example of ‘stacking’ (combining multiple benefits or revenue streams) values by applying digital control technology to create benefits for grid operators and facility owners through installing a single class of energy-efficiency measures. In 2018, these direct control technologies accounted for 27% of all enrolled demand-response resources in the US. More traditional appliance cycling programmes, an earlier form of direct control, accounted for an additional 20% of enrolled capacity. This approach to demand response is also growing in Australia, Europe and Japan.\(^{26}\)

We expect technological progress in sensors, communication and data processing to continue driving adoption of more advanced building controls. Regulatory and public sector action will be needed to ensure that solution providers and facility owners can monetize the full range of benefits from load management. These actions include the following:

- Broad implementation of time-differentiated electricity tariffs.
- Implementation of demand-response programmes, including extension of direct control to a broader range of end uses.
- Expansion of the range of energy products that can be served by demand response.

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Supporting policies and programmes

Building codes and zero-net energy:

Building codes have been one of the most effective levers for reducing energy use in the building sector. Buildings conforming with the most recent versions of the International Energy Conservation Code and ASHRAE 90.1 use roughly 25% less energy than comparable buildings built to codes in force 10 to 15 years prior. 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 EU 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 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 EUR 82–165/m² 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.

Governments worldwide have been moving in deliberate fashion to integrate ZNE principles into building codes. Prominent examples include the following:

- ZNE is required for new construction in homes in California, US, by 2020, and in commercial buildings by 2030. Regulatory change in 2016 has prepared the market by requiring more stringent thermal performance and installation of structural, electrical, and mechanical components to accommodate solar energy and battery storage.

- Japan’s road map for a low-carbon society includes the goal to incorporate ZNE principles into building codes by 2020.

- The Canadian province of British Columbia has a code moving construction practices significantly closer to ZNE principles.

Municipal Initiatives: Cities are playing leading roles in promoting energy efficiency in buildings. Local governments are harnessing their traditional powers including zoning, permitting, and other building regulation, assessment and collection of property taxes, and regulation of property transfer. The examples below highlight three such efforts.

New York, US: Since 2010, New York City has implemented laws requiring owners of large buildings to undertake energy audits, post the results to a public database, and undertake other activities to disclose energy consumption.

Mexico City, Mexico: The city’s Sustainable Buildings Certification Programme (SBCP) offers owners or tenants of residential, commercial and industrial buildings an opportunity to reduce and demonstrate the environmental impact of their properties.

Seoul, Republic of Korea: As part of its wider One Less Nuclear Power Plant energy policy, the Seoul Metropolitan Government has a programme to spur retrofitting in government, commercial and residential buildings. The core of the programme is a loan support scheme to support the uptake of technologies such as high-performance insulated windows and doors.

3.4.3 ENERGY DEMAND AND ENERGY EFFICIENCY IN INDUSTRY

Manufacturing sector energy demand

As the manufacturing sector is one of the three major users of energy (see Section 3.4.1), reducing its carbon footprint is a key climate action. Several methods that can help include the following.

1. Making the products using less energy, including:

   - **Process change**: redesigning manufacturing processes to be less energy intensive, heat recovery being a common example
   
   - **Technology change**: using equipment such as motors or boilers that are more energy efficient
   
   - **Product innovation**: for example, using raw materials, or producing products, that are less energy intensive. Different formulations of animal feed could be less energy intensive, as could producing ‘greener’ bricks in the ceramics sector

   - **Behaviour change**: operating equipment more efficiently and effectively.

2. **Changes in energy supply**: for example, electrification of manufacturing processes combined with greater use of renewables for electricity, shifting from coal to natural gas, using renewable power to produce hydrogen (as discussed in Section 3.5).

3. **Reducing demand for products**: measures for increased ‘material efficiency’ include longer-life products, circular-economy initiatives, and shifting buying behaviour.

Carbon capture, utilization and storage (CCUS) could also be an important option for certain high-emission sectors such as cement, iron and steel, refining and chemicals. This technology has been slow to commercialize due to the high costs of development. However, CCUS is likely to increasingly feature as a CO₂-reducing technology from the early 2030s.

Numerous international collaborations, such as Mission Innovation and the Carbon Sequestration Leadership Forum, provide further focus on this potentially important technology. The US Government is funding five American companies aiming to test their emerging CO₂ capture technologies at Technology Centre Mongstad, Norway, the world’s largest facility for testing and improving capture.

Demand for manufactured goods continues to rise, but more slowly than the rates of population or economic growth, as more economies are becoming dominated by service sectors. Continued improvement in material efficiency leads to a reduction in the ratio of base materials to manufactured goods. Combined with improved energy efficiency in manufacturing, this leads to manufacturing energy demand starting to decline from the late 2030s.
Supervisory control and data acquisition (SCADA) systems are the main mechanism for operating and controlling manufacturing plants. We predict that greater digitalization and data analytics combined with greater connectivity within the Industrial Internet of Things (IIOT) will lead to better data and control, more efficient production, and improved energy efficiency.

**Energy efficiency in manufacturing**

Our ETO Model’s prediction of a peak in energy demand in the 2030s rests partly on efficiency gains continuing to lower energy intensity of manufacturing processes.

Manufacturers have long made efforts to improve energy efficiency, reduce costs and improve competitive performance. Now though, increasing urgency to address climate change, coupled with demands for clean air, are leading to stronger political policies and regulations. These are driving and incentivizing manufacturers to achieve more. Article 8 of the EU Energy Efficiency Directive (2012/27/EU), which has been transposed into national legislation in all EU Member States, requires large enterprises (non-SMEs) to comply with the energy audit obligation. With this requirement, we are seeing greater awareness in the industry and increasing rigour in the auditing process. In the Middle East, there is also a greater drive for energy efficiency with power prices, and oil and gas prices, increasing, and states aiming to lower local consumption. Examples include Middle East companies like Al Ain Distribution Company (AADC) and Abu Dhabi Water and Electricity Company (ADWEC) looking to support their end customers to reduce demand by advising them on energy-efficiency measures.

Trends that we see in the manufacturing industry to improve efficiency and reduce carbon emissions are:

- **Alternative energy sources:** As discussed in Section 3.4.1, electrification of manufacturing is a major trend. Replacing fossil fuels with electrical energy addresses both the drive to improve energy efficiency and lower carbon emissions. In Greater China’s thirteenth five-year plan (running from 2016 to 2020) there is also a shift from using coal to combined heat and power (CHP). While CHP has less potential than electricity for reducing carbon emissions, it is a significant improvement.

- **Co-location:** There is an increasing trend, likely to be more applicable in future decades rather than the next five years, for co-location of industrial plant. Co-location provides the opportunity to design combined systems that are more efficient than the separate facilities, such as using the lower-temperature waste heat from steel production to warm greenhouses.

- **Process changes:** Review and revision of the manufacturing process can be one of the most cost-effective methods of achieving efficiency gains resulting in leaner, on-demand processes.

- **Raw materials sourcing:** There is an increasing trend to conduct broader assessment of the raw materials for a manufacturing process. One outcome may be to improve the efficiency of producing the raw materials; but in some cases, using alternative raw materials or alternative sources may have a greater impact on the efficiency and reduction in carbon emissions of the whole manufacturing process.

As mentioned previously the net effect of goods production rising but making use of increasingly efficient processes is for energy demand to decline from the late 2030s. However, demand for electricity for manufacturing is forecasted to almost double from 33 EJ in 2018 to 61 EJ in 2050.

**Supporting policies and programmes**

Energy Management Systems have been an important way for companies to better understand their energy demand and to use the data insights to reduce it. Since its release in 2011, the international standard on energy management, ISO 50001, has been taken up by companies in many markets, with over 21,000 certificates issued in 2017. Particularly strong is
Germany (8,317 certificates issued in 2017) where companies have enjoyed tax benefits on implementation of the standard. The German Government has been mandating implementation since 2014 for companies with energy demand over a certain amount. The UK has also had good uptake driven by companies expecting positive impacts on their energy costs. Some regions have seen very low take up, often due to cost or knowledge. For example, Canada issued only 17 certificates in 2017 despite incentives offering up to half the cost of implementation. Greater China had over 1,500 certificates issued that year, a relatively modest tally given its number of companies.

Carbon tax and/or Emissions Trading Schemes (ETSs) are now more widely implemented globally, with many more scheduled or under consideration, which will continue to help reduce industrial and power sector emissions. Greater China is piloting an ETS scheme led by the National Development and Reform Commission, which will cover three billion tonnes of CO₂ emissions (30% of Chinese national emissions).

As well as policy and market structures to help drive energy efficiency gains in the manufacturing sector, there is considerable investment from development banks. For example, the World Bank is committed to USD 200bn of funding between 2021 and 2025 to help emerging economies tackle climate change; a lot of it will go on driving energy efficiency.

**Demand-side response**

Industrial demand-side response (DSR) will play an increasingly important role to as the energy transition progresses, further details are provided in Section 3.2.

### 3.5 POWER-TO-GAS

Some 3% of global energy consumption today is used to produce hydrogen. Only 0.002% of this hydrogen, about 1,000 tonnes per annum, is used as an energy carrier. In our ETO Model the contribution of hydrogen as an energy carrier results in it meeting only 1.7% of total global energy demand by 2050; yet there is the potential for hydrogen to become a major clean energy carrier in a world struggling to limit global warming.

Decarbonization is the main driver for using hydrogen this way. Hydrogen can be an effective decarbonization agent if its production has a low-carbon footprint. Such hydrogen can heat buildings, fuel transport, provide heat to industry, and be a medium to capture the value from surplus power from renewables. Enabling and limiting factors for these applications include learning rates for technology, e.g. electrolysers and fuel cells; regional natural gas consumption; development of hydrogen-distribution infrastructure, such as pipelines and fuelling stations; and, uptake of CCS. The topics highlighted in the following paragraphs are those that could potentially be seen closer to 2050 and beyond, depending on the development of these enabling and limiting factors.

Several countries may see hydrogen-heated buildings as a good decarbonization option. Australia, Canada, the Netherlands, South Korea, UK and US are the most likely to adopt this at significant scale. These countries predominantly use gas for heating buildings, and have infrastructure that can be adapted to hydrogen distribution and storage. This application requires substantial policy push and public co-funding to materialize. Hydrogen use for industrial feedstock will keep going, but hydrogen will not see substantial scale for industrial process heating due to other decarbonization options being more

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28 Hydrogen is today used as an energy carrier only for mobility. According to h2tools.org/hyarc/hydrogen-consumption, there were about 10,000 active fuel-cell vehicles at end of Q3 2018, including 180 buses. Assuming an average fuel consumption of 100 kg hydrogen per vehicle per year, which may be a conservative assumption, this translates to 1,000 tonnes of hydrogen.
Main options for production, storage and transport of hydrogen

**HYDROGEN PRODUCTION OPTIONS**

- **Source**
  - Power + water (Green)
  - Natural gas (Blue)
  - Coal (Orange)
  - Biomass (Red)

- **Hydrogen Production**
  - Electrolysis (White)
  - Reforming (Yellow)
  - Gasification (Purple)
  - Gasification or biogas reforming (Blue)

- **Decarbonization Measure**
  - Low-carbon electricity (Green)
  - Carbon capture & storage (CCS) (Blue)
  - Carbon capture & storage (CCS) (Blue)
  - None = neutral
  - CCS = negative

**STORAGE AND TRANSPORTATION OPTIONS**

- **Storage Options**
  - Pipeline infrastructure (Green)
  - Subsurface gas storage (Blue)
  - Compressed hydrogen (Orange)
  - Liquid hydrogen (Red)
  - Ammonia (Yellow)
  - Liquid hydrogen (Green)

- **State of Transport and Storage**
  - Compressed hydrogen (White)
  - Cryogenic liquid hydrogen (Blue)
  - Ammonia (Orange)
  - Liquid organic hydrogen carrier (Green)

- **Transportation Options**
  - Pipeline (Green)
  - Truck (Blue)
  - Ship (Orange)
  - Rail or barge (Red)
mature and simpler. There will potentially be some hydrogen-fuelled heating in industries such as cement by 2050.

The power sector’s interaction with hydrogen is through the potential production of ‘green’ hydrogen by electrolysis using surplus renewable generation. In this scenario, electrolyzers operate intermittently in step with fluctuating power prices, and hydrogen storage is available for matching supply and demand. This may be one of the enablers for greater market penetration of renewables.

Using hydrogen for peak shaving in electricity systems may be viable in 2050. This requires large-scale storage of hydrogen and hydrogen power-generation systems that can be deployed on demand. However, the application has significant energy losses; each MWh of output power requires 3 MWh input power to the electrolyser. This implies that the number of hours during a year when hydrogen for peak shaving is cost effective is limited.

Cheaper green hydrogen and fuelling infrastructure could boost uptake of fuel-cell EVs. We expect a decline in the cost of green hydrogen and continued development of refuelling infrastructure to trigger broader uptake of fuel-cell EVs. We estimate that by 2050, almost 80% of hydrogen demand for mobility will be for buses, trucks and other long-range heavy vehicles.

3.6 DIGITALIZATION

‘Digitalization’ can be a poorly-defined term. It can be helpful conceptually to distinguish between ‘making things digital’ from ‘the opportunities created by making things digital’. In the power industry, for example, making operations and maintenance digital can involve enabling field personnel to collect data using tablet devices. The opportunities created by this may include automated operations based on models predicting component reliability by using the real-time data collected from the field.

In the context of this study, the important facets of this group of related concepts are as follows:

- Computers, both large-scale and small, ranging from distributed computing to the cloud, and which enable larger simulations; models such as ‘digital twins’ running in real time; and, edge computing where calculations are performed and decisions made at the edge of a network, close to where the data are collected.
- Connectivity, with improved communications allowing large numbers of devices to communicate seamlessly and robustly even if mobile, with multiple protocols.
- Sensors and data, with the proliferation of data resulting from a decreasing cost of sensors, some with substantial built-in intelligence and processing power.
- Software and advanced analytics, tools for understanding and making use of the large amounts of data, including machine learning and AI.

Digitalization is not an end in itself, but is a means to an end; an ‘enabler’. In the case of the power system, digitalization is the enabling of the decarbonization and decentralization referred to in previous chapters. These factors apply across the entire energy system from generation through transmission and distribution, and in end-users’ plant and machinery (Figure 3.18). 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. For example, the Cornwall Local Energy Market trial in the UK is testing the use of automation of flexible demand, generation and
storage for domestic and business power users. The overall objective is a more efficient and intelligent system where electricity demand and consumption are better matched to reduce transmission losses and remove the need for distribution network physical upgrades.²⁹

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. Importantly though, digitalization is enabling new business models, which threaten disruptive change to well-established industries.

Digitalization’s total impact is hard to quantify as it is widely spread throughout the energy system, but its influence will continue to grow. We see digital technologies and digitalization as key enablers of the transition to a low-carbon energy system. Stakeholders across the power system will be affected differently by digitalization, and the implications of this are discussed in Chapter 4.

²⁹ https://www.centrica.com/innovation/cornwall-local-energy-market

FIGURE 3.18

The impact of digital technologies across power supply and use stakeholders

Digital technologies will impact all stakeholders by making the power system more:

- CONNECTED
  - ENERGY SUPPLIERS & AGGREGATORS: Data sharing between asset owners, operators, regulators and investors enabling enhanced cooperation between stakeholders leading to a more connected energy system.
  - PROSUMERS & CONSUMERS: Increases data collection and communication, distributes control, allows greater empowerment.
  - DISTRIBUTION SYSTEM OPERATORS: Artificial intelligence and machine learning for automated scheduling of charging based on forecast usage, generation and distribution network usage leading to a more sustainable energy system.
  - POLICY MAKERS & REGULATORS: Blockchain for decentralized energy transactions, renewable energy provenance, metering and billing leading to a more intelligent energy system.

- INTELLIGENT
  - ENERGY SUPPLIERS & AGGREGATORS: Digital Twin for wind turbine remaining life calculations enabling operational decisions to be automated in response to grid signals leading to a more reliable energy system.
  - DISTRIBUTION SYSTEM OPERATORS: Drone and remote sensing (UAVs) for efficient solar park inspections leading to more efficient operations.
  - POLICY MAKERS & REGULATORS: Support further technology developments, requires new regulation.

- EFFICIENT
  - ENERGY SUPPLIERS & AGGREGATORS: Improves forecasting, lowers costs of monitoring and control, improves performance.
  - DISTRIBUTION SYSTEM OPERATORS: Provides new tools for balancing the system resulting in greater flexibility.

- RELIABLE
  - ENERGY SUPPLIERS & AGGREGATORS: Improves forecasting, lowers costs of monitoring and control, improves performance.
  - DISTRIBUTION SYSTEM OPERATORS: Provides new tools for balancing the system resulting in greater flexibility.

- SUSTAINABLE
  - ENERGY SUPPLIERS & AGGREGATORS: Improves forecasting, lowers costs of monitoring and control, improves performance.
  - DISTRIBUTION SYSTEM OPERATORS: Provides new tools for balancing the system resulting in greater flexibility.
CHAPTER 4

TAKEAWAYS FOR STAKEHOLDER GROUPS
4 TAKEAWAYS FOR STAKEHOLDER GROUPS

This section draws on Chapters 2 and 3 to provide insight on the implications for specific types of stakeholders.

4.1 GOVERNMENT/REGULATORS

For the power sector, the energy transition is dominated by the massive increase in generation from variable renewable sources. As this transition progresses and the levelized cost of energy from solar PV and wind continues to drop, there will be less dependency on government support to encourage investment in new renewable generation. Growth in subsidy-free renewables will be less policy driven and more market driven. However, policy and regulation will still play key roles in a successful transition to a low-carbon energy system.

Solar PV and wind power plants are capital intensive, so developers and investors seek stable long-term returns. Policymakers need to ensure that policies in the coming years are stable and apply over long-enough periods to give the market confidence to invest in the energy systems of the future. This principle also applies to investments in grid infrastructure and electrification of energy use.

As technological advances continue to accelerate, such as the improved efficiency of solar panels, better performance and lower cost of battery storage, and the proliferation of digitalization, policies have become ‘technology following’ rather than ‘technology leading’. Policymakers and regulators will need to regulate to stimulate efficient and effective markets for the latest technologies while continuing to safeguard life, property and the environment. This is a complex challenge, and we consider it to be an important takeaway from our projected energy transition.

Any solution will require a balanced ‘pull-push’ policy approach; for example, tax incentives for electric vehicles (‘pull’) complemented by funding the latest research into battery technology development (‘push’).

Our modelling predicts that the most likely energy transition is one which fails to meet the 2°C limit in the Paris Agreement. Policymakers and broader society will need to consider whether this is acceptable, or if greater efforts should be made to speed up the energy transition. For example, many areas of the world could get greater value from wind power by easing restrictions on wind-turbine tip heights, but at the risk of potentially greater visual impact. It will be up to governments to determine the balance between the ‘gain’ and ‘pain’ of potential changes. The energy transition will also require market regulation that gives sufficient recognition to the value of new and alternative solutions for our energy systems; for example, adding storage on the grid. Historically, use of the network has been bundled into electricity prices. In the energy transition, regulators will increasingly need to consider how markets can be structured to better capture the value of electrical energy at the place and time that it is used.

4.2 FINANCIERS

The finance community has acquired a good understanding of the opportunities and risks involved in the energy industry over decades. This understanding is being challenged as an energy transition involving a substantial shift
in the status quo will present a new range of opportunities and risks. The ETO’s most significant takeaway for financiers is the large scale of investment that will be needed to facilitate a successful transition. There will be substantial opportunity for investment in new generation, most notably solar PV and wind; new and upgraded grid infrastructure; and, in new applications in energy use.

Solar PV and wind have been attracting a variety of investors including, in more recent years, larger pools of low-cost capital such as pension funds. This has been catalysed by maturing technology and government subsidies reducing the revenue risk. Pension funds’ willingness to accept lower returns for lower-risk but longer-term investments has helped to reduce the cost of capital for the renewables industry, thereby reducing the levelized cost of energy.

Green bonds, such as those recently issued by TenneT, have been successful for raising finance for investment in renewables and associated grid connections (see text box). There will be a need to engineer new financial products to ensure an effective and efficient energy transition as it accelerates.

There will also be a need to streamline and in many cases, digitalize the transaction process in new infrastructure to cope with increasing investment in relatively diverse generation and grid infrastructure.

As well as the substantial investment opportunities, our ETO highlights risks that will need to be analysed and evaluated carefully. One risk is wholesale electricity price cannibalization for variable renewable generation; Section 3.1.1 covers this in detail.

The ETO also flags up the risk of stranded assets due to the clear shift away from using fossil fuels. It forecasts new coal- and gas-fired electricity generation capacity in some regions, and continued use of fossil fuels in manufacturing. Investment decisions for new fossil-fuel assets will need to carefully consider the life of these assets; will the drive for lower carbon emissions result in them becoming stranded assets?

With the support of five banks\(^a\), electricity transmission system operator (TSO) TenneT raised EUR 1.25 billion (bn) in May of this year (2019) to invest in green projects in the Netherlands and Germany. The TSO is to connect large-scale offshore wind to the onshore electricity grid.\(^b\) Over the next 10 years, it expects to invest EUR 35bn in offshore and onshore grid connections across the two countries, driving the energy transition. Approximately 80% of TenneT’s investments are related to renewables, such as wind and solar energy.

a: ABN AMRO, Barclays, HSBC, NatWest Markets and SMBC Nikko
4.3 RENEWABLES DEVELOPERS

The clear takeaway for renewable developers is the sheer scale of new renewable generation predicted to be operational over the coming decades. The timing and rate of growth vary between regions and technologies, but there are clear opportunities for substantial and sustained growth. We know from the support that we provide to the industry that developers often have to be agile, making the most of market opportunities, and reaching particular milestones to qualify for support mechanisms. With the continued growth in renewables, developers will continue to work swiftly, streamlining their processes to make the most of the opportunities. However, as renewables become more widespread and enter a subsidy-free phase, developers will need greater understanding of electricity market opportunities and risks. They will also need to assess alternative approaches to maximize the value of their developments, such as incorporating storage into their projects.

It is worth repeating here that the risk of price cannibalization (see Section 3.1.1) is a source of uncertainty about the revenue stream for renewables projects. Renewables developers will need to ensure that they understand how this may impact their development projects, where and when it may be most prevalent, and how it might be mitigated. Long-term corporate power price purchase agreements (PPAs) sharing risk with other parties could be one mitigation strategy.

With increasing renewables generation, developers will also need to consider how their own project adds value to the broader energy system. For example, if most solar projects are being built in a concentrated area, then there is potentially value in developing elsewhere. Even if the average resource may be lower in an alternative location, the value of generating where (and when) others are not may outweigh the lower average generation.

While the energy transition has positive climate effects, the shift requires wind farms and solar parks in new areas. Their spatial footprint will provoke ‘not-in-my-backyard’ protests, which renewables developers will increasingly need to address. There will also be a level of competition with other sectors for some locations. We have already seen some shipping lanes adjusted to accommodate new offshore wind farms.\(^\text{30}\)

4.4 RENEWABLES MANUFACTURERS

There are clear growth opportunities for the renewables manufacturing sector. Substantial investment in R&D and manufacturing capacity will need to continue to achieve the improved energy capture, lower costs and increased supply of products that the market will require. With the increasing drive for a lower carbon economy and lower levelized cost of energy, renewables manufacturers will need to give greater consideration to the life of their products, designing for longer life and recycling at the end of life. Manufacturing processes will also need to be developed to make best use of recycled material.

They will have to evaluate the supply of critical raw material as the volume of products increases. As prices of products such as solar modules continue to drop, transportation becomes a larger percentage of the cost of the final delivered product; manufacturers will increasingly need to assess where plant is located relative to demand.
4.5 POWER COMPONENT MANUFACTURERS

The growth in demand for electricity around the world will require new generation, substantial investment in grid infrastructure, new electric vehicle charging infrastructure and more electrification of homes, offices and industry. The investment in the grid will be necessary not only to manage the increased flow of energy, but also the shift in where and when that energy is flowing. For power component manufacturers, this will result in opportunities to provide more equipment to more customers around the world. Many such customers will not previously have had to devote much attention to their electricity use, or to what benefits electrification can bring. Power component manufacturers will need to reach out to these new customers to better understand their needs and, and to work with them to help achieve a successful energy transition.

The specification and design of grid components will change as the requirement of power systems of the future diverge from those of the past. For example, power component manufacturers will need to plan for new components potentially being designed for thermal performance rather than to withstand a short circuit.

Greater consideration will also need to be given to how future components are designed to maximize the value of digitalization in the energy sector, providing better data capture and management, decentralized power management, and improved cyber security. Digitalization assists the move towards more active operation of distribution networks instead of the ‘fit and forget’ principles of the past.

Manufacturers of batteries will need to also assess their ability to meet the level of demand, particularly from EVs, and give further consideration to their supply chains and the risk of exposure to decreasing availability of critical raw materials, such as cobalt.

The rise of renewables is driving the development of grid-connected storage. Independent testing and verification of energy storage systems help manufacturers build user confidence in performance, safety and reliability.
4.6 UTILITIES AND INDEPENDENT POWER PRODUCERS

In this section, we refer to utilities and independent power producers (IPPs) largely from the perspective of them owning generation. Section 4.7 below includes energy suppliers, covering the delivery of that generation to consumers. We appreciate that many utilities around the world both own generation and supply to consumers, but we have made some separation to discuss the ETO’s takeaways.

We also recognize that ‘utility’ is commonly used in North America and elsewhere to describe private or publicly-owned entities that are publicly-regulated, 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.

For owners of generation, the ETO’s first key takeaway is consideration of how their portfolio of assets will grow and change over the coming decades to meet the increasing demand for electricity and the needs of society to drastically reduce carbon emissions. In the near term, there is a risk that coal assets will become stranded, particularly in Europe and North America, where the shift away from coal is swift. Further into the future, the risk of price cannibalization, as discussed earlier in this section and in Section 3.1.1, will also need evaluating by utilities and IPPs.

Although the ETO Model shows substantial growth in installed capacity of solar PV and wind, many utilities and IPPs will already have variable renewables in their operational portfolio. The drive for a lower-carbon future, as well as commercial drivers, will require owners of these plants to also assess how to maximize the value of their ageing wind and solar PV assets through options such as life extension or repowering.

In operating their generation portfolios there will be a growing need to provide value to a system with increasing variability. For coal-fired power plants, this results in reduced utilization due to it being uneconomical to run the plant during periods of lower power price. The periods will be more frequent when low-margin solar PV and wind plants are generating. The consequence for many ageing coal-fired plants in more developed regions is that operational costs increase as they run less efficiently at low utilization, leading to an acceleration towards decommissioning.

For variable renewables and other generating plant such as gas, the utilities and IPPs will need to maximize opportunities from advances in digital technology bringing larger volumes of better quality information about market conditions and the performance of generation portfolios. It will allow them to optimize operations for maximum profit. Operators will make more use of automated processes, potentially linking generation and flexibility options to create virtual power plants providing greater value to the market.
4.7 ENERGY SUPPLIERS AND AGGREGATORS

Complex arrangements involving both energy suppliers and aggregators may emerge in liberalized markets. 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, suppliers take the role of aggregators, making it difficult to see differences in how the energy transition impacts on the two business models.

The transition will present opportunities for both. Greater electrification, particularly EVs, will mean suppliers selling more energy and participating in an entirely new market. For aggregators, the growth in renewables will boost demand for flexibility services.

The proliferation of EVs shown in the ETO, and the related opportunities, are a takeaway combining growth in electrical demand and the increased requirement for flexibility. Many suppliers are already aware of this and some major players among them have moved early to acquire operators of charging points for EVs. The vehicle-to-grid services that can be provided from the growing number of EVs with increasingly powerful batteries is likely to be a valuable aspect of the efficient integration of variable renewables. Suppliers and aggregators will need to understand the needs of this new customer base and maximize the value that will be enabled by the increasingly smart, connected vehicles and charging infrastructure.

Greater demand for flexibility services in the energy transition, combined with ever-smarter technology, will result in aggregators being able to tailor services for smaller and smaller groups. This ability, combined with continued reduction in the cost of solar PV modules and battery storage, will mean suppliers and aggregators having to rethink some of their business models, such as providing Energy-as-a-Service (EaaS) rather than simply selling kilowatt hours. For example, the service could be to provide a comfortable room temperature, solar PV on the roof, a battery in the basement, and charging for your EV whenever and wherever it is needed, all of it managed by the energy service provider for a simple monthly fee.
4.8 TRANSMISSION AND DISTRIBUTION
SYSTEM OPERATORS

The ETO predicts that electricity’s share in total energy demand will rise from 19% currently to more than 40% by 2050, and highlights shifts in how that power will be generated. This future poses significant challenges for transmission system operators and distribution system operators (TSOs and DSOs), who will need to expand, reinforce and upgrade the grid to ensure its reliability. The expansion of the transmission system is most notable in new high-voltage alternating current (HVAC) overhead lines, largely in Greater China and the Indian Subcontinent, but impacting all regions. The need for higher degrees of interconnections including HVDC technology leads to extremely large capex programmes. For DSOs, extension of their systems and improved reliability in developing regions will be part of the energy transition; in developed regions, network reinforcement will be required for increasing electrification of energy use.

Investment in grid infrastructure is inherently long-term and needs to be planned sufficiently in advance. Solar PV and wind generation is being developed and deployed faster than the large-scale centralized thermal generation of the past, and EV charging loads can appear extremely quickly in hotspots. The ETO Model shows these trends are set to accelerate over the coming decades. TSOs and DSOs will thus need to accelerate their planning and deployment processes to facilitate an efficient and effective energy transition. Where the investment in the grid is placed will be key to these processes. Some of the ETO’s regional results can help to guide location decisions that will also require more localized modelling and grid studies before planning deployment.

Electricity transmission and distribution systems will experience much greater variations in power flows, and more extremes of high usage and low usage, including periods of reverse flow in distribution systems. Planning upgrades to cope with this is an important takeaway for system operators. One of the solutions for DSOs will come in the form of non-wire alternatives; for example, utilizing storage to cope with peak power usage may delay or avoid an upgrade. New infrastructure will also be needed to cope with potential problems from harmonic currents due to larger volumes of demand and generation being converter-connected.

Digitalization will significantly impact the automation of power grids; from smart metering and associated technologies, to the observability and controllability of lower-voltage grid levels and intelligent (digital) substations. This automated control will reduce communication network traffic as signals are processed locally, and will improve constraint mitigation as network violations are resolved locally.

As well as planning for greater digital applications, TSOs and DSOs will also need to consider the cyber security implications. The most secure system is an isolated one (e.g. ‘islanded’). In contrast, digitalization promotes the interconnection of sensors and systems. The enactment of cyber-security laws for critical infrastructure in the energy industry could potentially slow the progress of digital initiatives.
4.9 CORPORATE ENERGY USERS

For corporate energy users, our ETO highlights the continued need to strive for more energy-efficient and low-carbon options. As discussed in Section 3.4.2, energy efficiency is a low-cost, readily available method of reducing carbon emissions; however, its current implementation is far lower than expected. There is also evidence of a clear trend for society and governments to be pushing for and setting zero-net carbon and ‘cleaner city’ targets. This means that corporate energy users will need to assess how they can comply with, and benefit from, changing policies and regulations, such as keeping a close eye on tax incentives to move away from fossil fuels.

Greater use of electricity will be part of the solution to achieving these targets for buildings and manufacturing. Corporate energy users can take away the fact that a growing number of technical solutions are becoming available, such as heat pumps for space heating, and electric arc furnaces for manufacturing. The consequent increase in electrical demand from corporate energy users also means there will be value in closer evaluation of future power prices.

Lower-cost renewables will help to keep power prices down, though greater variability is likely. While corporate energy users will need to manage this variability, it presents them with opportunities to provide increased value to power markets through demand-side response. It will also allow them to participate further in power markets by investing in local generation and storage.

Our ETO Model predicts that electricity use for heating and cooling in residential and commercial buildings will almost double between 2018 and 2050. Advances in technologies such as heat pumps will result in heating (space and water) and cooling being increasingly provided by these efficient devices over the coming decades.
5 THE NEXT FIVE YEARS

The ETO Model makes forecasts based on our assumptions about long-term trends. This section identifies trends that are likely to have a greater impact on the power sector over the next five years.

USE OF POWER

In the next five years, there will be a significant acceleration in the electrification of transport, in particular light vehicles and city buses. This will be led by Greater China, OCED Pacific, Europe and North America. Other regions such as Sub-Saharan Africa will hardly be impacted by electric vehicles (EVs) in this period.

The EV revolution will have a significant impact on the broader energy transition as society moves away from reliance on fossil fuels to a cleaner sustainable energy system. For the power sector, it will be one of the main drivers behind increased demand for electrical energy. In our ETO Model, EVs also play an important role in the integration of variable renewable generation due to the flexibility that will be available from smart charging and vehicle-to-grid (V2G) services. The impacts of EVs on both demand for power and the efficient integration of renewables generation underscore the importance of monitoring how electrification of transport develops by 2025.

As highlighted in Section 3.4.2, energy consumption in buildings could be reduced by 30%-40% in the OECD and other major economies by using already proven technologies. It seems likely that these will be applied over the next five years to boost the energy efficiency of equipment and electrification of end use, and to better control energy use. Building codes and regulations allied with innovative incentive and financing schemes will be key drivers of this.

While there are opportunities for the electrification of heat to improve energy efficiency and reduce carbon emissions in manufacturing, we do not see this having a significant impact on the ETO over the next five years. This is due to relatively substantial investment in existing equipment, which is only likely to be replaced with electrical options once it is close to the end of its life, which can often be 40 years.

THE GRID

New business models will be required in the midterm. System operators, utilities and electricity markets must provide greater focus on how the increasing volume of renewable energy is to be integrated efficiently while maintaining high levels of grid reliability for consumers. This will have a profound effect on markets with variable renewable energy contributing more than a quarter of the energy mix. Over the next five years, this will result in more flexibility options, new markets for local ancillary services, V2G and other behind-the-meter services.31

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31 Behind-the-meter services: the generation, or change in use of power, potentially combined with storage, by end consumers in order to provide services to the grid. Services from multiple consumers are often aggregated.
Large investments in network extensions will be driven mainly by renewable energy integration, interconnection and electrification. With an increasing share of renewables, operation of the system becomes more and more complex, which will result in grid operators investing in improved control room functionality for renewables. New platforms are needed to satisfy the increased information exchange between market participants for reliable system operation. Investment will start to be made in newer technologies, such as high-voltage direct current (HVDC) electric power transmission systems and for deploying alternating current / direct current (AC/DC) hybrid grids. We anticipate more interconnectors between larger market areas, creating ‘supergrids’.

We expect a greater focus on digital solutions for the grid, including data-driven asset management systems and greater use of autonomous risk-based strategies for grid management. We will see significantly higher levels of monitoring and analysis of primary equipment, leading to more sophisticated condition monitoring and lifetime consumption predictions. There will be more sophisticated supervisory control and data acquisition (SCADA) systems; greater autonomy of decentralized generation and grid operation; and, further integration of IT and OT (operational technology).

**GENERATION**

Coal generation in Europe and North America will drop significantly over the next five years, to approximately 30% and 16% of today’s levels respectively. While this trend is not predicted for other regions, it needs monitoring over the coming years to assess whether coal will decline earlier than predicted in these geographies; political will and technological advances will be the deciding factors.

The installed capacity of solar PV and wind plants will more than double in five years, from 1040 GW currently to 2450 GW in 2024. Government policies will continue to shift incentives from fossil fuels to low-carbon generation. Technologies will keep getting better and cheaper, leading to a reduced...
levelized cost of energy (LCOE). Lower LCOE will result in an increasing number of subsidy-free renewables projects, which will be a tipping point for accelerated growth of renewables.

Increased installation of variable renewables will bring an associated rise in the application of flexibility options over the coming five years. These options will include adjusting gas generation; demand-side response; storage; and, potentially, curtailment of solar PV and wind output. As costs of solar PV and battery storage continue to fall, they will be increasingly installed together. This may prove a very effective solution to managing daily fluctuations in solar generation for more rural areas.

**CLIMATE**

The world has been aware of debate on climate change for decades. “Global climate disruption is the biggest threat to our future,” Al Gore, former U.S. vice president in 1997 as he presents a speech on global warming and climate change. The focus of the international community on global warming has steadily risen along with the growing consensus among scientists and increasing coverage in the media. “Right now, we are facing a man-made disaster of global scale. Our greatest threat in thousands of years. Climate change. If we don’t take action, the collapse of our civilizations and the extinction of much of the natural world is on the horizon,” Sir David Attenborough, broadcaster and natural historian, speech at the 2018 UN Climate Change Conference, Katowice, Poland. This increased awareness and attention from society has led to many declaring that we are now in a ‘climate emergency’.

Our ETO modelling predicts that the average global temperature is most likely to be 2.4°C above pre-industrial levels by the end of the century. This is based on current knowledge and trends, combined with projections of key drivers such as population, economic growth and technological advances.

This level of warming is considered to be associated with “very high risks of severe impacts” by the IPCC (IPCC, 2014a) and the scientific community.

What can be done to close the gap between our most likely forecast of 2.4°C down to 1.5°C? There is no silver bullet. We do believe however, that a combination of measures can get us there. One such combination for the decade ahead includes ten-fold growth of solar power increasing to 5 terawatts (TW) and a five-fold increase in wind power to 3 TW. Fifty million electrical vehicles (EVs) per year will be needed, requiring a 50-fold increase in batteries, and large-scale charging infrastructure. We also see the need for: annual investments in the region of $1.5tn for the expansion and reinforcement of power grids including ultra-high voltage transmission networks; annual improvements in global energy intensity (the energy use per unit of output) by 3.5%; increased application of CCS; and low- and zero-carbon hydrogen to heat buildings and industry, fuel transport and capture value from surplus renewables.

If the world is to avoid dangerous warming, policy must develop to tackle at least three fronts simultaneously: more efficiency, more renewables, and industrial-scale CCS. ‘Closing the gap’ is covered in more detail in Chapter 8 of our main report.

The power sector is intrinsically linked to governmental policies. Societal and political thinking and responses to climate change will consequently have a significant impact on how the power sector develops. Within the next five years we will know whether national governments have successfully acted in global interests, or focused too much on protecting national interests. We may see populist movements force governments to move faster on global issues than they currently intend. We will be closely monitoring climate change developments, policies, regulation, opinions, and consequences for energy industries including power generation and use over the next five years and beyond.
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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 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 2017) numerical data is mainly based on IEA data from World Energy Balances © OECD/IEA 2018, www.iea.org/statistics, License: www.iea.org/t_c; as modified by DNV GL.

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ENERGY TRANSITION OUTLOOK
Our main publication details our model-based forecast of the world’s energy system through to 2050. It gives our independent view of what we consider the most likely trajectory of the coming energy transition, covering:

- The DNV GL Model and our main assumptions; on population, productivity, technology, costs and the role of governments and policy
- The global energy demand for transport, buildings and manufacturing, the changing energy mix, energy efficiency and expenditures
- Detailed regional energy outlooks
- The climate implications of our outlook and an assessment of how to close the gap to well below 2°C

POWER SUPPLY AND USE
This report presents implications of our energy forecast to 2050 for key stakeholders involved in electricity generation, including renewables; electricity transmission and distribution; and energy use. Amidst electricity use increasing rapidly and production becoming dominated by renewables, the report details important industry implications. These include:

- Substantial opportunities for those parties involved in solar and wind generation
- Massive expansion and reinforcement of transmission and distribution networks
- Further need for implementation of energy efficiency technology
- Acceleration of the electric vehicle revolution
- The energy transition is fast, but not fast enough to meet the goals of the Paris Agreement
OIL AND GAS
Our Oil and Gas report discusses how these hydrocarbons remain key to the secure supply of affordable energy up to 2050. Key features include:

- Gas becomes the primary energy source from the mid-2020s as oil and gas companies decarbonize portfolios and gas increasingly complements variable renewables
- Gas demand growth plateaus in 2033 but it remains the dominant primary energy source, supplying 29% in mid-century. New sources of gas (e.g. biogas, hydrogen and synthetic methane) are will be introduced to domestic and commercial energy systems, helping to decarbonize gas consumption
- Oil supplies 17% of primary energy in 2050, despite oil demand peaking in the mid-2020s
- A need for greater efficiency and investment in new oil and gas production are indicated

MARITIME
This year’s Maritime Forecast zeroes in on the IMO strategy to reduce greenhouse gas emissions. New fuels, and energy-efficient design and operation, are key to this. We detail:

- New ‘barometers’ indicating world-fleet decarbonization and readiness of alternative fuels
- Uptake and characteristics of relevant technologies, i.e. dual-fuel engines, fuel cells, and battery electric power
- How fuel flexibility and bridging technologies can smooth transition from traditional fuels
- CO₂ emissions and which fuels are likely to be in the mix towards 2050
- A new multi-scenario approach for robust newbuilding strategy based on our expanded concept of future-proof ships
DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. Operating in more than 100 countries, our professionals are dedicated to helping customers in the maritime, oil & gas, power and renewables and other industries to make the world safer, smarter and greener.

DNV GL delivers world-renowned testing, certification 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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