# RENEWABLES, POWER AND ENERGY USE FORECAST TO 2050

Energy Transition Outlook 2017

SAFER, SMARTER, GREENER

# FOREWORD

**DITLEV ENGEL**
**CEO**
**DNV GL – ENERGY**

Our model of the world energy system up to 2050 shows that a cleaner, more electrified world is within our reach. By mid-century, the world will run much more on electricity as its share in total energy supply rises to 40% compared with 18% today. 72% of electricity will be from wind turbines and solar panels, as producing power from wind and sunlight becomes cheaper than burning fossil fuels. However, our findings also flash a red warning light over global warming. In our outlook, we forecast that the average global temperature will rise by 2.5 degrees Celsius compared with pre-industrial levels before the end of the century, significantly beyond the Paris Agreement's least ambitious target to limit warming to 'well below 2°C'.

Consequently, we call upon the energy sector, and all relevant industries and stakeholders, to take responsibility and act now to ensure that the transition will be rapid and global. Our report – part of DNV GL's series of energy transition outlooks – shows that the energy industry, more than any other, has the power and knowledge to flip the current warning light from red to green. The report provides fact-based evidence and new insights to help accelerate much-needed change in our sector. Public and private organizations involved in energy supply, wind, solar, transmission, distribution, storage and energy efficiency can use this evidence to speed up the transition.

The energy transition will profoundly affect society everywhere and at many different levels. We predict massive growth of offshore wind in China and the US to outstrip Europe in the 2020s, for example. Communities blighted by energy poverty might jump straight to renewables-only local networks with storage, without needing to wait for connections to large, expensive, distant grids.

Our report concludes that no single action will guarantee a clean, electrified world by 2050. Getting there will take multiple actions from global through to local level, involving collaboration within the energy sector and across industries and borders.
In my view, we need to stimulate the adoption of renewable energy by enabling much faster growth of solar, wind, and in particular

offshore wind. We must leverage the cost and efficiency benefits of digitalization, and develop cyber-secure grids with the necessary flexibility, balancing and storage solutions to enable the rapid growth of renewables. We should further invest in and promote electrical vehicles and electrification of heat, and save energy at home and in businesses. Ultimately, regulation, subsidies and political initiatives need to shape consumer behaviour as public acceptance of the transition is a key to the future.

The energy industry must adopt new technologies, business models and drive down costs, but also regulators and politicians should embrace the clean energy agenda at the highest decision-making levels. Together, we can put the brakes on global warming and thereby limit the global temperature increase to below 2°C. I cannot think of anything more important right now for all of us.

This report arms all relevant sectors with a wealth of factual ammunition to act now, adapt strategies, and be bold in making evidence-based decisions to transform energy systems and improve prospects for all societies and people. We hope you recognize the importance of this transition as much as we do, and the roles we all must play. I invite you to start the dialogue today.

**DITLEV ENGEL**

> No single action will guarantee a cleaner, more electrified world by 2050. Getting there will take multiple actions from global through to local level, involving collaboration within the energy sector and across industries and borders

# ACKNOWLEDGEMENTS

**We wish to thank the wide range of experts from industry and academia for reviewing early drafts of this report. Their comments and suggestions have been of great value, and any remaining errors and inelegancies remain our own.**

**Our external collaborators include:**

**CARLOS SALLÉ ALONSO**
IBERDROLA

**ANDREW GARRAD**
FORMER PRESIDENT
AND CEO OF GL GARRAD HASSAN

**CHRISTOPH GRÄFE**
EURELECTRIC

**ODD HÅKON HOELSÆTER**
HAFSLUND ASA

**NINA SKORUPSKA**
RENEWABLE ENERGY ASSOCIATION, UK

**GRY JOHANNE ÅMODT**
STATKRAFT

**This report has been prepared by DNV GL as a cross-disciplinary exercise between DNV GL's Energy business area and a core research team in our central R&D unit, including:**

**DNV GL – Group Technology and Research:**
Kjersti Aalbu, Jørg Aarnes, Sverre Alvik, Bent Erik Bakken, Theo Bosma, Ervin Bossanyi, Hendrik Brinks, Christos Chryssakis, Caroline Brun Ellefsen, Anne Louise Koefoed, Onur Özgün, Asun St.Clair, Bjørn Johan Vartdal.

**DNV GL – Energy:** Leo Akkerman, Carlos Albero, Lucy Craig, Marcel Cremers, Gerben Dekker, Juan José Díaz Gonzáles, Erik Dugstad, Matthew Freeman, Paul Gardner, Jonathan Farland, Guro Fasting, Matthew Fitzgerald, Tom Geurink, Bart in 't Groen, Christian Hewicker, Gunnar Heymann, Johan Holstein, Raymond Hudson, Peter Lindersen, Ronald Meijer, Paul Noble, Tim Pohlenz, Robert Ramirez, Rob Rawlinson-Smith, Rubén Ron, Mitchell Rosenberg, Paula Schulze, Kamal Soundararajan, Jason Symonds, Peter Vaessen, Wim van der Veen, Ulrika Wising, Patrick Wolbers.

**HISTORICAL DATA:**

# CONTENTS

# 1

# EXECUTIVE SUMMARY

# 1. EXECUTIVE SUMMARY

## An era of abundant and cleaner energy lies ahead of us, according to DNV GL's modelling of the world energy system.

Three global themes emerging over our model's forecasting period are most relevant for this report on its implications for renewables, power, and energy use:

— Final energy demand plateaus around 2030 at 430 exajoules (EJ), 7% higher than in 2015, due mainly to greater efficiency of end-users, less use of fossil fuels at relatively low thermal efficiency, and slower population and productivity growth.

— Electricity consumption increases by 140% and it becomes the largest energy carrier[1], followed by gas. Other energy carriers, such as coal and oil, experience significant reductions or only slight increases in consumption.

— Electricity production becomes dominated by renewables – Solar photovoltaic (PV), onshore wind, hydropower, and offshore wind, in that order. Already mainstream today in many countries, these renewables together will account for 85% of global electricity production in 2050.

### MAIN IMPLICATIONS

These three main themes and many others stemming from the model's results reveal a host of implications – some immediately apparent, others not so obvious – for stakeholders across the energy value chain and for consumers, law makers and regulators. It is clear, for example, that sweeping change will come to the way in which the extensive and sophisticated power grids of industrialized nations are set up and operated, and to who can access them to buy or sell electricity. Here, we summarize some of the main implications in brief before discussing them more fully later in this report.

### 1. GROWTH IN GLOBAL ENERGY DEMAND CEASES WITHIN 15 YEARS

Realizing that future growth is not guaranteed, market participants will switch from expansion-led to defensive behaviour. In sectors set to slow or shrink, big players will seek to diversify into predicted growth sectors: a strategy already visible in renewables and electricity supply, where oil and gas majors are shifting their focus into renewables.

1 i.e. for final consumer demand; at the point of consumption

## 2. ELECTRICITY GENERATION WILL GROW

While global electricity consumption will increase slightly faster than recent trends, the average rate will mask sharper change in individual countries and specific locations. These include areas with rapidly expanding residential solar and/or electric vehicles (EVs), and where major thermal generators are closed. This will create challenges for electricity network operators, regulators, and governments. Such challenges are already being addressed in areas where renewables are important generators.

As consumer-scale technologies such as PV and EVs become cost-competitive without subsidies, governments will lose the ability to control rates of deployment. Change can then become rapid, and may also be derived from increased electric heating and better energy management systems for buildings.

Network operators will modify the way in which they analyse their systems and will pay greater attention to what is connected to them. There will be a need for changes to regulations governing use of and connection to electricity networks, and charging. This will pose a political conundrum: should changes apply across user classes, only in areas where a problem exists, or only to those deemed to be responsible for creating the conditions that demand change? Grids will cease to be operated in the way they have been since their inception. This trend has already started.

Increased monitoring and automation of networks is a clear response. Very high levels of cyber security will be needed. If hackers successfully attack them, severe economic loss could result. Electricity networks may be vulnerable because they are spread across extensive territories, serve huge numbers of end-points, and use equipment from multiple suppliers, with items being added or modified daily.

Changing demands on electricity networks will occur faster and less predictably than in the past. Network planning will no longer be treated deterministically, even on lower-voltage distribution systems. This shift requires new tools, and favours technologies that can be installed quickly, such as protection upgrades, dynamic rating and, perhaps, relocatable battery storage. »

### 3. ELECTRICITY SUPPLY BECOMES DOMINATED BY VARIABLE RENEWABLES

The very large increases in PV and wind capacity and production do not appear to introduce any insuperable new issues in order to maintain secure electricity systems. Such major penetration is beginning to take place in various European grids, and the system operators have shown themselves capable of addressing problems. As penetration increases further, so will innovation.

There is no experience of managing electricity systems in circumstances envisaged in the later stages of the forecasting period. However, potential solutions already exist and others are expected to be developed. New business models will also develop to cover variability of demand and renewable energy generation. They will present opportunities for new players: local governments, housing authorities, equipment suppliers, industrial users and possibly EV suppliers.

### 4. THE LINK TO HEAT SUPPLY

Variability is less challenging in regions of lower seasonal variation in renewables supply; typically, regions close to the Equator with PV resource, where variations occur mainly on a daily timescale. Higher latitudes with a substantial wind contribution face the challenge of smoothing production over months. Under conventional market conditions, investors in wind generation will risk substantial periods of low or zero prices for electricity.

Electricity can be coupled with other energy networks that either store heat directly, or produce transportable hydrogen or methane: both provide opportunities for substantial seasonal energy storage. These options are expensive, but in a future when heat must be decarbonized, the current fossil-fuel options for heating will be unavailable. Governments may therefore have to justify heat supply becoming significantly more expensive. They already face decisions about decarbonizing heat, which involve very large and long-term investments in gas or heat supply infrastructure. Integration with renewables-dominated electricity supply adds further variables.

### 5. CONSOLIDATION FOR THERMAL

Electricity production from nuclear and natural gas changes only slowly over the forecasting period, indicating that robust industries will likely continue, doubtless with some consolidation.

Our model does not suggest a 'nuclear renaissance' or a 'shift to gas'. However, and particularly for nuclear, energy security and industrial policy issues may take precedence over cost. These decisions are not represented in our modelling.

### 6. GROWTH RATES FOR RENEWABLES

For both wind and PV, forecast growth depends strongly on continuing cost-reduction trends. This implies further technology developments, and substantial learning by doing.

The model's forecast of short-term growth in renewable generation, particularly offshore wind, reflects the fact that these technologies are now already cost competitive with thermal generation. As the relevant stakeholders across the globe wake up to this new reality, installation rates are likely to accelerate. In the short-term, 10-year horizon, it must be noted that our forecast implies rapid changes – for example, in regulation and in the supply chain, especially in new markets – to reach the predicted installation rates, particularly for offshore wind. Hydropower shows less dramatic but continuing growth into the 2030s.

### 7. PROJECT SIZE AND INVESTMENT

Large transmission network projects will likely increase in number, thereby continuing the trend of connecting new centres of high energy demand with locations of significant generating capacity, including large renewables plants, sometimes a great distance away. These developments will include extended and strengthened transnational and national electricity interconnectors in regions such as Europe and Asia.

At the other end of the scale, much new generating capacity may be 'behind the meter', particularly for PV, producing power for on-site use at home or in business premises. Even on industrial or commercial sites, generating capacity per site may be no greater than several hundred kilowatts.

The results of our modelling have important implications for investors. Portfolios of network projects, some as small as residential installations, could become more significant than single large projects. Investment horizons will reduce from the 12 to 20 years currently deemed appropriate. This change will also be seen in investments at residential, commercial and industrial scale, such as battery storage, or energy efficiency measures.

## CRITICAL WATERSHED

The entire electricity industry and its supporting infrastructure have reached a critical watershed, and dramatic changes are in progress. The next few years will be the last in which grids in industrialized nations are organized and operated in the same way as they have been for recent decades. Electricity will increasingly be generated by different means, predominantly from renewables, and across all generation scales from massive offshore wind farms to domestic rooftop PV. New owners, users and traders will spring up, and the EV revolution is just about to start. By the end of our forecast period in 2050, the electricity system, its culture, and its personnel will be unrecognizable. Engineers, regulators, governments, business management, and C-suites will need to rise to this challenge. ■

> New owners, users and traders will spring up, and the EV revolution is just about to start

# 2

# INTRODUCTION

# 2. INTRODUCTION

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

Around 70% of our business is energy-related. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil and gas, and the power and renewable energy industries. We also provide certification services to customers across a wide range of industries.

As independent energy experts, we see it as our responsibility to forecast to our customers and stakeholders what the world's energy future will look like and how the transition will unfold. We share our foresight on supply and demand trends and our high-level analysis of these.

This publication is one part of DNV GL's new suite of energy transition outlook (ETO) reports. When taken together, the four publications provide predictions through to 2050 for the entire world energy system and 10 global regions.

The outlooks are based on our own model of the world's energy systems, which tracks and forecasts regional energy demand and supply as well as energy transport between regions. Key demand sectors such as buildings, manufacturing and transportation (road, air, rail and maritime) are analysed in detail.

Alongside the company's main outlook report[2], the suite includes reports discussing implications for separate industries in which DNV GL is an important stakeholder: oil and gas[3]; renewables, power, and energy use (this document)[4]; and maritime[5].

Our core ETO model employs system dynamics feedback and is implemented with the Stella modelling tool. In a crowded field of energy forecasting, we seek to create value through:

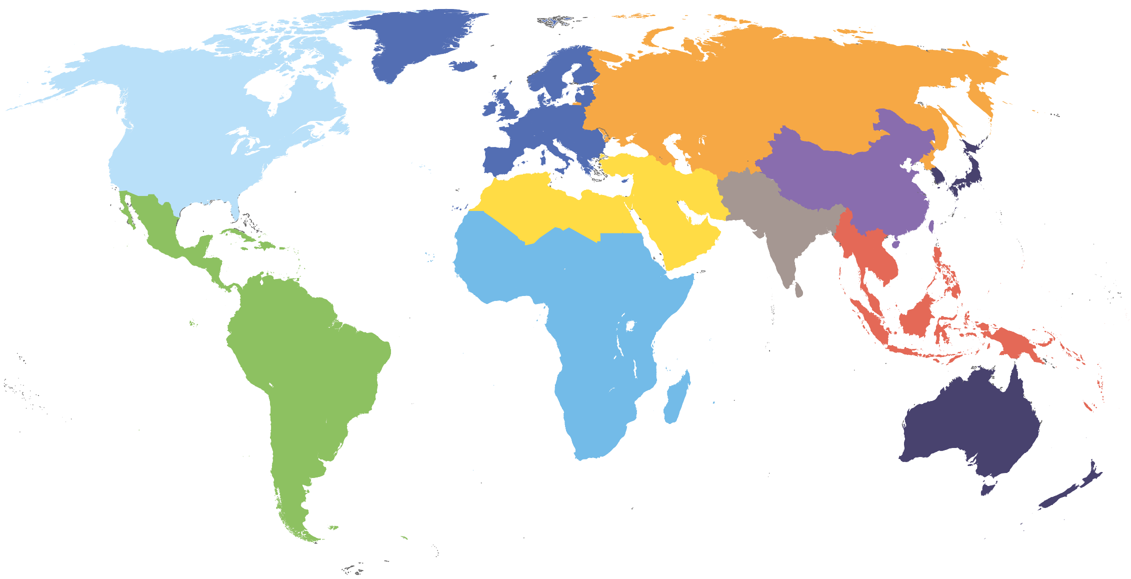
— Global analysis of the entire energy system from source to end use.

— Examining how energy transitions both drive and are driven by technology.

— Focusing more on the ongoing transition than on the status quo.

2 'Energy transition outlook 2017', DNV GL, September 2017
3 'Energy transition outlook 2017: oil and gas', DNV GL, September 2017
4 'Energy transition outlook 2017: renewables, power, and energy use', DNV GL, September 2017
5 'Energy transition outlook 2017: maritime', DNV GL, will be published in late 2017

## WE ANALYSE 10 GLOBAL REGIONS




Our outlooks, including this report, present our independent view of what we consider to be the most likely future amid the energy transitions unfolding around us. Our predictions are based on facts and do not represent 'wishful thinking'. Unlike some other published studies, we do not attempt to define actions that may be needed to achieve specific goals: instead, this is DNV GL's consistent vision of what our experts expect to happen, given current status and expected developments.

We also stress that our model presents only one 'most likely' future, not a collection of scenarios. The coming decades to 2050 hold significant uncertainties, notably in areas such as future energy policies; human behaviour and reaction to policies; the pace of technological progress; and trends in the costs of existing and new technologies.

In this report, we review our energy forecast's implications for key stakeholders in several industries which DNV GL advises and assists: electricity generation, including renewables; electricity transmission and distribution; and energy use.

The implications are intended to be relevant for investors, owners, operators, suppliers, consumers, regulators and policymakers. The enabling roles of digitalization and emerging technologies are also considered.

Some key predicted regional trends and analysis are included in this publication. More detailed analysis is available from DNV GL. We can also tailor such content to the needs of individual organizations and companies. ■

# 3

# KEY CONCLUSIONS FROM OUR MODEL

# 3. KEY CONCLUSIONS FROM OUR MODEL

This chapter summarizes the main results from our model which are relevant to this report.

The share of each type of generating technology in global electricity production and generation capacity is shown in figures 3-1 and 3-2.

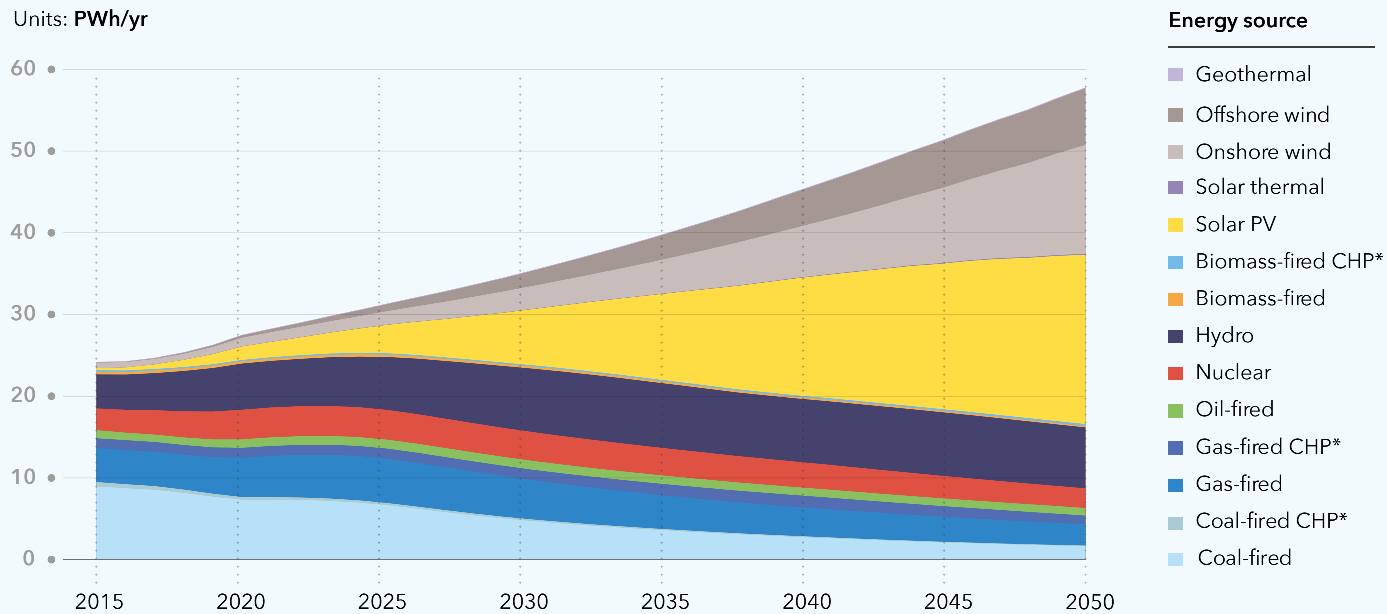
The main report shows that the 140% increase in electricity production from 2015 to 2050 occurs despite global energy demand growing only slowly then levelling off around 2030, because of transfers of energy consumption to electricity. This includes electrification of transport and heat, and results in major decarbonization of energy supply.

Figure 3-1 shows dramatic growth of electricity production from PV, onshore wind, and offshore wind. In comparison, current levels of nuclear, gas, biomass and hydropower are maintained with relatively little change; coal is dramatically reduced.

Growth of renewables generating capacity (3-2) is even more dramatic, because capacity factors[6] of renewables are significantly less than the capacity factors of the thermal generation they replace; in other words, more MW installed capacity is needed to produce each MWh.

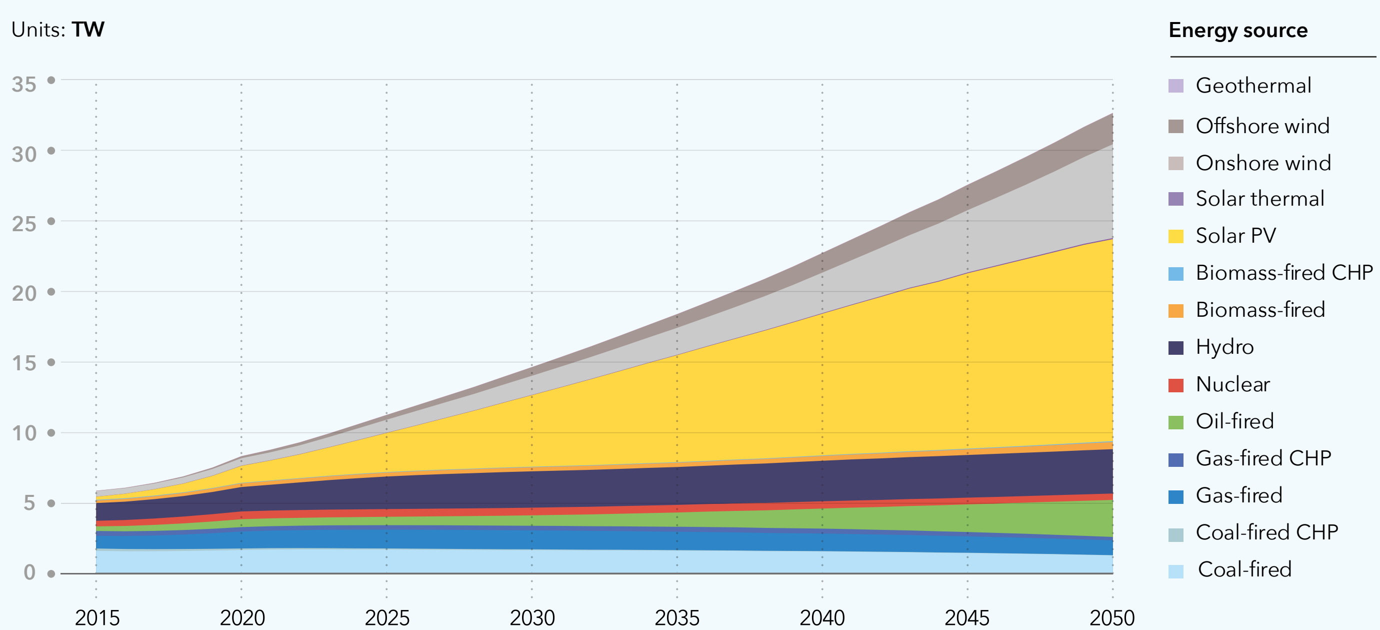
6 Capacity factor: annual energy production (MWh) as a fraction of production possible if operating at 'nameplate' or rated power all year

## GLOBAL ELECTRICITY PRODUCTION BY GENERATION TYPE (FIGURE 3-1)




*CHP = Combined heat and power

## GLOBAL ELECTRICITY GENERATION CAPACITY BY GENERATION TYPE (FIGURE 3-2)



The new renewable generation sources will not be located near to the plants they replace, but many will be near where the electricity will be consumed. They will be more distributed, smaller, though larger in total capacity, and will cause major changes to power flows across electricity networks. The changing consumption patterns will also contribute to this, resulting in new demands on electricity networks.

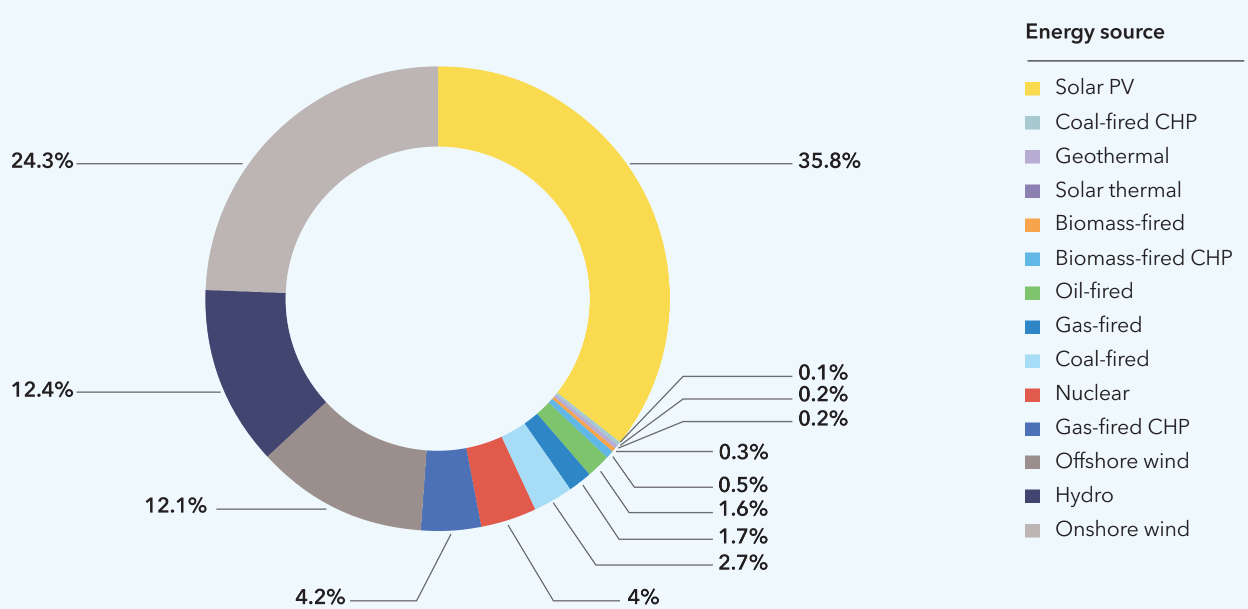
Figure 3-3 shows global electricity production in 2050. The global picture hides substantial differences between the modelled regions: figures 3-4 and 3-5 compare a PV-dominated region (Middle East and North Africa) with Europe, which has the highest wind capacity installed of any region – though still with substantial PV.

## THE VARIABILITY ISSUE

Given the model characteristics, and the very large capacity of PV and wind forecast by the model, it is important to consider here the 'variability' issue. There are, in fact, two separate issues raised when variable renewables form a large part of electricity production: security (insufficient production, 'keeping the lights on') and surplus production (low prices).

To address **security of supply**, our model estimates peak electricity demand in each region, and builds more generating capacity if necessary, to ensure the total generating capacity exceeds the peak demand. Allowance is made for non-availability of generating capacity: for example, nuclear is assumed

GLOBAL ELECTRICITY PRODUCTION IN 2050 (FIGURE 3-3)



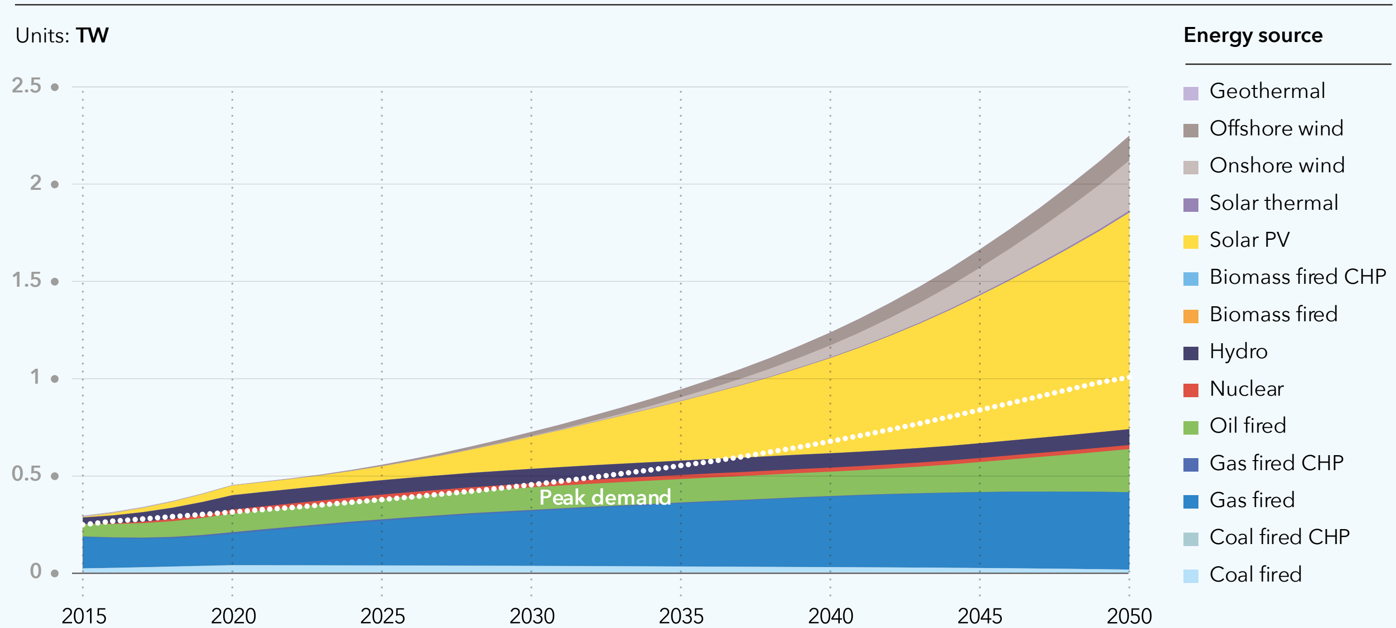
to be 85% available, gas 80%, and hydropower 50%. Wind and PV are assumed to provide a smaller fraction of their 'nameplate' capacity at the time of peak demand. The additional generating capacity is assumed to be 'peaking' plant, i.e. low capital cost but high operating (fuel) cost. In the figures, it is labelled as 'oil fired', but it could equally be diesel, gas engines, or open-cycle gas turbines.

Also, energy storage capacity is added as a function of the fraction of variable renewables. The storage is assumed to be batteries for the purposes of costing, and the costs are added to the costs of the variable renewables when deciding new capacity additions. In reality, pumped hydro and other longer term storage options would complement the picture.

This may be an unfair allocation of costs, as the storage provides benefits to the entire electricity system, but for simplicity this conservative assumption is adopted. Figures 3-4 and 3-5 shows the estimated peak demand in relation to the total generating capacity, for two regions.

The second issue, **surplus production**, occurs because periods of high wind or PV production will not always coincide with periods of sufficient electricity demand. For example, in figure 3-5, the maximum output of either the wind or PV generation alone in 2050 are greater than peak demand, so for substantial periods of the year there will be surplus wind or PV generation. If nothing else is done, this will result in substantial curtailment of renewables »

**MIDDLE EAST AND NORTH AFRICA ELECTRICITY CAPACITY (FIGURE 3-4)**



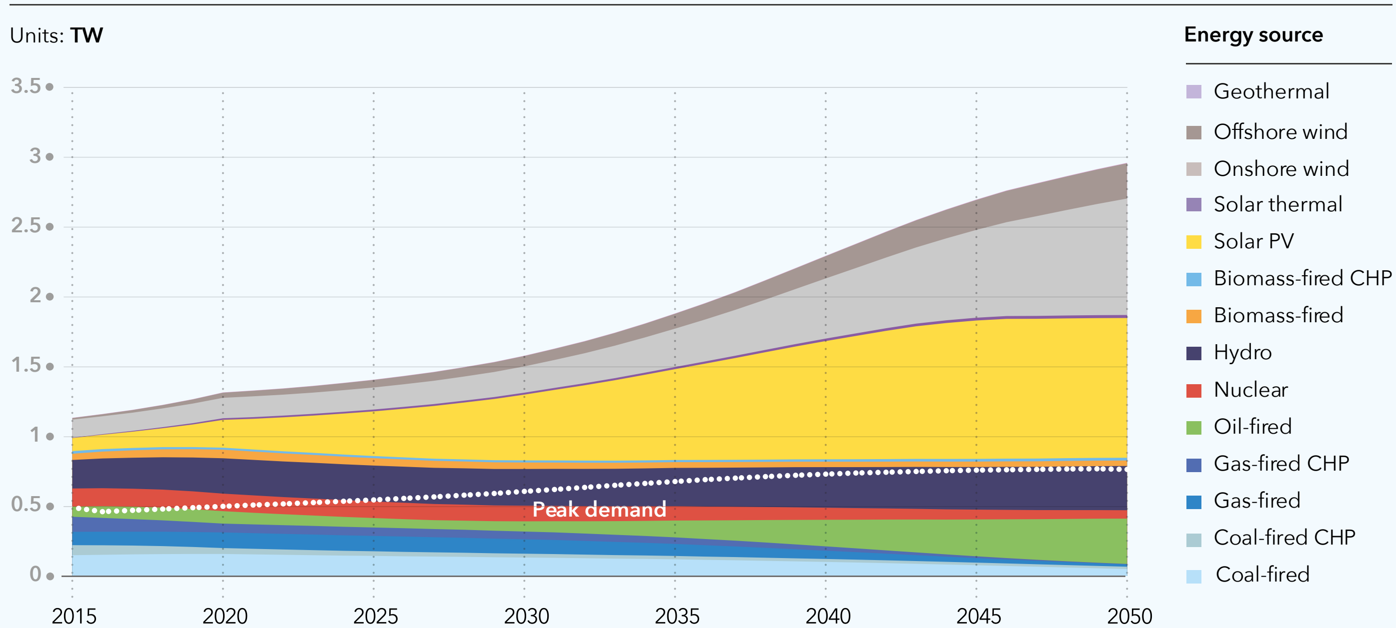
production, which in effect becomes a major economic penalty. Currently our model does not account for this cost.

For PV in regions close to the Equator, where there is little seasonality, the solution may be to store the surplus for a few hours to cover the night period. It is already seen that battery technology of a few hours' capacity could be economic for this. However, for regions with greater seasonality, battery storage of timescales of weeks and months will be extremely expensive. Over the geographical extent of the regions analysed, there will be substantial averaging effects which will mitigate the impacts, but not remove them entirely.

Credible solutions for 'seasonal' storage are:

- Hydropower with reservoir and pumped hydro storage, where suitable topography exists.
- Thermal storage, for use for space and water heating, and cooling.
- 'Power to gas' or 'power to fuel', i.e. production of hydrogen or methane, for injection into existing gas networks, for new gas networks, and for production of transport fuels.

**EUROPE ELECTRICITY CAPACITY (FIGURE 3-5)**



The latter two are attractive as they contribute to decarbonization of heat supply and transport, which are otherwise difficult to achieve. The storage capacity in existing gas networks is significant.

The best solutions for the 'surplus' problem are not at all clear yet. Therefore, the model results for the later years of the forecasting period cannot include the possible effects: this is an area for further development in future revisions of the modelling work, including the link with demand for decarbonized heating and cooling. ■

## SELECTED KEY ASSUMPTIONS IN OUR MODEL

### SECURITY OF SUPPLY

A full description of our model and its assumptions is published in our main report, Energy Transition Outlook 2017. It is useful to stress here, however, that it works on an annual-average basis that does not directly represent variations in demand and generation on shorter timescales such as seasonal, daily or even briefer.

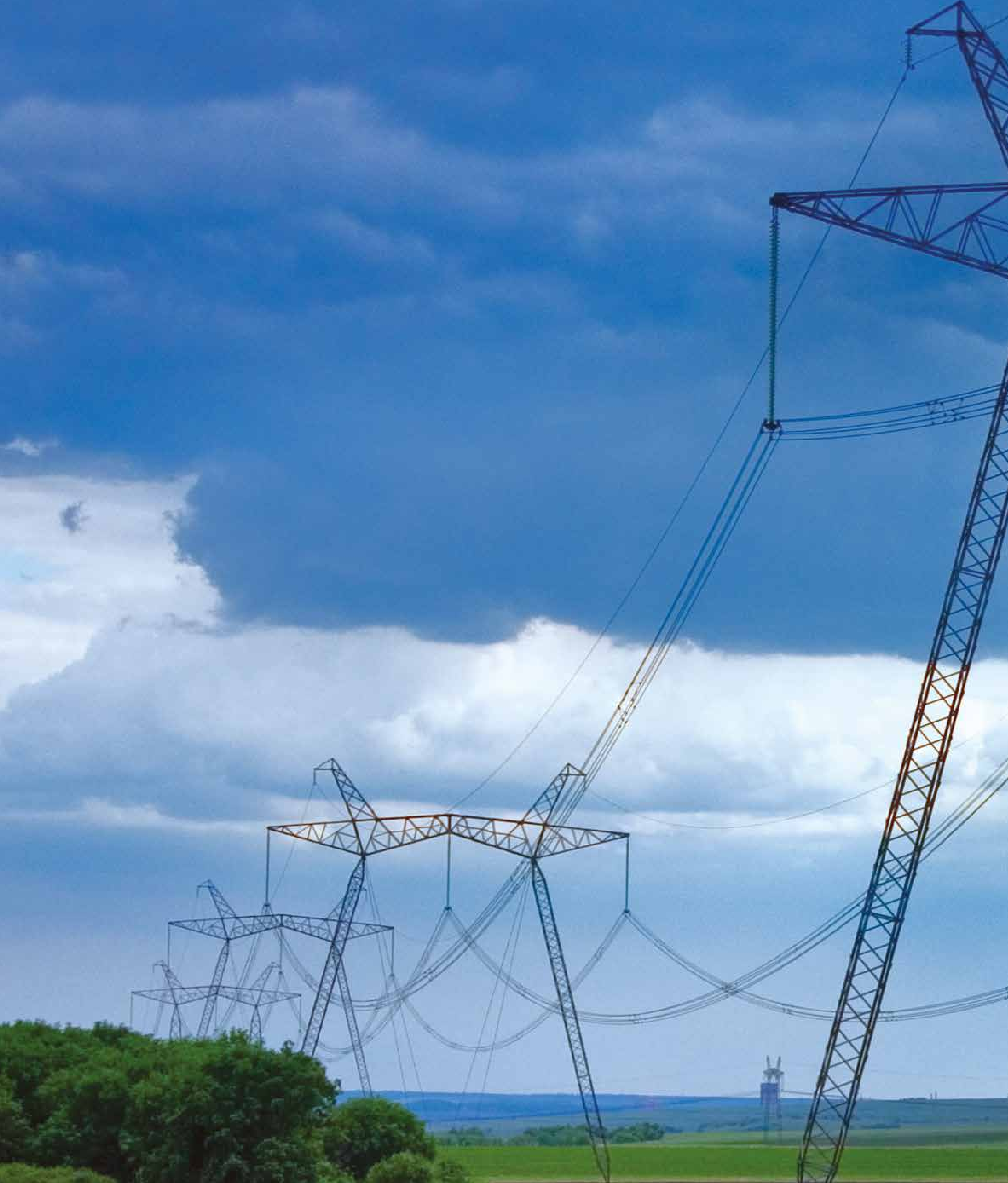
Key points for the purposes of this report on the model's implication for renewables, power, and energy use include:

— The model chooses new electricity generating capacity only when expansion is needed – either due to increasing demand, or older plants being closed. The generating technology is chosen on Cost of Energy – i.e. the lowest levelized cost of energy: no other constraints are applied. Results are therefore highly sensitive to assumptions, for example on future cost developments. Some constraining factors are considered in chapter four of this report – supply-chain limits on growth rates, and electricity market regulation, for example.

— The model assumes that, within any region, electricity transmission and distribution networks will be expanded as necessary to accommodate changes in electricity consumption and generation. An allowance for costs of transmission for remotely-located renewables is included. Construction and permitting timescales, though significant, are assumed to be manageable.

— The model adds some short-term electricity storage capacity – assumed to be batteries for the purpose of costings – as a function of the proportion of variable renewables. The costs of building this storage are attributed directly to wind and PV in the model's decisions about building new generation capacity. This means that variable renewables become more expensive in high penetration regions at the end of the forecast period, in spite of steady lower costs of turbines and PV panels.

— The model is not aiming to achieve any targets, for example  for decarbonization.



# 4

# TECHNOLOGIES AND SYSTEMS

This chapter will concentrate on summarizing the industry implications for the electrical power and renewables industries from the forecasts of DNV GL's model of the world energy system. It concentrates on key technologies and systems, focusing both on results from the model and on the expected key developments which may follow.

## 4.1 ONSHORE AND OFFSHORE WIND

Our model forecasts a very bright future for the wind industry with sustained and accelerating growth in installed capacity reaching around 670GW in 2020, 2000GW in 2030, and 9000GW in 2050 (figure 4-1). The rate of incremental additions will grow to approximately 200GW/yr in 2030, with even more rapid growth forecast between 2035 and 2050, particularly in onshore wind (figure 4-2).

Onshore wind remains substantially larger than offshore wind throughout, with China expanding significantly faster than the other two established regions of Europe and North America (figure 4-3 and 4-4). There is substantial growth everywhere else, with Indian Subcontinent and Latin America each exceeding 500GW before 2050. In offshore wind, China again dominates, claiming 33% of global capacity by 2050. Europe loses its current leading position: both China and North America exceed European installed offshore wind capacity by the early 2020s, and growing offshore wind in OECD Pacific matches European levels by the 2030s.

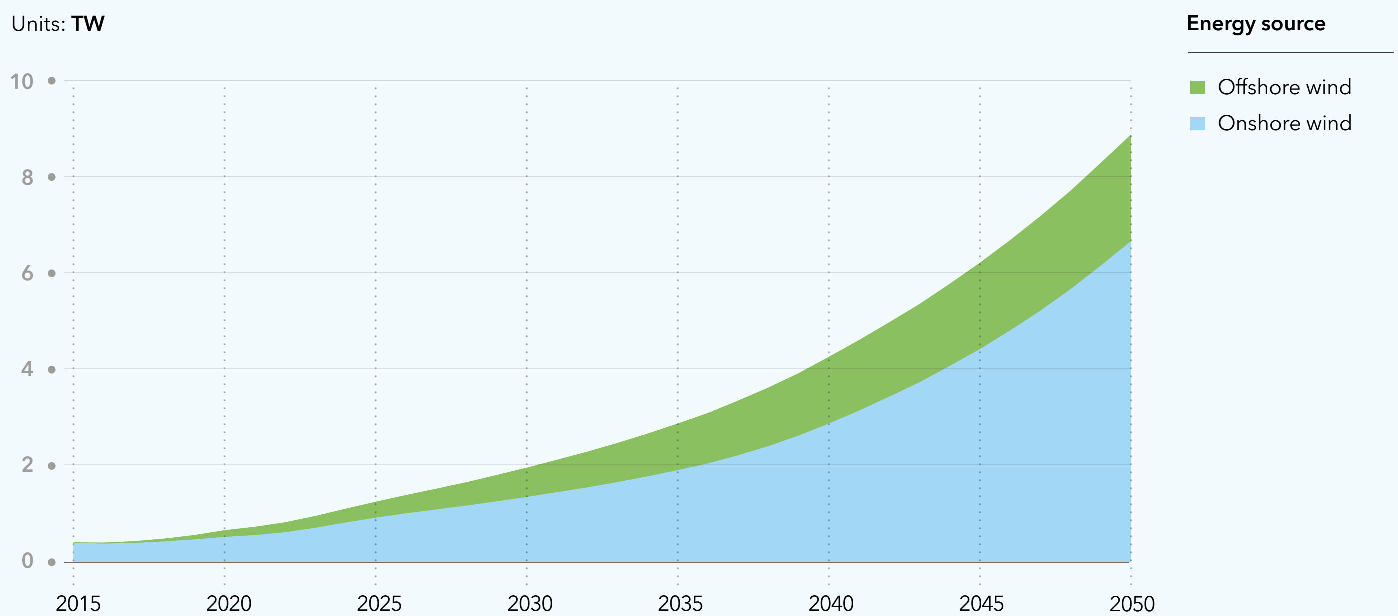
The model's forecast of short-term growth in offshore wind reflects the fact that cost will no longer be a significant constraint on the use of this technology. As a wider range of stakeholders wake up to this new reality, installation rates are likely to accelerate. In the short-term, 10-year horizon, however, we must acknowledge that installation rates for offshore wind, particularly in nascent markets such as North America and China, depend on rapid development of the supply chains and enabling regulatory processes.

Due to increased competition from other renewables resources, exacerbated by the trend for new capacity additions to be subject to competitive auctions, such sustained growth requires a continued sustained reduction in Cost of Energy, particularly for offshore wind. We foresee improvements in all aspects of the technology, project execution and operation.

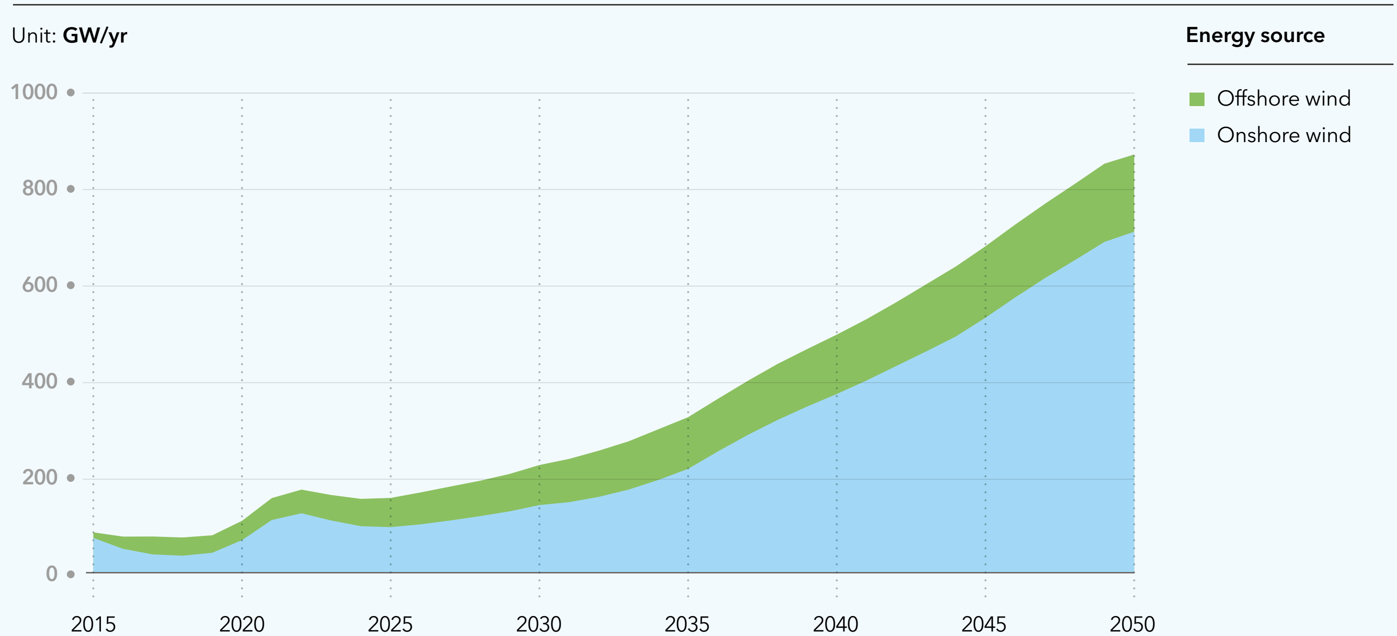
As highlighted in DNV GL's Technology Outlook 2025[7] further developments in turbine technology include lighter, more flexible blades; new aerodynamic control devices; innovation in transmission systems; new sensors; and smart control systems. Of equal importance will be the intelligent management of large numbers of turbines using condition monitoring and central data acquisition and analysis to optimize operation and maintenance. There will also be an increased focus on the value such assets bring to the overall energy system.

To ensure that the wind industry meets the joint challenges of further cost reduction while maximizing the value that wind assets bring to the energy system, all stakeholders will need to take advantage of learnings available from analysis of huge quantities of data generated over project lifecycles. »

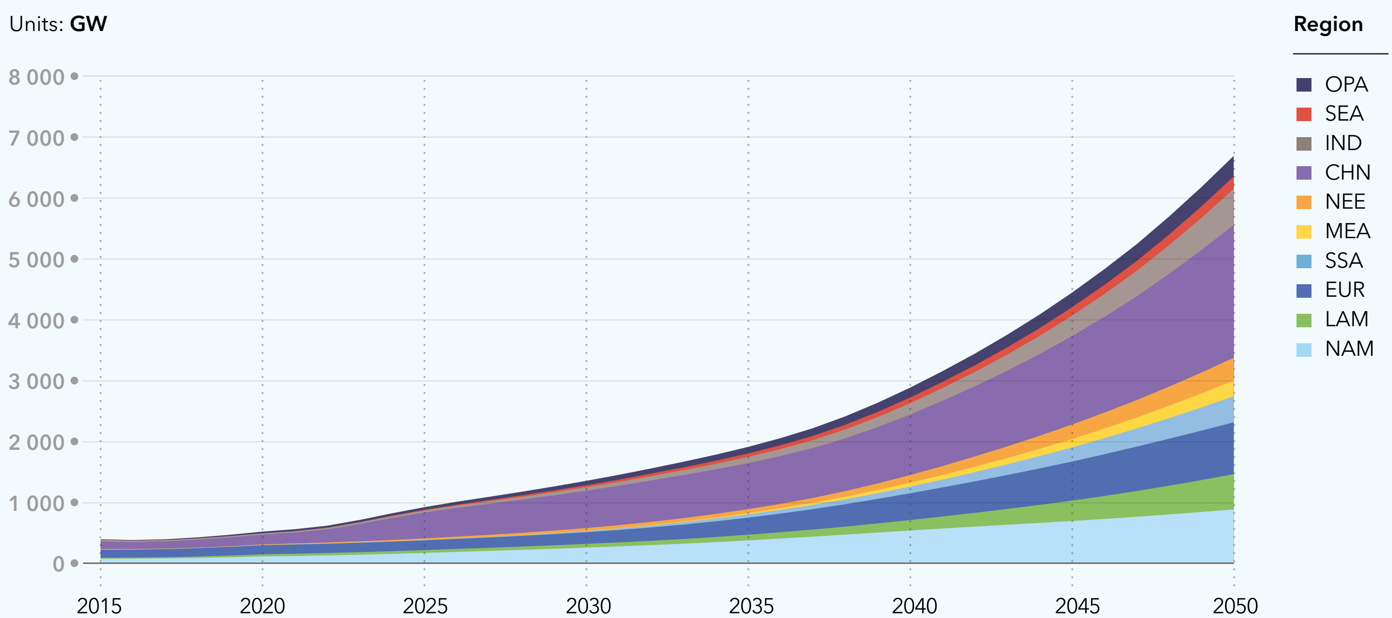
## INSTALLED CAPACITY (FIGURE 4-1)



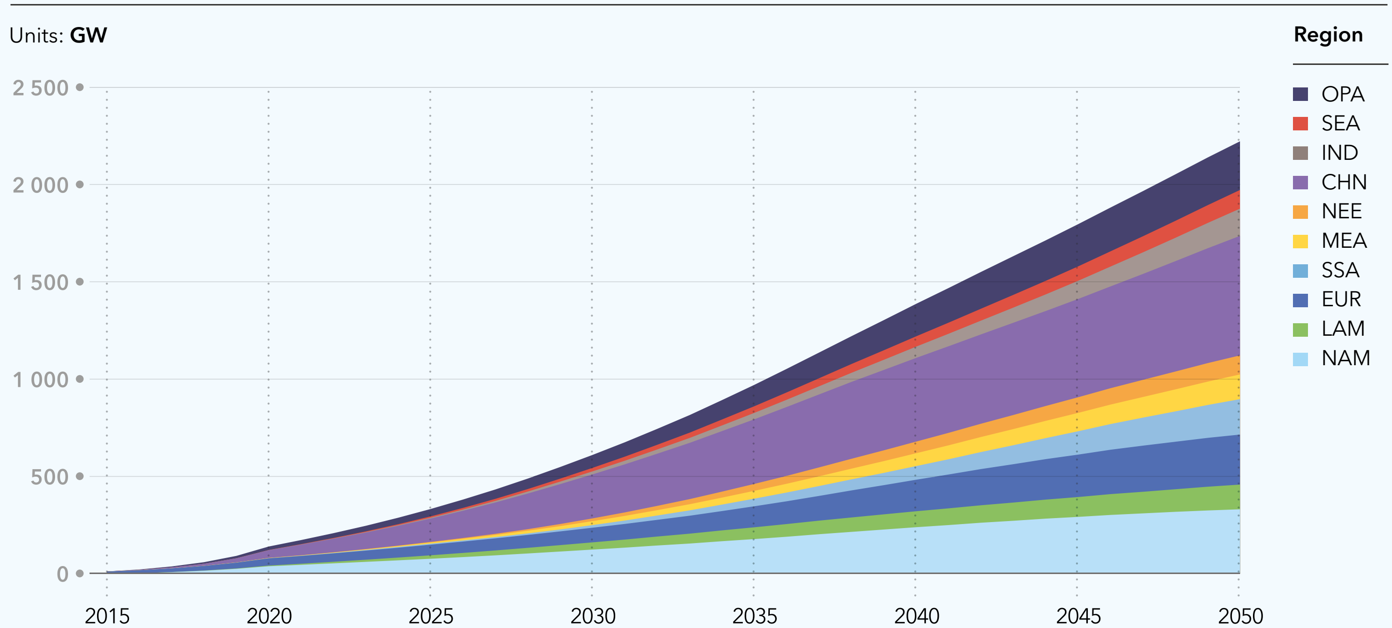

## INCREMENTAL WIND CAPACITY ADDITIONS (FIGURE 4-2)



### ONSHORE WIND CAPACITY BY REGION (FIGURE 4-3)




### OFFSHORE WIND CAPACITY BY REGION (FIGURE 4-4)



This approach enables deeper understanding of how design choices, particularly for improved control, made in the development phase impact on operational performance. Analysis of the project lifecycle data can also further validate the tools used in the development and design phases so as to reduce uncertainties and lead to increased efficiencies.

Offshore wind energy has its own specific challenges while being able to benefit from technology developments in the much larger onshore industry. Great strides have been made over the last decade, and the current generation of 6-8MW turbines represents the first truly offshore class of technology. Increasing turbine scale has brought major balance-of-plant savings but, as highlighted by the UK's Cost Reduction Monitoring Framework[8], significant benefits are yet to be exploited in the area of integrated design. In addition, the disappointing scale and rate of growth of the offshore market has restricted the potential for learning by doing. Offshore turbines around 10MW in size are now coming forward, but as the focus moves from Northern Europe to other regions, it is essential that the industry learns from experience and does not repeat mistakes.

Respective shares of onshore and offshore wind in the future generation mix will depend heavily on their relative rates of cost reduction, and also on the availability of infrastructure to support development, of offshore in particular. Our model assumes total cost as the determining factor, and recent European auctions have shown that where the public sector bears some development risks or power transmission costs, the headline cost of offshore wind can compete even more effectively with other forms of power generation.

Given the size of the potential market, floating offshore wind technology may well become competitive during our forecasting horizon, though this is not specifically modelled in the analysis.

The rapid and sustained growth projected in figures 4-3 and 4-4 above also depends on continued public acceptance of wind energy projects. Where there is currently little experience of onshore or offshore wind, growth may be constrained not only by lower public awareness, but also by lack of experience among regulators, spatial planners, network operators and land management bodies. It is important that the vast experience which has been gained in some countries is shared effectively in new markets for offshore wind. ■

7 'Technology Outlook 2025', DNV GL, 2016
8 'Cost reduction monitoring framework 2016: summary report' Offshore Wind Programme Board, UK, 2016

# 4.2 SOLAR

We forecast substantial growth of solar photovoltaics (PV) to become a major contributor to the energy supply in 2050, rivalling oil in magnitude. We foresee PV providing around a third of the world's electricity by then (figure 3-3), similar to our forecast for combined onshore and offshore wind generation. This represents an increase of 85 times over the outlook period.

PV grows in all regions over the next decades (figure 4-5), with China leading (figure 4-6) until Indian Subcontinent exceeds China's installed capacity just after 2045. In Europe, North America, and OECD Pacific, PV levels off towards 2050.

These extraordinary results are driven by continuing cost reductions and performance improvements for PV. This includes efficiency improvements, manufacturing continuing to scale, development of financing mechanisms, and the system development process being more streamlined. They also depend on system designs that are attuned to storage, peak demand and demand-response solutions. Large-scale PV is already the lowest-cost form of generation in several markets, as evidenced by open competitive tenders. It is the lowest-cost low-carbon option in many additional markets. Distributed smaller-scale PV – such as for 'behind the meter', residential use, commercial, and industrial installations – is more costly per unit of capacity than utility scale systems. These smaller scale PV systems have the benefit of being located near the load and support reduced transmission and distribution losses and costs. Rooftop PV also faces fewer challenges in obtaining consents, and has the additional advantage of not competing with other land uses.

Similarly to wind, learning from other markets, better asset management, and advanced analytics – particularly of large datasets of operating experience – will contribute to achieving envisaged cost reductions. Improvements in standards and local regulations on issues such as module and inverter testing and accreditation are already occurring in some countries, and this process will continue.

Concentrating solar power (CSP) is not included as it is predicted to be very small compared to PV for electricity generation because of CSP's higher cost of generated electricity[9].

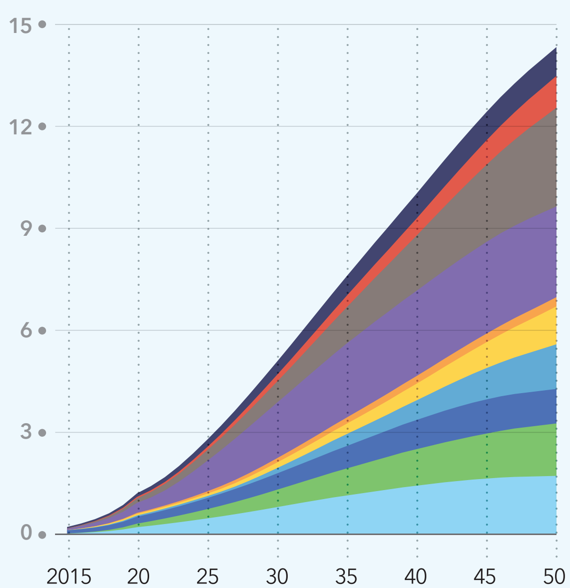
The enormous growth of PV presents challenges for governments, regulators and network operators:

- Behind-the-meter distributed PV will expose weaknesses in electricity tariff mechanisms. There are separate challenges for energy costs, and for network (capex recovery) costs, for example. This is already happening, and regulators and utilities are responding by moving to time-of-day or, eventually, spot pricing for energy, as well as implementing network charges that reflect the true grid capex needs to support larger amounts of solar. Such moves will possibly increase volatility in charges to consumers, a trend which may become politically difficult, especially when low-income consumers are affected. Some users may respond by 'defecting' from the traditional utility grid structure.

9 Cost assumptions are described in Energy Transition Outlook 2017, the main report on our model

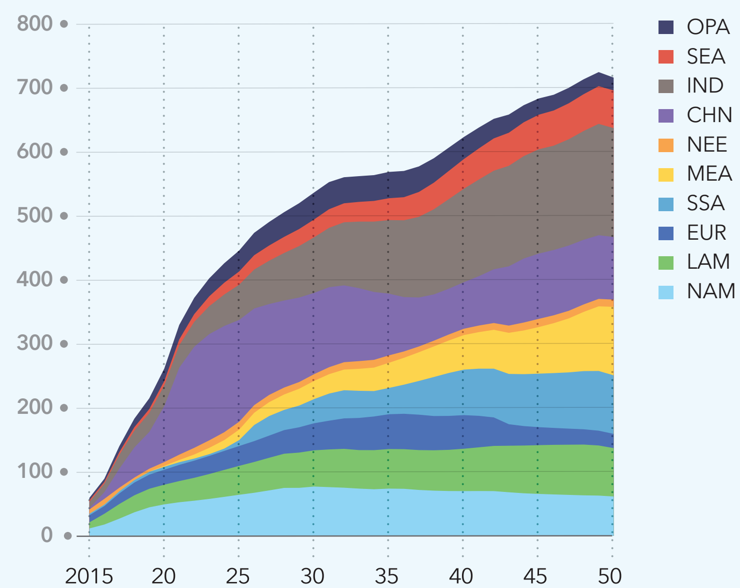
SOLAR PV CAPACITY BY REGION (FIGURE 4-5)

Units: TW




SOLAR PV CAPACITY ADDITIONS BY REGION (FIGURE 4-6)

Units: GW/yr




— PV installations at all scales can be developed rapidly. Once it is economically attractive to electricity consumers without subsidy, its growth is hard for electricity system operators to plan, control or monitor. This may require some form of licensing, even for small installations, or mandatory product standards that include communications capabilities.

Where these issues are not resolved in time, they will potentially impede growth of PV, even where it would otherwise be justified economically. However, the widespread adoption of PV also brings new opportunities:

— Solar combined with storage will be increasingly common and assist in supporting network stability and provide supply resiliency. Cost reductions in storage will facilitate the deployment of the combined application.

— Through distributed generation installations and micro-grids, PV will help bring electricity to locations that are presently without it. This will support reduction in the use of high-polluting small fossil fuel generators and enable developing economies in particular to leapfrog into an era of electricity.

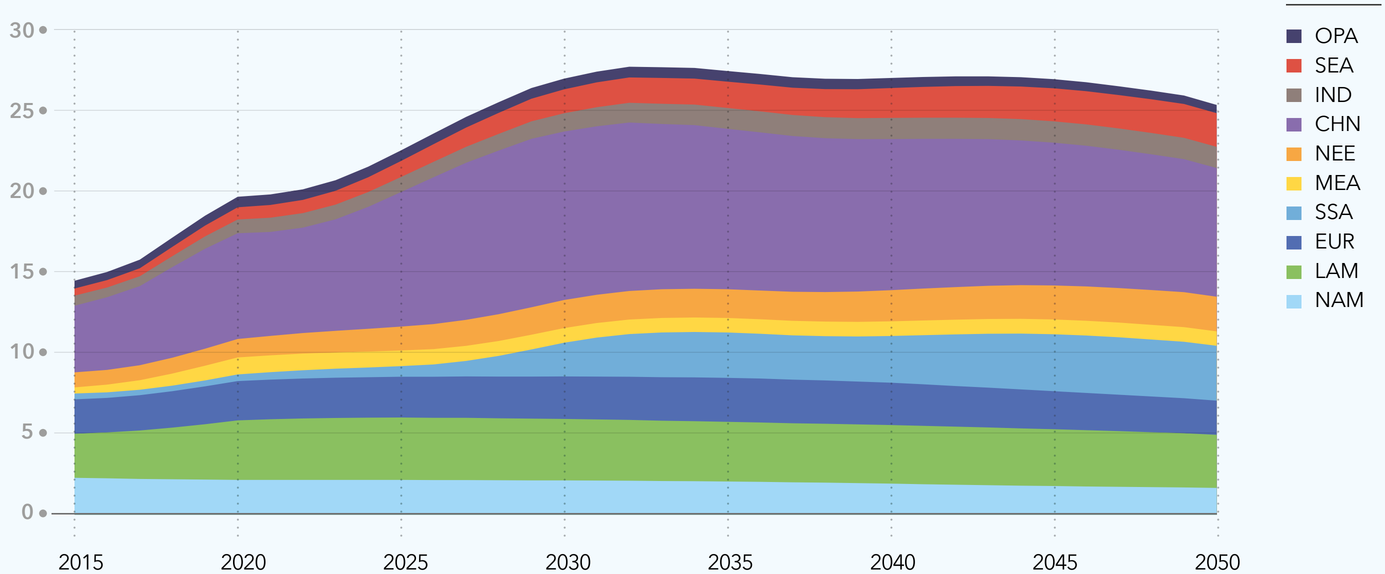
# 4.3 HYDROPOWER

Hydropower is a mature technology providing a low-cost power generation option. Total installed capacity and estimated generation in 2016 were around 1,250GW and 4,100GWh respectively, according to the International Hydropower Association.

Hydropower is well understood but perhaps not as widely exploited as it could be, for reasons including long lead-time, high capex and, for certain projects, opposition based on real or perceived environmental and social impacts. Hydropower has been growing quite rapidly in recent decades, and we judge that this will continue until around 2030 (figure 4-7). It is currently the dominant renewable source of electricity generation, and our model predicts that it will retain this position until into the 2030s, when wind and PV will surpass it. Our forecast indicates hydropower capacity expanding rapidly in China over the next decade, growing slowly in other regions up to 2040, and maintaining its current share, about 17%, of electricity production, followed by a slight decline towards 2050.

**WORLD PRIMARY HYDROPOWER SUPPLY BY REGION (FIGURE 4-7)**

Units: **EJ/yr**



Hydropower comprises three main types of generation plants: run-of-river; hydropower with reservoir; and pumped hydro storage. Run-of-river is based on a simple barrier in the river to exploit the energy passing by, and has lower environmental impact. Hydropower with reservoir creates opportunity to store large volumes of water offering flexible dispatch, and is used for balancing out generation over months, seasons, or years. In addition, hydropower with reservoir is very often multipurpose, combining power generation with other benefits such as water management, flood prevention, or waterways for transport.

Pumped hydro storage is today the dominant form, and lowest-cost option for large-scale storage of energy for a power system. In 2017, it accounts for more than 95% of all active, tracked storage installations worldwide. It has a total installed nameplate capacity exceeding 150GW, according to the US Department of Energy's storage database. Typically, it is used to pump water up during low-price periods of the day or night, and then to produce power when prices are high. Depending on the volume of the storage reservoir, it can cover seasonal or shorter periods. ■

## 4.4 BIOMASS

We see biomass, including waste, providing only a very small contribution to electricity production in all regions, and for that reason it is not considered further in this report. Its role in global energy production is substantially greater, as described in Energy Transition Outlook 2017, the main report on our forecast. ■

> Hydropower is currently the dominant renewable source of electricity generation

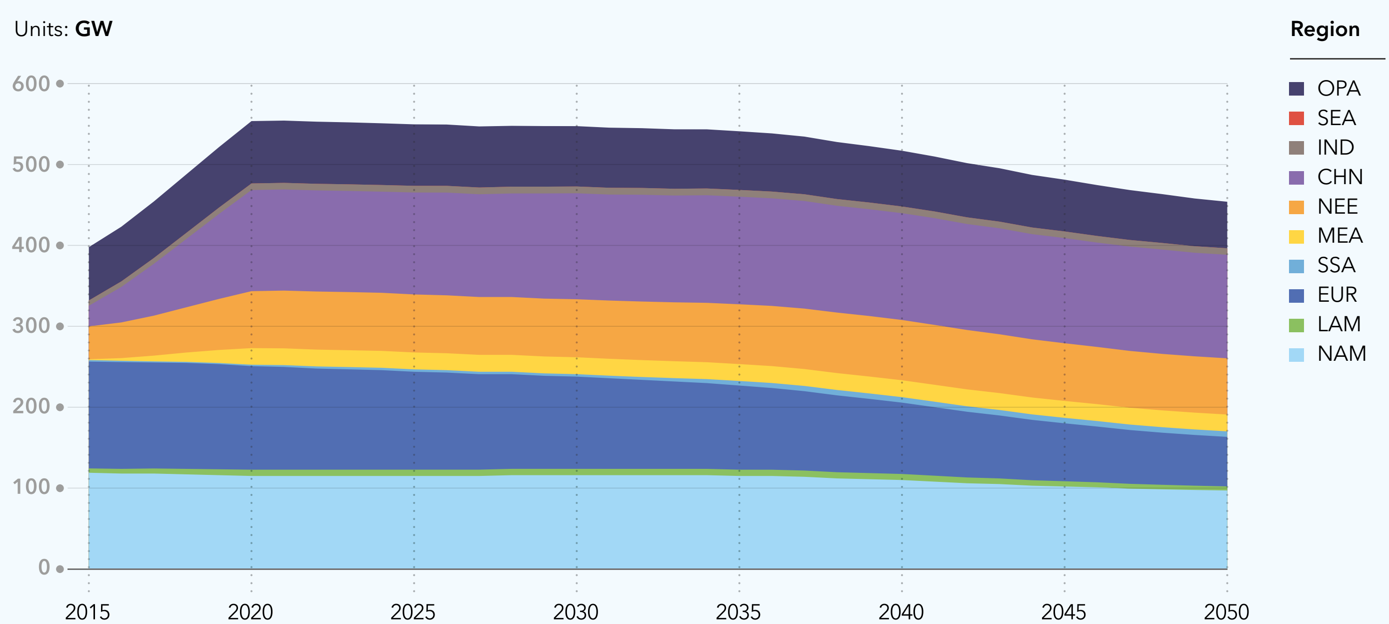
# 4.5 NUCLEAR

Nuclear is a major source of low-carbon generation, with current annual production close to gas or hydropower, and significantly greater than solar and wind.

We forecast marked growth in the medium term (figure 4-8), concentrated in a few regions, and driven directly by policies and construction programmes known at the time that the model's assumptions were determined.

Please note, however, that the short-term prediction is somewhat skewed because part of the growth is due to the modelling technique, where 2015 to 2020 is used as a transition period from historical to simulated data. Hence, a caveat might apply to China, where our best estimate is that the predicted growth is likely to take longer to materialize than shown by our model.

**NUCLEAR CAPACITY BY REGION (FIGURE 4-8)**



This is followed by gentle decline, resulting in nuclear's contribution to world electricity generation in 2050 being two-thirds the level of gas, and less than a third of the level of offshore wind.

However, for nuclear, and probably more so than for other generating technologies, our assumption that capacity is chosen primarily on Cost of Energy grounds is open to challenge. As in the past, energy security issues, perhaps coupled with desires to develop and maintain a technology lead, could result in governments opting for nuclear. Particularly in Indian Subcontinent, this could lead to substantially more nuclear generating capacity than our model predicts. ■

# 4.6 COAL

Coal has been fundamental for industrialization and raising living standards, but is the most carbon-intensive source of electricity, and is currently responsible for the largest share of the world's greenhouse gas emissions.

Only large-scale deployment of carbon capture and storage (CCS) can secure a role for coal in a decarbonized future.

Coal offers cheap electricity generation, but when CCS costs are added, gas with CCS and tight control of methane emissions is likely to be even cheaper. In addition, coal is a very strong contributor to poor air quality, to which substantial numbers of early deaths can be directly attributed.

For both these reasons, recent strong expansion of coal in developing economies is being halted and reversed. Our model results show global production of electricity from coal dropping by around 80% by 2050, by which time it disappears from all regions except Indian Subcontinent , where coal use for power generation remains relatively constant. ■

# 4.7 TRANSMISSION GRIDS AND SYSTEM OPERATION

## TECHNICAL FUNCTION OF TRANSMISSION GRIDS

Society now and in the future will depend increasingly on reliable access to electric power provided mainly through grids. Economies with well-developed electricity infrastructure have established transmission grids run by transmission system operators (TSO)[10] to transport power from generation units to the largest industrial consumers, and to distribution systems which directly supply the majority of consumers. The TSO is responsible for operating, maintaining and developing the transmission system in an area and, where necessary, its interconnections to other systems. TSOs enable integrated energy markets, and provide conditions for non-discriminatory connection of consumers and new power plants.

Transmission grids play an important role as the backbone of the power system, enabling the connection of multiple generation sources and loads. These grids form a control area or areas, where total generation and demand on the system must be balanced in real time. If demand is higher than generation, frequency is reduced: if generation outstrips demand, frequency rises. Typically, TSOs in regulated markets are legally obliged to maintain frequency within limits specified by regulators.

The grids enable transmission at high voltages (HV), typically 400 kilovolts (kV), over long distances without huge transmission losses. They are especially important in electrical systems with remote generating plants, such as many hydropower plants or offshore wind farms. At ultra-high voltages, such as 1,000kV alternating current (AC) or 800kV direct current (DC), losses are further reduced (e.g. to 5% over 1000 km). Some regions have established plans for 1050kV AC and 1100kV DC links. In Germany, consideration is being given to converting some existing AC lines to DC to increase their capacity, and 500kV DC underground cable technology may be adopted.

## CHALLENGES

To recap, an electricity transmission system must fulfil basic functions even when it is subject to contingencies[11]. It must:

— Allow power to flow from generators to consumers

— Maintain current, frequency, and voltage within limits to prevent damage to generators, consumers, other connected systems, or the system itself.

The energy transition to low-carbon generation and greater electrification of demand will make these objectives more difficult for TSOs to meet.

The growth of PV and wind creates more frequent, larger, and faster fluctuations in electricity production. Further, the TSO has to manage greater uncertainty in the short term, such as electric vehicle owners' charging decisions, and in the long term, such as the

10 Also termed Regional Transmission Operator (RTO) or Independent System Operator (ISO)
11 Contingency: an unplanned yet credible event such as a failure of a component of the network, loss of a generator, sudden change in electricity demand, or combination of such events

location, timing, and size of new generating plants. Consumers or prosumers (producer-consumers) may become active providers of services to the system operator, most likely through new aggregators, brokers for a group or groups of customers (see section 4.8: *Distribution Grids*).

These impacts will create a need for: improved communication between TSOs, distribution system operators (DSOs) and prosumers; common highly-regulated standards; complex algorithms; and strong cyber-security standards.

As the number of large thermal generators in operation reduces, to be replaced by converter-connected sources such as PV and wind, stability in response to disturbances becomes an issue. Balancing services, including frequency response and inertia, are required.

As power flows from more generation sources, more widely distributed, and with greater variability, TSOs will apply the following tools to create the needed flexibility:

— More 'power-flow steering' technology, such as phase-shifting transformers and highly-controllable embedded voltage-source converter HVDC links.

— More HVDC interconnectors in transmission systems, creating hybrid grids in which AC and DC coexist (figure 4-9).

— Expanding demand response from large loads, which are often already in place, to include aggregated loads, such as electric vehicle charging, in the distribution system.

— Utilizing the power electronic converter capabilities of renewables to provide short-term response to frequency changes, and reactive power for voltage control.

— Grid-connected storage for balancing services over a range of response times, and to avoid or defer the need for transmission reinforcement.

— Utilizing the dynamic capabilities of overhead lines and cables, based on weather conditions, for example.

For many of these, new computational tools will be needed for both design and operation.

TSOs may not necessarily own or operate the equipment to provide these functions: as at present, some may be provided as contracted services, by generators or electricity suppliers, for example. Regulators and governments will favour market mechanisms for such services in an attempt to ensure optimum economic solutions. There will be substantial development of markets, which may see new roles emerge.

Though we provide no explicit forecast of grid capacities, the energy future we envisage has several implications for transmission grids and their sound operation.

— The transmission system of the future needs to facilitate the rising share of renewables, particularly PV and wind, in power generation and for all regions.»

Substantial transmission system reinforcement or expansion will be required in many regions to meet increased electricity demand.

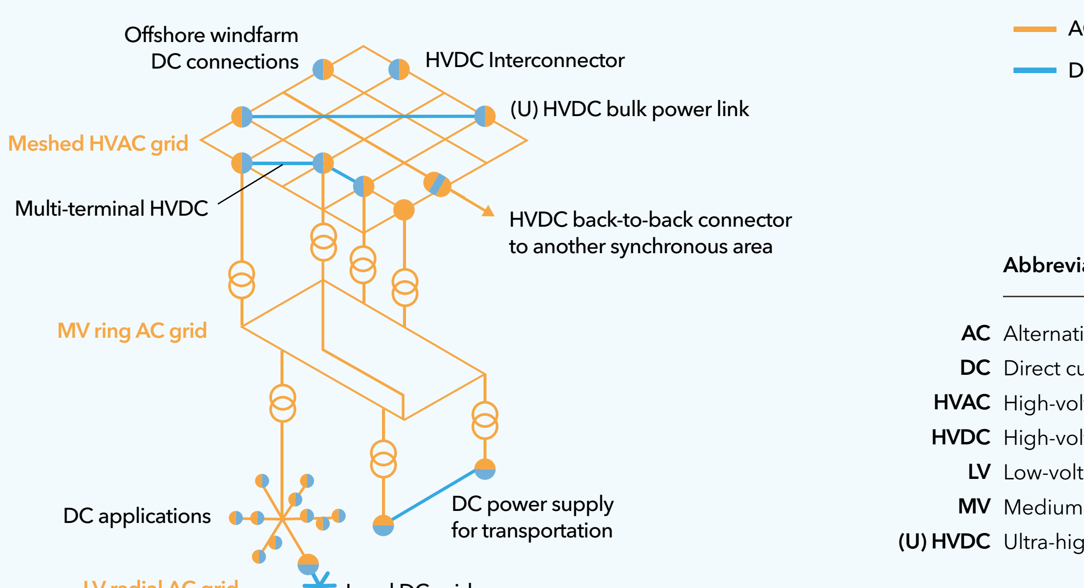
— Though not specifically modelled here, it is possible that in regions where small-scale PV dominates, the amount of energy passing through the transmission system will reduce initially as more is generated on distribution systems or 'behind the meter'. It will then increase again as PV production starts to flow 'up' out of distribution systems to balance spatial variability.

— Our model assumes a 'perfect' transmission system in each region, meaning that sufficient capacity is assumed to be built in time and at acceptable cost to accommodate changes in generation and demand. This will require substantial co-ordination on international scale. This entails major technical changes, including higher voltages, and greater use of HVDC for very long distances.

— China already transports power over thousands of kilometres via traditional HVDC links. The country's projected significant increase in wind and solar capacity from 2020, and rising total electricity demand, will drive conversion of traditional HVDC links to voltage source converter technology. It will also spark the creation of an HVDC overlay grid, to connect large areas of renewables resource to load centres and other markets.

— Indian Subcontinent will face similar challenges, though with more uniform distribution of electricity demand and renewable resources, its optimum transmission solution may look different.

**FUTURE POWER SYSTEM GRID ARCHITECTURE – AC+DC HYBRIDIZATION (FIGURE 4-9)**




**Abbreviations**

| | |
|---|---|
| **AC** | Alternating current |
| **DC** | Direct current |
| **HVAC** | High-voltage alternating current |
| **HVDC** | High-voltage direct current |
| **LV** | Low-voltage |
| **MV** | Medium-voltage |
| **(U) HVDC** | Ultra-high-voltage direct current |

— Fewer synchronous thermal generators, and more inverter-connected PV and wind generation with no direct inertia contribution, will require new approaches to stabilizing transmission systems.

— Large quantities of new storage capability for electricity will be needed from around 2030. We foresee about 150GWh being installed by then, primarily in China and Indian Subcontinent. For comparison, this is around half of the current global pumped hydro storage capacity.

The overall picture is one of greater complexity and faster change, amid which the increased use of data, data analytics, and communications technologies will be essential management tools. ■

# 4.8 DISTRIBUTION GRIDS

Distribution grids are the key infrastructure for getting power to final customers. They also connect to smaller, decentralized generation facilities. The vision of consumers transforming into prosumers actively participating in capacity, energy and ancillary services markets is focused on the distribution level. Prosumers may range from householders to highly-engaged professional energy managers. Their rising participation may lead to a range of improved forecasting and asset management tools.

### TECHNICAL FUNCTION OF DISTRIBUTION GRIDS

Traditionally, energy is delivered over long distances and across international borders by transmission grids. Distribution grids operated by Distribution System Operators (DSOs) supply electricity to residential and commercial customers, and all but the largest industrial consumers. These grids play an important role in enabling flexible power-supply options from decentralized sources of generation, storage, and demand. Most renewable generation sources in the future will be connected to distribution systems, either as generating plant or 'behind the meter' sources owned by electricity consumers.

### IMPACT ON SYSTEM OPERATION

DSOs[12] are responsible for the secure operation of their networks, with increasing emphasis on distribution congestion and voltage management. They play a key role in providing data on the behaviour of consumers and distributed generation, which are becoming of greater importance to TSOs. Aided by smart meters, this information can be provided closer to real time to increase the possibility of controlling demand better. »

12 The term Distribution Network Operator (DNO) is often used; but as distribution systems become more 'active', with more generation and more complex power flows, the operator's role in many locations will also become more active, and may take on some functions similar to TSOs – for example, contributing to control of the system frequency. The term DSO is becoming more widespread.

## CHALLENGES

The energy transition will drive much closer cooperation between TSOs and prosumers. This will in turn require DSOs to take on some responsibility for managing relations between prosumers, embedded generators, and TSOs.

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

Smart distribution substations of the future will play a key role through their ability to manage and control local low-voltage (LV) grids and serve as an intelligent medium-voltage (MV) layer interface.

In the decades ahead, DSOs in many countries will have to invest heavily in MV grids and associated MV/LV distribution substations – sometimes called underlay grids – to cope with the increased share of dispersed and distributed renewable generation. These investments have been estimated to be of the same order of magnitude, or even greater, as those needed for transmission.

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

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

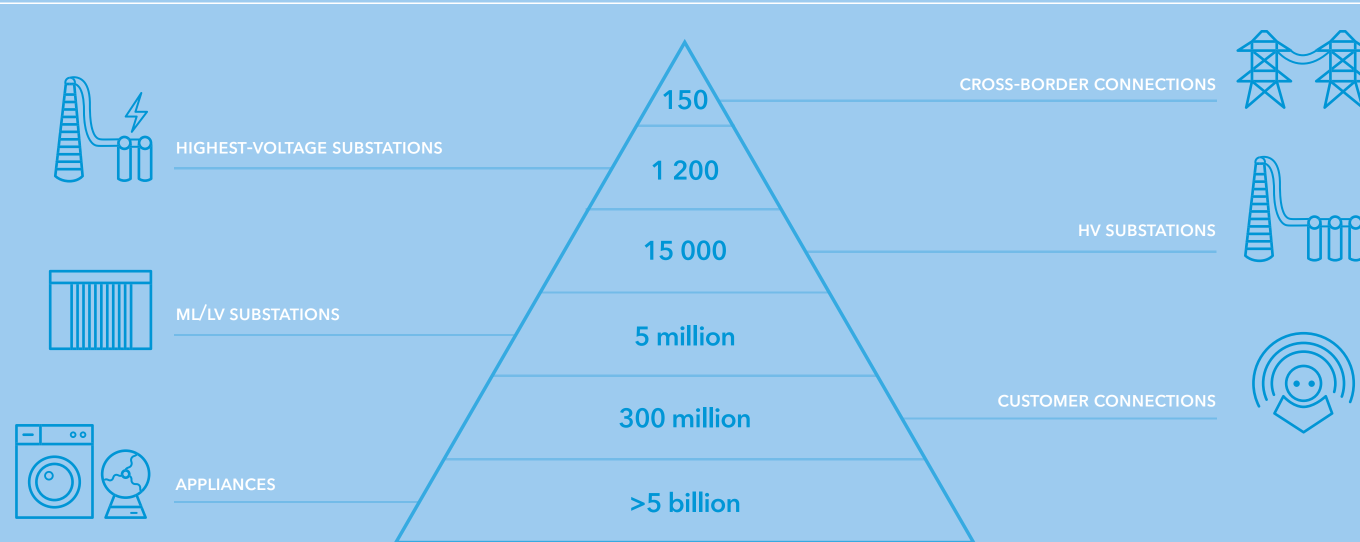
Given the future that we predict, the quantity and complexity of grid equipment needs to increase significantly at the distribution level, and we believe it will.

A rough DNV GL inventory of Europe's electricity transmission and distribution infrastructure and end users illustrates the scale of potential opportunities for the supply chain. The pyramid in figure 4-10 displays six estimates: 150 connections between countries; 1,200 substations at the highest voltage levels; 15,000 HV substations; five million MV/LV or transformer distribution substations; 300m customer connections; and more than 5bn appliances.

Everything at the top of the pyramid is automated, whereas only a very small percentage of the five million MV/LV substations are equipped to take measurements, and an even smaller percentage have actuators or controllers. One big question concerns the degree of automation and control needed for the various voltage layers of the grid. Due to the increase of renewables at the distribution level, it is estimated that as many as 30% of the MV/LV substations should be automated, upgraded, or replaced by 2030 to cope with the capacity and voltage requirements.

One trend that will have a very large impact in the future is that grids will become 'inverter-rich' due to solar, wind and battery systems being connected and requiring conversion of types of current. This will enable more automatic switching (reconfiguring) and active control of generation, load, power flow and voltage. It will also change network behaviour with respect to faults and short-circuit current. The increased complexity involved will require major overhaul of protection systems, monitoring and control. New skills, tools and procedures to validate correct operation, robustness and security will be needed.

TRANSMISSION AND DISTRIBUTION SYSTEM ELEMENTS IN EUROPE (FIGURE 4-10)




Source: DNV GL

As prosumers become more prevalent, the volume of electricity transported by the distribution system may decrease markedly as discussed earlier. The cost of providing a secure and stable system will remain constant or increase, however. This presents difficulties for methods of charging for these costs: new charging methods and business models will be required to ensure a sustainable electricity market. In the past, the distribution grid was a system which took the energy from source to customer; in the future, its major contribution will probably be through guaranteeing a secure supply. ■

“

Grids will become ‘inverter-rich’ due to solar, wind and battery systems being connected and requiring conversion of types of current

# 4.9 OFF-GRID AND MICRO-GRIDS

Our forecast does not separate out electricity demand and generation for small and isolated electricity systems[13], because their impact on energy would be hard to see on either a global or regional scale.

That said, there will undoubtedly be substantial substitution of diesel generation by renewables and energy storage for isolated electricity systems, and this is already starting. This was driven previously by environmental concerns and a desire for autonomy, but there is increasingly a strong economic case for avoiding the costs of diesel in remote locations with good renewable resources, even where the capital cost of diesel plant is already fully paid-off.

The power electronic converter technology now provided in wind, PV and battery systems offers grid-forming capabilities that can provide electricity supply at satisfactory quality – as measured by frequency and voltage, for example – from small or zero synchronous generator capacity.

More dramatically, communities with no electricity supply now have opportunities to jump straight to renewables-only local networks, with storage, without going through a stage of connecting to large distribution and transmission networks. This is already happening in Africa, mirroring how some countries there went straight to mobile phones without developing copper networks. The renewables with storage option may also be relevant in some Asian countries. The best business models for this transition are not yet clear, however. Nor is it obvious whether cost fundamentals will eventually lead to the interconnection of such community networks to form grids.

Some small networks connected to larger systems can also be treated as microgrids. These are typically industrial or commercial sites with on-site generation and a relatively weak or limited network connection. They can also be 'weak' parts of distribution systems; 'edge of grid', for example. In these cases, network reinforcement can remove weak connections; or reduced costs for renewables, coupled with high grid-connection costs, could encourage complete disconnection, so-called 'grid defection'.

Some locations may reach a tipping point, where the capital costs of solar, or wind, with storage becomes lower than the network operator's capital costs for supplying a grid connection. This has significant implications for network operator revenue mechanisms, and is likely to provoke a move to more cost-reflective tariffs, as discussed for distribution systems in the previous section of this report. This in turn will increase incentives for customers to reduce peak demand, as this is the major driver of distribution network costs.

Operators may face difficult decisions about charging based on marginal or long-term costs. Marginal costing is often used for large electricity systems and may be preferred on the basis of pure economic theory; but for small systems with few users, it may result in substantial volatility in tariffs. ■

13 Typically islands, remote communities, and remote industrial sites such as quarries and mines

# 4.10 ELECTRIFICATION OF ENERGY USE

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

Residential space heat, water heat, and transportation as end uses are ripe for electrification given recent advances in commercialized technologies. This is reflected in our forecast. The status of technology and market development for electrification for these three energy uses is as follows.

## RESIDENTIAL SPACE HEAT

Heating domestic residential space accounts for 20% to 30% of total energy use in buildings in developed economies. Fossil fuels account for 70% to 80% of all energy used for residential space heat. Recent advances in ductless heat-pump technology have lowered the capital cost of purchase and installation, and increased operating efficiency. These changes have vastly improved the economics of converting fossil fuel residential space heat systems to electricity, but significant barriers remain to rapid uptake in heat-pump technology.

These partly explain why forecasted residential electrification remains slow:

— Consumer economics and behaviour: The customer value of conversion varies greatly with local climate and energy price conditions. A recent US study found that conversion from fossil fuel systems to electric heat pumps reduced lifecycle costs of ownership only in warmer climate zones and in instances where the heat pump replaces both central heating and cooling equipment. Moreover, reductions in lifecycle cost averaged only USD25 to USD200 per year, a level of savings that does not present a compelling case for investment in major home energy system replacements[14]. Experience in similar issues shows that due to the 'hassle factor', households do not often respond well to policy signals even when the economic case is clear. Millions of individual decisions are required to produce a significant impact, unless households are incentivized or regulation drives change.

— Energy savings and emissions reduction: Realization of region-wide energy savings and emission reductions through conversion to electric heating depends heavily on the fuel mix of the local electric system and the efficiency of the gas systems replaced. The US study cited above found that conversion to electric ductless heat pumps consistently yields savings in primary energy demand in areas with a typical generation fleet, in warmer climate zones and/or where the efficiency of the baseline residential heating system is well below current international standards. »

14 'Comparative energy use of residential gas furnaces and electric heat pumps', S Nadel, American Council for an Energy-Efficient Economy, Washington DC, 2016

If the mix of renewables in the local electric supply system is assumed to be 50%, conversion to electric heat pumps yields primary energy savings and emissions reduction in nearly all replacement scenarios. In developing countries, space heat is provided primarily by local bio-fuels. In these cases, electric space heat will likely leapfrog fossil fuel systems due to relatively low initial costs and the high costs of natural gas delivery infrastructure. Electric ductless heat pumps are already prevalent in urban areas in developing regions.

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

**RESIDENTIAL HOT WATER**

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

Recent technical advances provide opportunities to reduce energy use and emissions in this end use.

— Consumer economics and behaviour:
The newest generation of heat-pump water heaters consume 50% to 60% less electricity than comparably-sized conventional resistance heating models, with average energy savings of around 2,000 kilowatt hours (kWh) per year. At current levels of installed equipment costs and electricity prices in the US, payback time on the investment to replace a resistance water heater with a heat-pump model ranges from three to six years. The economics of converting from gas to electric hot water heating are less straightforward and depend on many conditions related to the individual home and its local gas and electric markets. Even under the most favorable assumptions, the difference in lifecycle costs between gas and electric heat pumps is negligible, however. Without subsidies and regulations to drive change, most customers would be unwilling to undertake the perceived risk and inconvenience of substituting a new technology for one that is very well-established.

— Energy savings and emissions reduction:
As is the case for space heat, region-level energy savings and emission reductions achieved through electrification of water heating will depend heavily on the fuel mix of the local generation fleet. Recent high-level analysis suggests that conversion of gas to direct electric hot water systems will result in a small increase in fossil fuel use and emissions in the US, where renewable resources currently constitute 15% of the generation mix. In many European countries, renewable sources already account for significantly higher shares of total electric consumption, however. In these cases, electrification of gas hot water systems will result in reductions in total fossil fuel use and carbon emissions.

— Load management and grid benefits:
Direct control of hot water heating has long played a key role in demand response programs in France and the US, and is currently being adopted on a smaller scale by distribution system operators elsewhere in Europe. In the US, direct control of water heat accounts for roughly 10% of enrolled demand response capacity, not counting load bid into forward capacity markets. The control technology and program designs for hot water load curtailment are well-established, and independent evaluation has shown them to be effective.

## ELECTRIC VEHICLES

Battery (BEV) and plug-in hybrid (PHEV) electric vehicles represent one of the most dynamic energy technologies. While EVs represent only about 1% of global vehicle sales today, annual volumes are growing rapidly. Results from the first quarter of 2017 suggest that annual unit sales will increase by 40% to 50% over 2016 levels. We forecast very significant growth in EVs.

As discussed below, substitution of EVs for conventional fossil-fueled cars yields significant emissions reductions, as well as distributed storage capacity that can be accessed to facilitate decarbonization of electric supply. Customers continue to face, or at least perceive there to be, many barriers to purchasing EVs. However, advancements in technology and business models to deploy EVs are likely to underpin accelerated growth. Supported by many industry predictions, we forecast that cost parity with internal combustion vehicles will come in five years' time, and that half of all light vehicles being sold between 2025 and 2035 will be electric, though this fraction will vary between regions.

— Consumer economics and behaviour:
Given current relative prices of gasoline and electricity, consumers in advanced countries can reduce personal transportation fuel costs by switching to an EV. In the US, this amounts to savings of USD500 to USD600 per year. Despite this, several barriers continue to inhibit demand for EVs. Spurred by environmental regulation and competition from start-ups such as Tesla, several major global manufacturers have made large investments in EV design and production. As a result, and combined with expected continuation of cost learning rates for batteries, it is expected that the cost of EVs will decrease and performance and range increase. Manufacturers have also begun to work closely with utilities and the public sector to accelerate the growth of charging infrastructure.

  - Lack of customer awareness of the availability and performance attributes of the product
  - High upfront capital costs compared with the alternative
  - Actual and perceived shortfalls on charging infrastructure and battery-size limitations
  - Charging time compared to refuelling a conventional vehicle
  - Lack of standardization in charging infrastructure and systems.

— Energy savings and emissions reduction:
EVs require roughly one-third less primary energy than their internal combustion counterparts. Net reductions in carbon emissions per light vehicle average 2.2 tonnes per year, given the typical generation fuel mix in advanced economies and average annual distance driven of 16,000 km.

— Load management and grid benefits:
Broader adoption of EVs will contribute to higher levels of generation and distribution system capacity utilization, especially if EV owners charge their vehicles during off-peak hours. Recent studies have shown that, even without time-of-use (TOU) tariffs being in effect, EV charging peaks late at night - the hours of lowest total demand on the system. Analyses of recent TOU tariff pilots for EVs have shown that such pricing mechanisms have been effective in shifting charging station usage further off peak. A recent study commissioned by California Investor-Owned Utilities forecast that application of TOU rates increases the benefits of promoting EVs by USD640 per vehicle over the life of the vehicle through deferring the need to reinforce local distribution grids. Several utilities in Europe and the US are now testing the feasibility and economics of using EV batteries to support demand response efforts. ■

# 4.11 BUILDINGS AND THEIR ENERGY EFFICIENCY

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

### TRENDS IN CONSUMPTION PER UNIT

In some developed countries, energy consumption per housing unit has been decreasing slowly since the late 1990s. In Europe, the decrease has averaged about 0.8% per year; in the US, it has been about 0.5% per year. The most recent residential energy use surveys in Europe and the US suggest that the pace of decrease in unit energy consumption has slowed or even reversed, however. The main reason appears to be the addition of consumer electronics and other household appliances, which has offset efficiency gains in heating and cooling. In Pacific nations, such as Japan and Korea, consumption per housing unit has increased slightly over two decades, again reflecting increased penetration of household appliances. Most world energy models, including our own, forecast that residential energy use per unit in advanced countries will begin to decrease more consistently by 2020, driven by slower population growth, full saturation of appliances and electronics, and increases in efficiency in lighting and space conditioning.

Developing economies provide a mixed picture on residential energy consumption. In general, use of local biomass is reducing and will continue to decrease going forward, but remain high and, in some cases, of concern from climate change and environmental perspectives. Both Indian Subcontinent and China have made considerable progress over the past three decades in shifting away from local biomass to fossil fuels and electricity. Use of local biomass greatly inhibits efficiency gains since conversion devices are inherently inefficient. More importantly, burning biomass such as wood and charcoal yields extremely high carbon and particulate emissions, and contributes to other environmental problems such as deforestation, flooding, and soil erosion. Despite more than a decade of rapid economic growth and urbanization, local biofuels supply 74% of all residential energy in Indian Subcontinent and 47% in China, however. In Africa, which has not seen the level of urbanization experienced in Indian Subcontinent and China, the share of total residential energy provided by biomass remains a very high 96% and is forecast to decrease only to 61% by 2040.

### TECHNOLOGY ADVANCES TO SUPPORT ENERGY EFFICIENCY

#### LED LIGHTING

In advanced economies, lighting accounts for 9% to 15% of total residential electricity use, and 30% to 40% in the commercial sector. Light emitting diode (LED) technologies offer energy savings of 10% to 70% energy depending on the specific application and baseline technology in place. Other consumer benefits including longer life and reduced maintenance costs are driving rapid increases in market share. Across all applications, the global market share of LED lamps grew from less than 2% in 2012 to nearly 13% in 2016. Further potential for energy savings as LED uptake increases is therefore significant. Strong competition among suppliers to improve performance, reduce price, and expand distribution channels is very likely to ensure continued growth of LED lighting. However, lower-quality LED lighting can distort the AC waveform, causing 'grid pollution' and increasing the need for reactive power.

## ENERGY INFORMATION SYSTEMS AND CONTINUOUS COMMISSIONING

Engineering case studies have long demonstrated that total energy use in most existing commercial buildings can be reduced by 10% to 15% through best practices in energy management. The rapid decreases in the cost of building energy system sensors and data communication infrastructure, combined with advances in wireless data communication, have increased the ability of building operators and managers to focus on operating improvements that will yield the greatest savings. The emerging practice of Strategic Energy Management (SEM) is becoming codified through international standards such as ISO 50001, and the usefulness of these methods is being demonstrated through third party verification. Major international property managers are adopting SEM in their leased portfolios to ensure high levels of tenant satisfaction and reduce tenant turnover. We anticipate that adoption of SEM will increase over the forecast period.

## ZERO NET ENERGY APPROACHES

Building officials and regulators in state and municipal jurisdictions throughout advanced economies have been working to make building codes governing energy use in new buildings more stringent, in some cases setting goals to reach zero net energy operation. This means that the amount of energy a building or cluster of buildings uses in the course of the year will roughly equal the amount of energy produced on site through renewable sources. In the US, California has adopted legislation to require that all new residential developments meet zero net energy (ZNE) requirements. Many other states are investigating similar regulations.

Different combinations of government, academic, and industry organizations in nearly every European Union member state are pursuing efforts to develop ZNE standards. According to recent studies, the incremental cost of building a ZNE home or commercial building, versus a comparable building that meets current building codes, is declining. This change has been driven by reductions in costs for components such as PV panels and inverters, as well as by increased experience with ZNE techniques among architects and builders. One report that compiled the results of cost information on 19 residential ZNE projects found that the incremental cost added by energy-efficient construction elements other than PV systems ranged from €45-€185 per square metre (/$m^2$). The cost of PV systems for these homes ranged from €12,000-€18,000 per house prior to the application of tax credits and other incentives. For commercial buildings, estimates of incremental costs for energy-efficient construction elements range from €82-€165 /$m^2$ higher than for comparable code-compliant buildings, before accounting for the costs of PV systems[15].

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

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

15 'California zero net energy buildings cost study', Davis Energy Group, Publ. Pacific Gas & Electric Company, 2012

# 4.12 ENERGY EFFICIENCY IN MANUFACTURING INDUSTRY

Manufacturing continues to grow, accounting for around 16% of global GDP and 14% of employment. Its relative share of an economy varies with its stage of development. Industrialization brings rapid growth in both manufacturing employment and output.

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

### TRENDS IN MANUFACTURING INDUSTRY

The energy intensity of industry has improved greatly since the mid-1980s, one main reason being industry's continual investment in new process equipment that tends to use energy more efficiently than previous generation models. Continued improvements in energy efficiency will require continued investment in technology developments.

There will be regional variations. Drawing from several sources, for Indian Subcontinent and China, energy intensity is expected to improve by up to 1.9%/yr until 2050; 1-1.25%/yr in North America and Europe; and 1%/yr in Africa and South America.

### ADVANCES TO SUPPORT ENERGY EFFICIENCY

Manufacturing industry's options for improving energy efficiency are generally incremental in nature and use known technologies to reduce the energy required for existing processes; for example, by reducing heat losses or improving process control. We have categorized these options as either 'no or low investment' or 'investment required'.

Within many business areas, energy efficiency options are often considered to be a 'good' investment without companies first considering what they can do with what they already have available. Companies have become more aware of this as they focus on how to decarbonize their businesses for climate change mitigation and other purposes including emissions reduction.

### ADVANCES IN 'NO OR LOW INVESTMENT' APPROACHES

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

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

Some other options requiring minimal investment include awareness campaigns for turning off equipment during shutdowns or other operational stops, or changing a company's thinking around energy culture. The latter is of increasing importance to manufacturers because significant savings can be achieved by changing how people think about energy and energy efficiency. This applies from small to large organizations, and the benefits can extend into employees' daily lives.

## ADVANCES IN APPROACHES REQUIRING INVESTMENT

Investing in technology for greater energy efficiency is related either to the industrial process, or to the consumption of utilities, such as hot water, steam, compressed air and lighting. Improving or changing processes typically reduces energy intensity. When the focus is on the utilities involved, investment in technologies such as combined heat and power (CHP), variable-speed drives, and LED lighting can deliver benefits. Improved heat recovery, using waste heat from one part of a process as a heat source for another, is another option.

Selecting investment choices follows a familiar path: identify opportunities within an organization; conduct a feasibility study of the options; make a final decision. Projects must comply with safety and legal regulations, and fit in with planned maintenance shutdowns, especially if construction work is required.

The energy efficiency options discussed here are only a small sample of what is available to manufacturers; the key message being that energy efficiency is becoming an increasingly important topic for them. ■

# 4.13 STORAGE

All electricity grids require energy storage on timescales of milliseconds to years[16], but conventionally this has been provided by the intrinsic properties of synchronous thermal generation: inertia, steam stored at high pressure, and fuel stocks. With increasing fractions of non-synchronous renewable generation, especially variable wind and solar, additional 'flexibility' functions are needed to allow electricity systems to continue to operate stably and economically.

There are several ways to provide flexibility. The principal ones are energy storage; increased interconnection between electricity systems; more flexible forms of generation, such as gas turbines and reservoir hydropower; advanced grid-connected inverter functions; and management of electricity demand.

In addition, for generation technologies which have low fuel or operating costs but higher capital costs – principally wind, PV, and nuclear, but also to some extent biomass and geothermal – there is also a separate economic driver to employ energy storage. Otherwise, at high penetration levels, there will be a need to curtail generation, which imposes a severe economic penalty on plants with low or zero fuel costs.

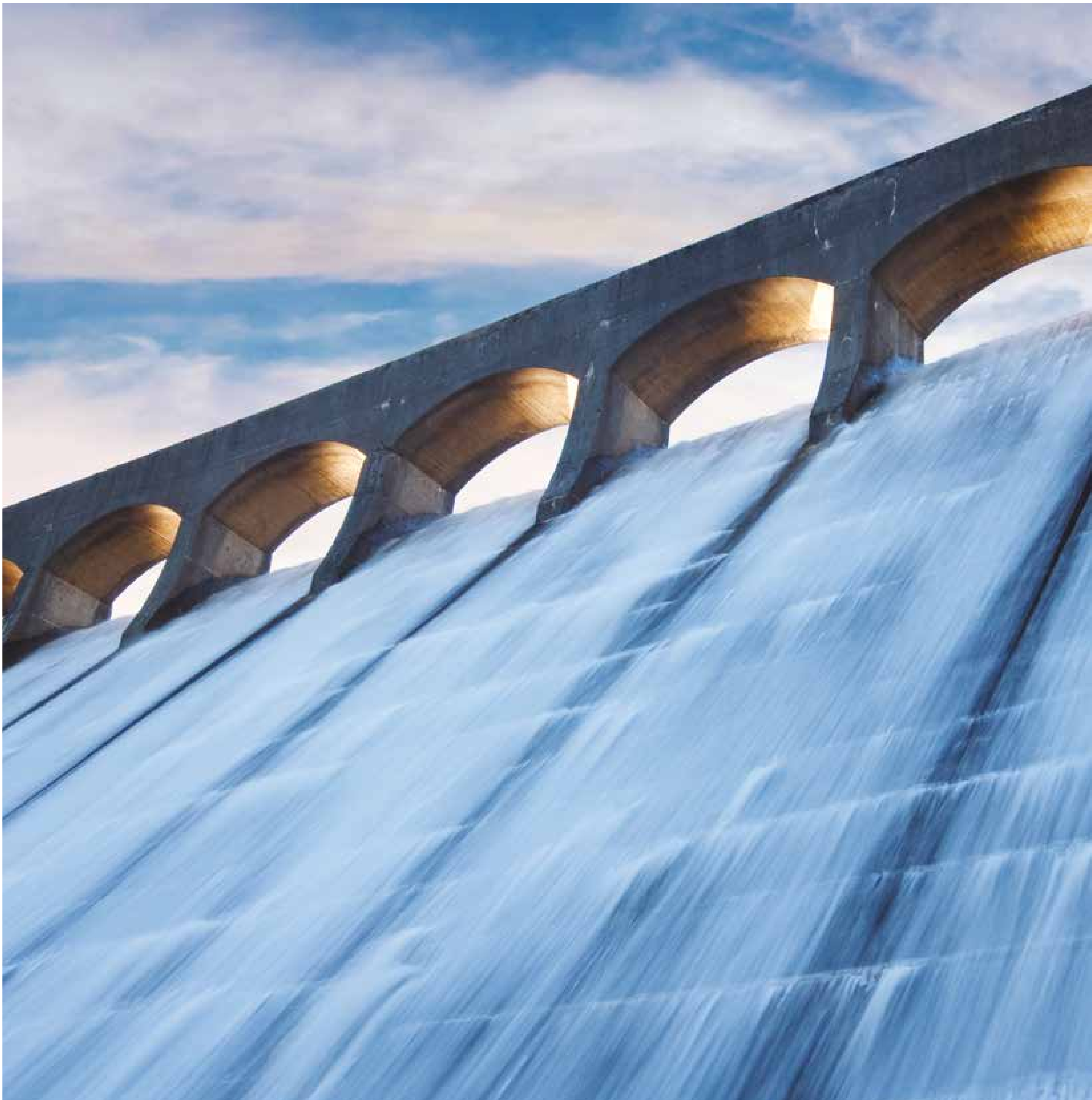
The principal electricity storage technology[17] has historically been pumped hydro storage; currently, 150GW of it provides well over 95% of all grid-connected electricity storage. Battery technology and costs have improved very rapidly, driven largely by EV developments, and these trends are expected to continue. Battery technologies cover a very wide size range: from hand-held devices to scores of MW. However, grid-connected battery capacity (2GW) is currently very small compared to pumped hydro storage, for which a further 20GW is in construction up to 2020. Other technologies such as compressed air storage may also be able to compete at utility scale.

Our model assumes new electricity storage is provided by batteries, but in fact the only impacts of this assumption are the costs that are assumed in our model. The need for new electricity storage is assumed to be driven only by the volume of variable renewables, wind and PV. In reality, battery storage installations may well be built for other reasons, such as provision of frequency response and other ancillary services, or deferral of network reinforcements. Our forecast also uses a small fraction of the battery capacity of the EV fleet to meet the storage requirement: this is a promising area for obtaining storage functions at low cost, but the technical implications and likely consumer attitudes are not sufficiently understood to allow a more detailed representation. Understanding these issues, and suitable business models, are areas of active interest.

Our model also indicates substantial need for new electricity storage to ensure a robust electricity supply with high fractions of wind and PV. The cost of this is included in the economic decisions about new PV and wind capacity, making them less attractive in regions with eventual high penetration. ■

16 A range of terms is used to describe the functions, including various terms for 'response' and 'reserve'

17 Electricity storage here means conversion of electricity to some other form of energy which can be stored, and then reconverted back to electricity when needed Conventional reservoir hydropower, or coal stocks, do not meet this definition. Also, using electricity to produce heat (or cold) which is stored for later use as heat is also excluded: this is instead a form of demand management.



# 5

# TAKEAWAYS FOR INDUSTRY STAKEHOLDER GROUPS

This chapter draws on chapters three and four to provide insight on the implications for specific types of stakeholders. One conclusion relevant for all is that change is going to be significantly more rapid than in the past.

## 5.1 TSOS AND REGULATORS

The principal 'takeaway' messages for TSOs are discussed here: many are also relevant for energy regulators or Government departments responsible for energy.

### ELECTRICITY CONSUMPTION

Very large increases in electricity consumption are predicted in all regions throughout the forecasting period. This is driven partly by population and GDP growth, by efforts to decarbonize other energy demands, particularly of heat and transport, and by the declining costs of renewable generated electricity, rendered possible by advances in technology.

In any specific country, changes may occur slower or faster than estimated by our model, because of the impacts of national policies for growth, industrial development, decarbonization of heat and transport, and others. Other factors including consumer attitudes will also be important.

There will be advantages for TSOs in being pro-actively engaged in national policy development.

### RELIABILITY

Ensuring a robust electricity supply in an environment of increasing uncertainty, as set out in other sections below, will require new analysis tools and improved forecasting.

New tools, processes and standards will also be needed to counter the new cyber security threats.

### RENEWABLES

There are very large increases in PV generation, onshore wind and offshore wind. Even in northern regions, PV generation is very significant.

The model makes no predictions about where the wind and PV will be located within each of the regions, but it is clear there will be implications for TSOs even if most renewable generation is connected to the distribution system. Predicting where this generation will emerge, and when, will continue to be difficult for TSOs.

Once the costs of renewables reduce to the point where no subsidy or other support schemes are needed, it will become very difficult to control the rate at which new renewable capacity is added. This is especially true for small-scale PV. TSOs should plan in advance for this eventuality.

Funding models for TSOs may need to change, in agreement with Government and regulators, to account for the increased uncertainty in transmission system expansion or reinforcement decisions: a 'least regrets' policy may become more attractive than attempting to optimize investment plans. Plans based on relatively small incremental investments, which can be modified as events unfold, will be more attractive than single large investments over long periods, even if lower cost.

New methodology for charging for connection to and use of transmission networks is likely to be needed, as more transmission capacity is required but the volumes of energy transported may reduce, at least until very high renewables penetrations are reached in the latter part of the forecasting period.

## SYSTEM OPERATION

Distribution networks will become more 'active', with more prosumers, distribution-connected generation, controllable demand (particularly electric vehicles), and storage devices. Some or most of this activity may not be 'visible' to the TSO, which will make system operation considerably more difficult and risky. TSOs and regulators should plan for this in advance. Potential options are:

- Establishing contractual and control relationships only with the DSOs, i.e. devolving substantial responsibility to the DSOs to manage their networks and users. The TSO then only needs to manage the interface with the DSOs. The DSOs have a substantially expanded role and must ensure that all users of their system meet technical requirements and obey system operation rules.

- Take responsibility for monitoring and if necessary control of all distribution-connected generators, prosumers, storage devices and controllable loads above a certain minimum size. This will require establishing contractual relationships with these entities, either directly or through the DSOs. It will also require substantial communications and control networks.

- Some intermediate combination of these two extremes.

TSOs and regulators need to be proactive rather than reactive in making these decisions.

System operation with fewer large synchronous generators will become more complex. Most of the technical issues are well understood, and for these the debate now is on how the required services are best provided, and how to verify that they will perform as expected to ensure a robust system.

## ELECTRIC VEHICLES

The issues of EV charging will be felt more by DSOs, but TSOs have opportunities to influence the contractual and regulatory arrangements in order to benefit system operation. This is one of the issues mentioned above where responsibilities need to be clearly defined between TSO, DSO, electricity supplier and vehicle owner. This is particularly true in some developing countries, where personal transport is moving straight to EVs (two-, three- and four-wheeler).

# 5.2 DSOS

### ELECTRICITY CONSUMPTION

As for TSOs, the increase of electricity demand will require substantial investment in distribution networks, against considerable uncertainty about location and timing of new loads and new generation.

DSOs may well find themselves in a position where they have to refuse to connect new residential PV installations or EV charging, for example, until the networks can be reinforced. New loads or generation can emerge significantly faster than DSOs can reinforce their networks. DSOs therefore need to establish new skills in forecasting what their connected customers may do.

In areas where substantial network reinforcement becomes necessary, some DSOs may find difficulty in significantly increasing their levels of investment in their networks.

### SMART GRIDS AND SYSTEM OPERATION

DSOs in principle can have more visibility of what is happening on their network than TSOs, but traditionally there has been relatively little measurement and monitoring. There will be major advantages in substantial increases in monitoring, communications and control functions for distribution networks, which are part of what is often loosely termed 'smart grids'.

These systems also represent a cyber security threat, and DSOs will have to add new skills, tools and processes to counter this threat.

Smart grids also include substantial interfaces between DSO and prosumers, directly or via aggregators. In the context of our model results, smart grids offer the ability to improve information flow from the connected customers, but more importantly could allow DSOs to control customers' loads to assist with system operation or to avoid reinforcements. The technical capability to do this is already available, but contractual relationships to allow this need to be established, and the trust. DSOs also need tools to enable them to judge the value to them, and to demonstrate this value to regulators.

### BATTERY STORAGE

Battery storage is in some circumstances already cheaper and more flexible than network reinforcement, and this is likely to increase. DSOs should seek to understand the benefits for their system, and incorporate this in their normal practices. This may require negotiation with regulators or government, as in some jurisdictions network operators are not allowed to own storage which may compete with generators.

### OTHER ENERGY NETWORKS

Some DSOs may be part of organizations which also operate gas or heat networks. In this case, they have the long-term opportunity to optimize their combined systems, particularly for heat supply, and for managing the variability of PV or wind generation on their system.

### ELECTRIFICATION OF RURAL AREAS

In some areas of Africa and Asia, there is an opportunity to provide electricity in areas currently unserved, using microgrids largely supplied by PV. This is currently happening, with many possible business models. Benefits are obvious and immediate. This type of microgrid may in future be preferred to traditional models of network extension.

However, difficult regulatory questions may arise later of rights to quality of supply, local monopolies, and eventual expansion and interconnection. ■

# 5.3 ENERGY SUPPLIERS AND AGGREGATORS

### BUSINESS MODELS

These two categories are considered together here, as it is likely that the value of services provided to electricity systems will grow relative to the value of energy supplied. Also, the services are likely to be supplied from a wide range of sources. Therefore, the distinction between energy suppliers and aggregators is set to become blurred: electricity consumers and prosumers are likely to have contractual relationships with their energy supplier or offtaker which include elements of demand control in order to provide services to the TSO or DSO.

In the context of our model results, the growth of electricity demand, particularly for heat and for EVs, expands the capabilities, and the loss of conventional synchronous generation expands the needs for such services.

The major issue is to identify the best business model. This will depend on local conditions, such as the opportunities to provide services to TSO and DSO, and the interest levels of consumers. Residential consumers in particular may be difficult to engage, as the net benefits to each per year may be small. There may be advantages in tying this in to larger investments, such as an electric vehicle, or heating system. ■

# 5.4 ENERGY CONSUMERS

### RENEWABLES

The forecast growth in PV and wind offers individual consumers and companies more opportunity to sign up to low-carbon electricity. There is currently a trend in corporate Power Purchase Agreements for purchase of low-carbon electricity, driven by corporate social responsibility aims, brand image, and cost certainty.

This is likely to continue and increase for some time; however, as renewables grow and electricity supply decarbonizes, the interest in the 'low-carbon' element is likely to decrease eventually. Those individuals and organizations wishing to demonstrate commitment to decarbonization are likely to move their focus to reducing and decarbonizing travel and transportation, and to heating/cooling demand.

### DEMAND RESPONSE AND PROVISION OF SERVICES

As discussed above for energy suppliers, electricity consumers and prosumers will have increased opportunities to provide services to electricity network operators. Multiple business models for this exist, and more will no doubt emerge. This will become 'business as usual' for commercial and industrial organizations: energy management will assume greater importance.

Further, as network charging evolves to truly reflect the costs of providing electricity network capacity and security, these larger customers will manage their demand accordingly, including installing battery storage 'behind the meter'.

Residential customers are unlikely to see enough cash value to be directly interested in provision of services to the networks. However, they may be more involved if this is part of major investments like house purchase or car purchase. Alternatively, if autonomous vehicles as taxis become widespread and vehicle ownership drops, the vehicle fleet operators will become major energy consumers with substantial ability to managing charging demand and location.

### HEAT

As well as decarbonization of electricity, it is also necessary to decarbonize heat supply. There is a complex set of options for this, as discussed elsewhere in this report, which includes dealing with the very strong seasonality of heat demand. An important impact for energy consumers in developed countries with established gas networks is that they may have to become accustomed to decarbonized heat supply costing significantly more than at present.

### BEHAVIOUR OF RESIDENTIAL CUSTOMERS

Although it is noted above that the cost advantage to individual householders is often not sufficient to gain interest and change behaviour, the experience of rooftop PV in some areas shows that there can be a strong 'demonstration effect'. This is probably related to visibility: so, similar effects can be expected with EV adoption, but probably not with better heating controls for example. ■

# 5.5 INVESTORS

Traditionally, the power sector was a long-term low-risk 'infrastructure' type investment. This is no longer entirely the case for power generation, and in future might not apply even to transmission and distribution networks.

### REGULATION

As noted earlier, change is likely to occur fast. Regulators have in the past been one of the impediments to change. Investors in new business models and emerging markets will need to understand the regulatory changes necessary for their investments to prosper, the likelihood of these changes occurring, and the risks of delay.

Likely examples where strong regulatory involvement is necessary include markets for ancillary services or for generating capacity, and the principles for charging for use of electricity networks.

### INVESTMENT DURATION AND SIZE

One of the features of increased rate of change is that long-term investments become less attractive. Short-term investments with greater certainty are favoured, particularly if they can be implemented incrementally. Thus, investment in multiple battery-storage installations at critical points on a distribution network may be preferable to large-scale reinforcement: at the very least, this buys time for the need for reinforcement to become certain.

### STRANDED FOSSIL ASSETS

The ETO model shows very substantial decline in coal use over the forecasting period, and hardly any new developments in new coal beyond the first decade. The other fossil fuels do not show the same decline, but notably oil is decreasing fast towards the end of the forecast period. Our model shows that new capacity is needed for both oil and gas throughout the forecast period, as field depletion is faster than demand reduction.

### LOCATION

There is a clear distinction in our forecast between regions with very substantial increase in electrification, where very large total investment will be needed both in networks and in generation, and regions such as North America and Europe with slower growth in comparison; largely because they already have significant infrastructure in place.

Note that our model makes the simplifying assumption that all generation capacity, once built, operated until the end of its design life. However in reality, market conditions may cause plants to become uneconomic well before that, particularly where the contribution to system security (capacity) is not fully rewarded. ■

# 5.6 POLICYMAKERS

### HEADING TOWARDS VERY HIGH PV AND WIND GENERATION

The cost predictions assumed in our forecast indicate that there will eventually be very strong price pressure to generate most electricity from variable renewables, particularly PV. Our model shows very high renewables penetration in most regions well before 2050. No experience exists with large-scale electricity systems in these conditions; Ireland and Iberia (Spain and Portugal) are perhaps the closest current examples. The model results suggest that the costs of ensuring a robust system by building sufficient 'peaking' plant such as gas turbines to cover periods of low renewable generation are not excessive, and the emissions from such plants on an annual basis are acceptable.

On the other hand, there will also be periods of substantial surpluses of renewable generation, particularly in northern latitudes with strong seasonal effects. This may well drive integration of electricity, gas and heat networks, as storage of heat or gas is likely to be preferable to storage of electricity for periods of weeks or months. Production of hydrogen for transport use is also feasible. The model does not currently quantify these effects, and further work on these issues will be important for policymakers in governments, and owners of electricity, gas and heat networks. Timescales for building substantial new networks such as district heating or hydrogen are long, so policy-making needs to start now.

The space required for the volumes of PV and onshore wind forecast by 2050 is substantial. Major new transmission lines will also be needed, though on the other hand coal extraction and transport will virtually disappear. Policymakers will need to develop ways to reconcile conflicting objectives, including public acceptance.

### CHARGING FOR NETWORKS

Investments in networks will have to be made amid considerable uncertainty, and this will affect investment decisions as discussed above. Policymakers will need to decide how much of this risk is 'socialized', either by direct Government support, or by allowing the costs of inefficient investment to be charged to the network's customers.

### DECARBONIZATION OF HEAT

As discussed above, populations in developed countries with gas heating may be faced with costs for decarbonized heat which are substantially higher than at present. Some of the options for decarbonization of heat supply will cause substantial disruption to individuals or communities, for example installation of buried district heating pipes in urban streets, or incorporation of electric heat pumps in existing homes. Some of these options also require high take-up rates to optimize cost. Policymakers will need to consider if this disturbance will be politically acceptable.

### POLICY LEVERS

As PV and wind become competitive without subsidy, one policy 'lever' for governments disappears. Regulators and network operators are likely to complain that both planning and operation of networks are becoming harder or impossible; governments may need to develop policy that controls EV charging, or residential PV for example, to rates at which the networks can adapt. It will be difficult to do this equitably, without accusations of favouring large customers over small, or urban populations over rural.

### SECURITY

Electricity networks will become even more important to society. Cyber security risks will present a greater threat, and policymakers will need to consider if mandatory demonstration or testing of the robustness of electricity networks is justified. ■

# 5.7 ACHIEVING 2°C: MULTIPLE ACTIONS NEEDED

The 'most likely' future presented in this report is not pointing towards the one we would like to achieve.

As explained in the main report on our model, its results show that the world is currently not on course to achieve the objectives of the COP 21 Paris Agreement. It also shows that no single further action can achieve even the limited aim to limit temperature rise to below 2°C. However, the report does indicate that multiple achievable actions can together achieve this. In the context of this report, the following possible additional actions are highlighted:

- Greater and earlier adoption of renewables;
- Greater and earlier electrification of heat and transport;
- Greater reduction in overall energy use through very substantial energy efficiency actions, and change in personal behaviours.

Policy and regulation in favour of these additional actions are needed if the pace of installation is going to be faster than dictated by cost factors alone. Public acceptance of these implications of the shift to a low-carbon economy is also a key factor in accelerating the change.

The main report elaborates further on these and other issues. ■

# 6

# THE NEXT FIVE YEARS

# 6. THE NEXT FIVE YEARS

The main report discusses several issues which are important to monitor over the next five years, which will indicate where the model's forecasts are diverging from actual outcomes. Those issues are also relevant for this report. Some additional issues are discussed here.

## NUCLEAR

Our model assumes some growth of nuclear over the next five years, based on knowledge of current projects, but assumes no growth after then. This assumption is very sensitive to changes in national policy, driven by energy security and climate concerns. Any such changes would not significantly affect generation capacity over the next five years, but would show where assumptions for future ETO analyses would need to change.

Increased nuclear could result in less renewable generation; or it could result in more rapid reduction in coal and gas.

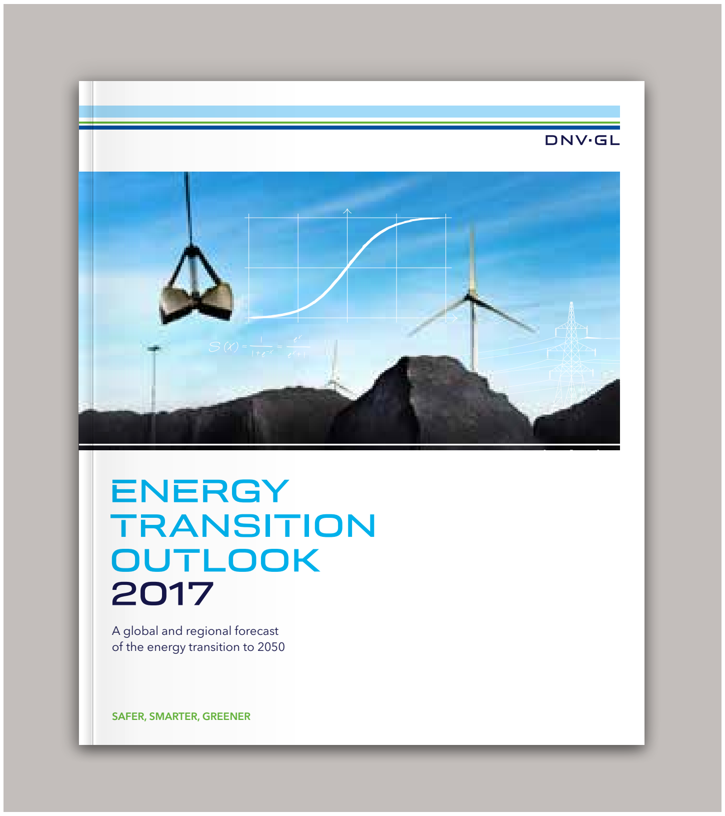
## COSTS OF INTEGRATION OF VARIABLE RENEWABLES

Our model assumes a 'perfect' transmission system over each region. There is some published evidence on the costs required to modify transmission systems to incorporate widely-dispersed renewables, but the picture is not clear and varies significantly between countries. The ETO model also includes some costs for dealing with the variability of PV and wind.

The general conclusion from other studies is that these costs are relatively low compared to the capital costs of the renewables. Experience in the next five years is likely to provide firmer evidence.

## CONSUMER BEHAVIOUR AND ELECTRICITY DEMAND

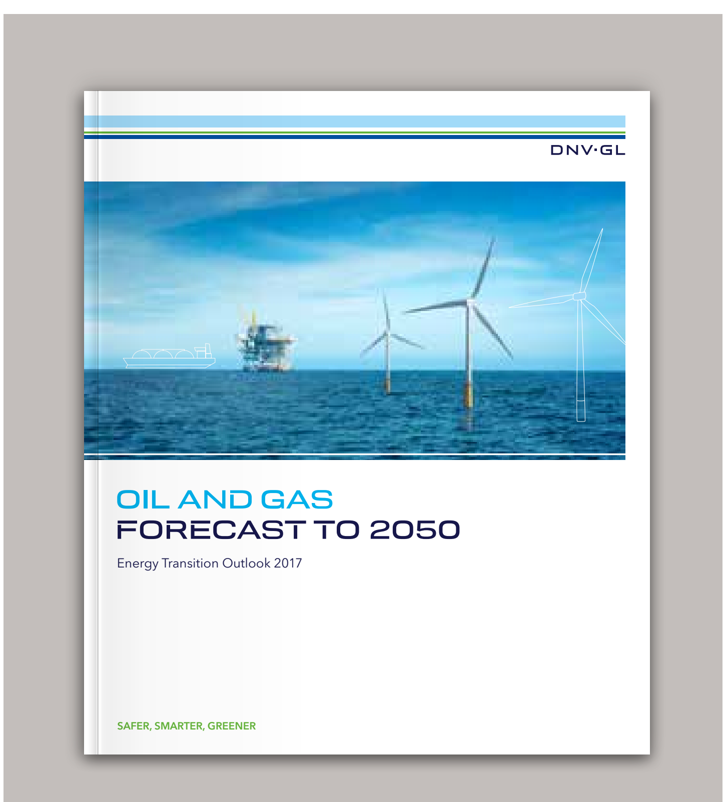
Our model currently has only a very simple treatment of the variation of electricity demand during the day and over the year. As consumers become more active over the next five years, greater information will become available on their attitudes to issues such as deferring demand, energy efficiency measures, and EV charging regimes. This could in principle significantly affect the amount of fossil peaking plants required to accommodate variable renewables, and the prospects for making economic use of surplus renewable electricity in the high-renewables situations towards the end of the forecasting period. ■




## ENERGY TRANSITION OUTLOOK

Our main publication deals with our model-based forecast of the world's energy system through to 2050. It gives our independent view of what we consider 'a most likely future', or a central case, for the coming energy transition. The report covers:

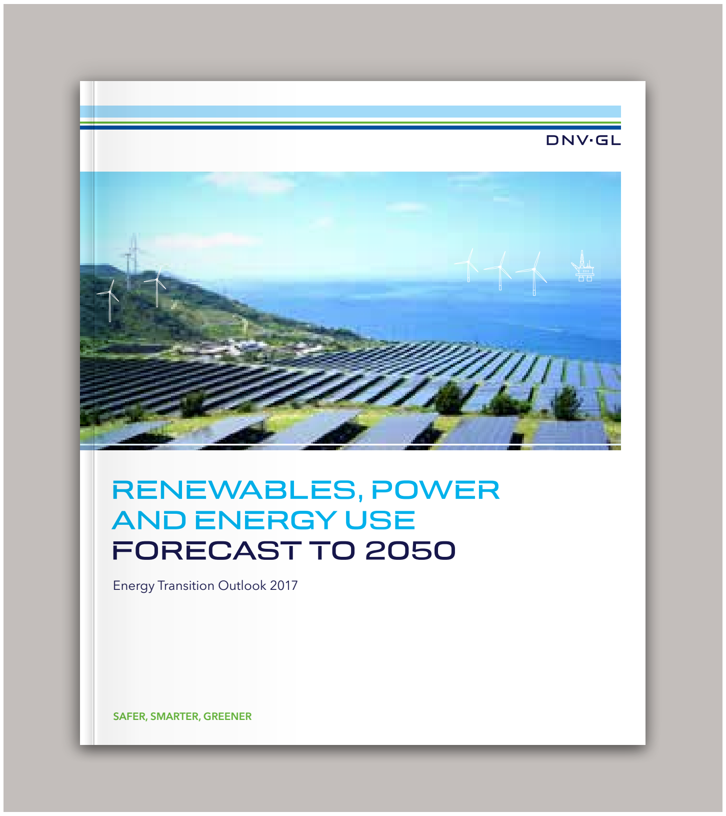
- Our main assumptions, on population, productivity, technology, costs and the role of governments
- The model behind our forecast results
- Our findings on global energy supply, demand and each of the energy carriers – and a sensitivity analysis.
- Energy forecasts for each of our 10 world regions
- Issues to watch in the next 5 years
- The climate implications of our outlook
- Highlights from our supplementary reports.




## OIL AND GAS FORECAST TO 2050

Oil and gas will be crucial components of the world's energy future. While renewable energy will increase its share of the energy mix, oil and gas will account for 44% of world energy supply in 2050, compared to 53% today.

In our oil and gas report, we have translated the energy requirements of key demand sectors into the trends we expect to see across the value chain. We discuss how the oil and gas energy system will meet this demand from existing and new production capacity. We also consider implications for LNG and pipelines, and the roles digitalization and emerging technologies will play across the value chain.




## RENEWABLES, POWER AND ENERGY USE FORECAST TO 2050

This report presents implications of our energy forecast for key stakeholders including electricity generation, including renewables; electricity transmission and distribution; and energy use.
The report covers:

- Key conclusions from our model
- Key technologies and systems, focusing on results from the model and on the expected key developments. The technologies and systems considered include: onshore and offshore wind; solar; hydropower; biomass; nuclear; coal; transmission grids and system operation; distribution grids; off-grid and micro-grids; electrification of energy use; buildings and their energy efficiency; energy efficiency in manufacturing industry; and storage.
- Takeaways for specific types of stakeholders
- Important issues to monitor over the next five years


## MARITIME FORECAST TO 2050

*Forthcoming*: our Maritime energy outlook will be published towards the end of 2017. It will explore the implications of our forecast for the shipping industry. The expected focus areas include the contribution of shipping to the decarbonization of the world's energy system and the impact of shifts in the energy mix on the demand and usage of vessel types and trading patterns. The forces driving this shift are not limited to emission regulations and physical risks to assets, but also changes in consumer preferences, new technologies, and the supply of energy, all of which will have an impact on shipping.

SAFER, SMARTER, GREENER

**DNV GL – ENERGY HEADQUARTERS**

DNV GL Netherlands B.V.
Utrechtseweg 310 – B50
6812 AR Arnhem
The Netherlands
Tel: +31 26 356 9111
www.dnvgl.com/energy

DNV GL is a quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable organizations 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 and advisory services to the energy value chain including renewables and energy efficiency. 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.

eto.dnvgl.com


**©DNV GL** 09/2017 **Design**: Infogr8 **Cover**: Fasett AS **Images:** Shutterstock (Cover, p 6, 12, 16, 51, 52, 62, 65).
**Paper:** Arctic Matt (115/250g) **Print:** 07 XPRESS

V. 0109