DNV·GL

ENERGY TRANSITION OUTLOOK 2018

A global and regional forecast to 2050

SAFER, SMARTER, GREENER

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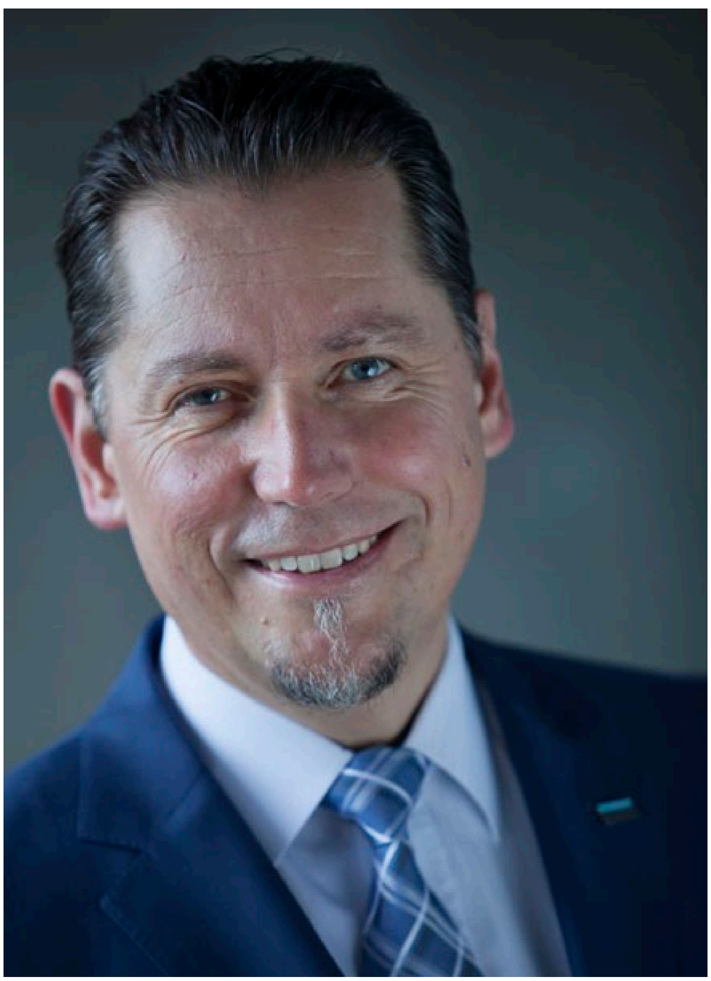
A global and regional forecast to 2050

FOREWORD

Our energy forecast has its foundations in the expertise of the thousands of DNV GL engineers working in both the oil and gas sector, and in power and energy use.



REMI ERIKSEN

GROUP PRESIDENT AND CEO
DNV GL

Those colleagues assess, survey, test and verify energy infrastructure being built now to supply the energy the world will need in 2050. And, for the technology not yet installed, we run more joint industry projects than any other organization in our industries, focused on new research driving better technology and improved process standards.

For us, and for many of our customers, the energy transition itself is the greatest source of risk – and opportunity.

Our own exposure, combined with our expertise and investments in future-looking activities, has enabled us to create an informed outlook on the energy transition, which I believe is worth sharing with our customers and others who influence policy and social decisions.

> "There are many signs that the energy industry is on the brink of profound change.

Globally, policy developments, despite some notable exceptions, continue to favour renewables technology. Last year, new renewable power capacity additions were more than double the new power capacity additions from fossil fuels. In capital markets, a reallocation of funds towards cleaner technology is underway. Where is all of this going to take us? That is what we aim to answer.

There are certain trends of which we can be reasonably certain. One of these has to do with cost, which, like water, constantly seeks lower levels. An important feature of this Outlook are cost learning curves associated with key energy sources – in other words, the rate at which costs decline with each doubling of installed capacity. For renewables and battery storage, this rate is in the high teens, and that will force a profound change in the world's energy mix in the coming decades.

But greater changes yet will emanate from advances in energy efficiency. Driven by pervasive electrification, especially of transport, and by ongoing efficiency gains in other sectors, linked in many instances to digitalization, we expect energy intensity (energy use per unit GDP) to decrease more quickly than the global economy will grow in the long run. The net result of that will be a peaking of energy demand worldwide in the 2030s. An energy market becoming smaller in less than two decades from now makes the quest for efficiency so much more strategic and urgent.

Naturally, the energy future is not likely to play out exactly in line with our forecast. The unexpected has a habit of turning up unannounced. Policy changes and technology and cost developments will unfold at uneven and sometimes unanticipated speed. That is why we have subjected our forecast to a number of sensitivity tests. While these adjustments lead to different outcomes, none is so different as to alter our main conclusion: that we have a rapid energy transition ahead of us with electrification and decarbonization of an ever-more efficient energy system. We forecast a very strong growth of solar and wind, initial growth in gas, and a decline in coal, oil and, eventually, gas, in that order.

This is the second year we have issued an Energy Transition Outlook. We have updated our model with new data and made adjustments on the basis of feedback and experience, and the result is a strengthening of the conclusions we came to last year.

In 2017, we forecast a levelling off in global final demand after 2030; this year our forecast points more towards a peaking of demand at a slightly higher level than last year, and, from 2035, a noticeable decline in demand to 2050. We have extended our work into other areas as well, and have more to say this year about effects of digitalization, resource limitations, cost of infrastructure and the role of hydrogen.

However, the future we forecast is not the future humankind desires. Even with a peaking of energy demand, and fast uptake of renewables and electric vehicles, the energy transition trajectory is not fast enough for the world to meet the ambitions of the Paris Agreement. Indeed, even if all electricity was generated using renewable sources from this day forward, we would still exceed the 2^{0}C carbon budget.

A mix of solutions is therefore required, including higher uptake of cleaner technology, more carbon capture and further improvement of energy efficiency. In those respects, our collective energy future enters the hard-to-forecast realm of political will and policy.

WE LOOK FORWARD TO YOUR FEEDBACK ON OUR 2018 OUTLOOK.

Remi Eriksen

ACKNOWLEDGEMENTS

This study has been prepared by DNV GL as a cross-disciplinary exercise between three of our business areas – Oil & Gas, Maritime, and Energy – co-ordinated by a core research team in our Group Technology and Research unit. The very many colleagues who contributed are listed on the last page of this report.

In addition, we wish to thank a wide range of experts from industry and academia for giving input to this report. Their comments and suggestions have been of great value, and any remaining errors and deficiencies remain our own.

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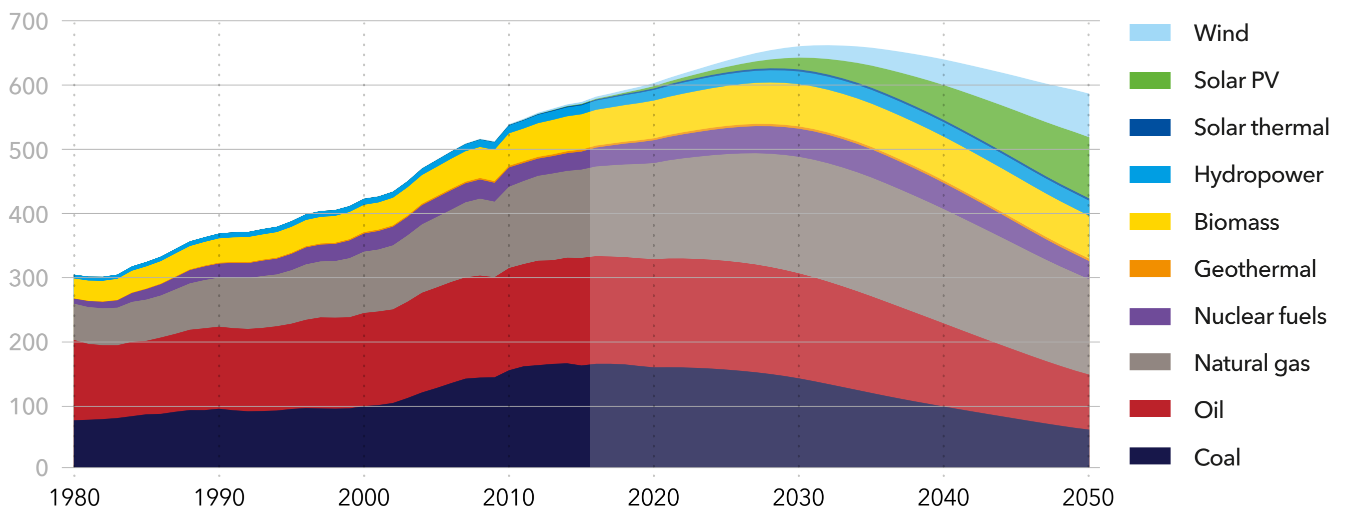
World primary energy supply by source

Units: EJ/yr



HIGHLIGHTS

1. The world will need less energy from the 2030s onwards owing to rapid energy efficiency gains; we forecast that primary energy supply will peak in 2032.

2. The world's energy system will decarbonize, with the 2050 primary energy mix split equally between fossil and non-fossil sources.

3. Oil demand will peak in the 2020s and natural gas will take over as the biggest energy source in 2026. Existing fields will deplete at a faster rate than the decrease in oil demand. New oil fields will be required through to 2040.

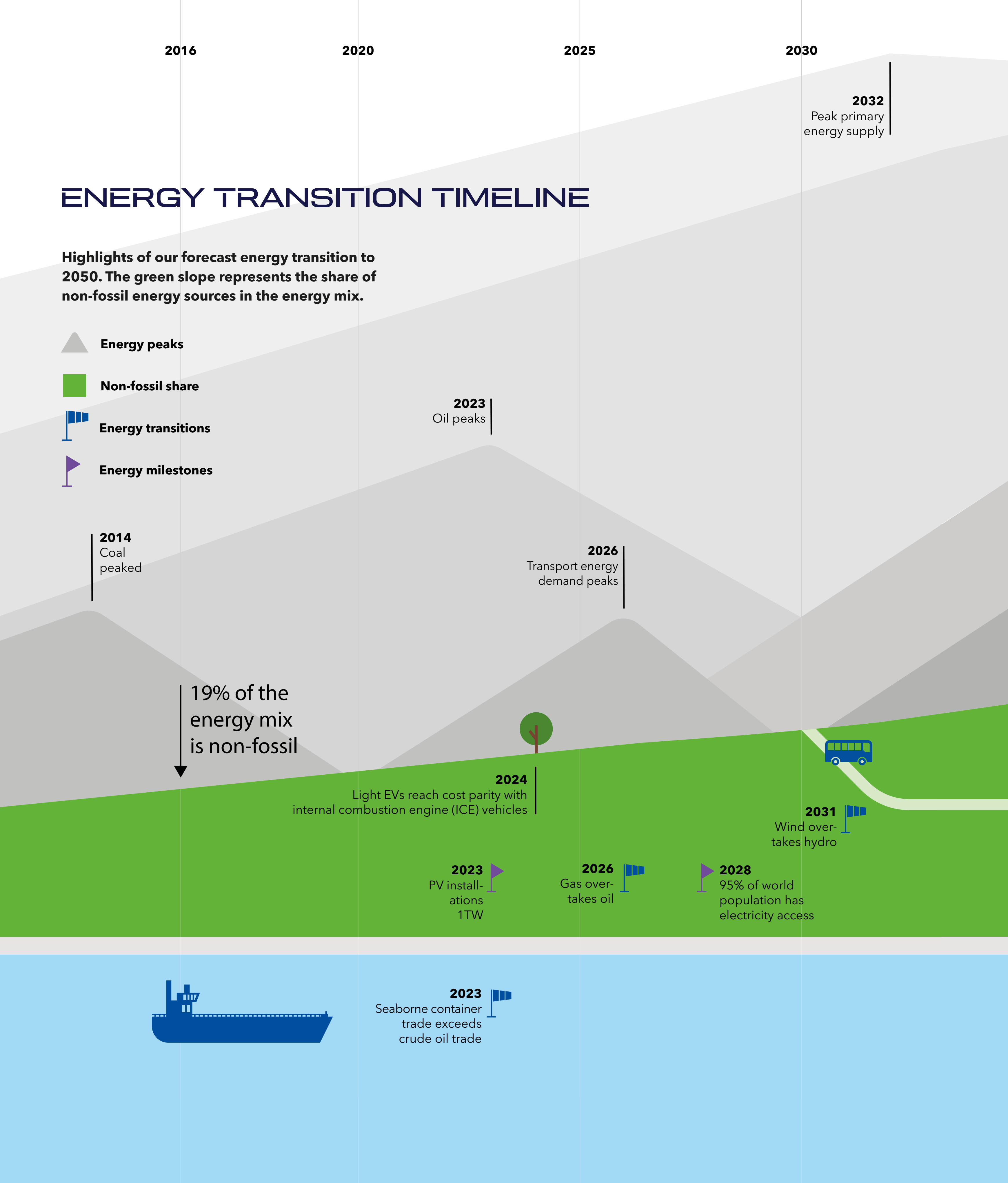
4. Electricity consumption will more than double by mid-century to meet 45% of world energy demand, and solar PV and wind energy will supply more than two thirds of that electricity.

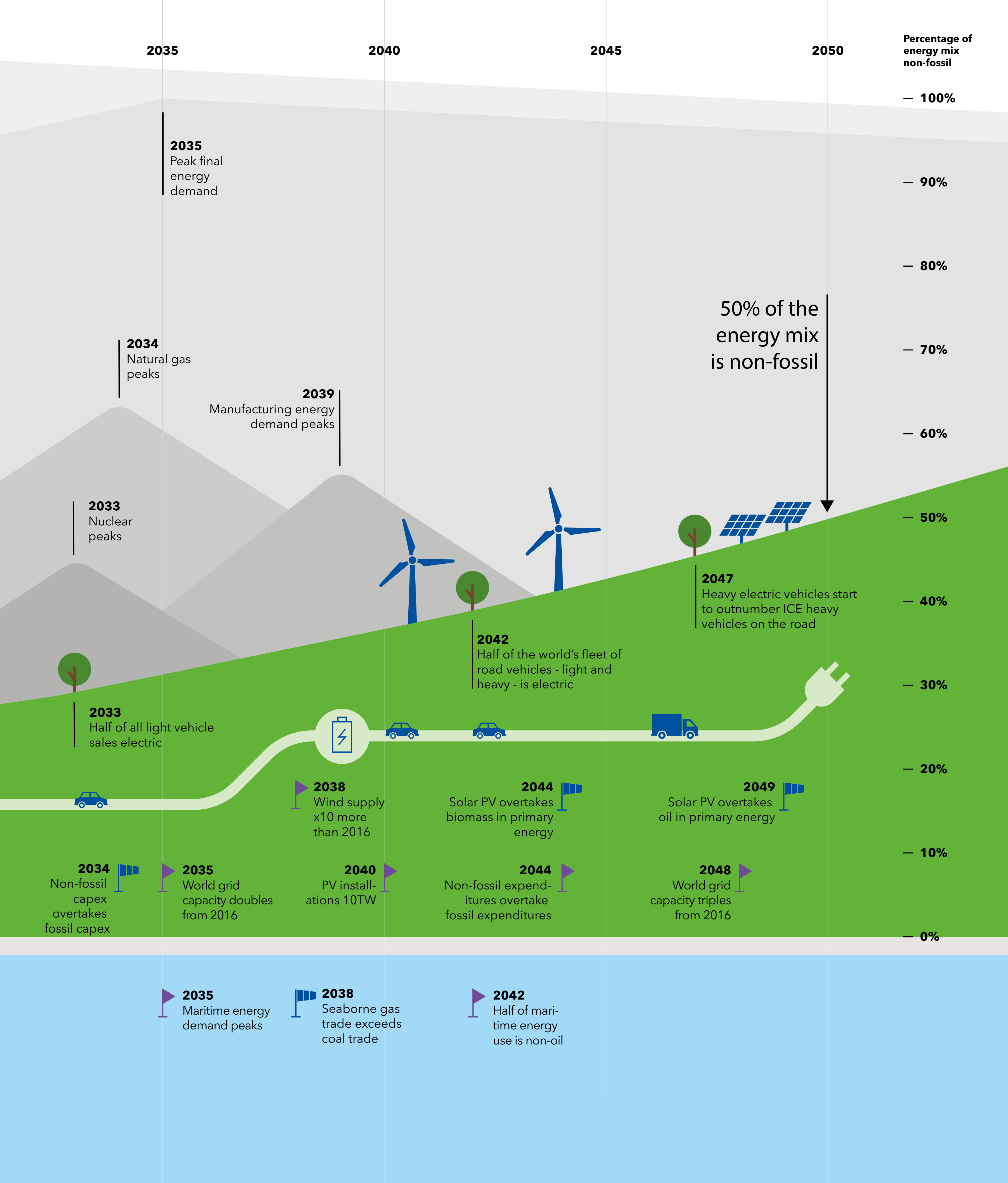
5. The energy transition is affordable. As a proportion of world GDP, expenditure on energy will be lower in 2050 than today. Big shifts in investments are expected: more capex will go into grids and renewables than into fossil projects from 2029 onwards.

6. The rapid transition we forecast will not be sufficient to achieve the less than 2°C climate goal. A combination of more energy efficiency, more renewables and more carbon capture and storage (CCS) is needed to meet the ambitions of the Paris Agreement.

ENERGY TRANSITION TIMELINE

Highlights of our forecast energy transition to 2050. The green slope represents the share of non-fossil energy sources in the energy mix.




2035
2040
2045
2050
Percentage of energy mix non-fossil
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2035 Peak final energy demand
2034 Natural gas peaks
2039 Manufacturing energy demand peaks
50% of the energy mix is non-fossil
2033 Nuclear peaks
2047 Heavy electric vehicles start to outnumber ICE heavy vehicles on the road
2042 Half of the world's fleet of road vehicles - light and heavy - is electric
2033 Half of all light vehicle sales electric
2038 Wind supply x10 more than 2016
2044 Solar PV overtakes biomass in primary energy
2049 Solar PV overtakes oil in primary energy
2034 Non-fossil capex overtakes fossil capex
2035 World grid capacity doubles from 2016
2040 PV install-ations 10TW
2044 Non-fossil expend-itures overtake fossil expenditures
2048 World grid capacity triples from 2016
2035 Maritime energy demand peaks
2038 Seaborne gas trade exceeds coal trade
2042 Half of mari-time energy use is non-oil


DNV·GL
VISITOR

EXECUTIVE SUMMARY

Over the next three decades, the world's energy system will become substantially cleaner, more affordable, and more reliable. Understanding this energy transition is critical for businesses, investors, and regulators.

WHAT IS THE DNV GL ENERGY TRANSITION OUTLOOK?

A STRATEGY TOOL

Based on DNV GL's independent model of the world's energy system, this annual Outlook aims to assist our customers' analysts and decision makers, and those in other stakeholder organizations in the global energy supply chain, to develop their future strategic options.

Our customers own and operate assets with useful lives that span decades – and during this period pivotal changes in the world's energy system will occur. On the brink of such changes between now and mid-century, we believe that it could be beneficial to take stock of business strategies and compare existing plans and investment decisions against the kind of model-based forecast that we have prepared.

Our findings indicate that immense challenges and opportunities lie ahead for the industries that we serve, and we explore these further in three 'industry implications' supplements:

- Oil and Gas
- Maritime
- Power Supply and Use

As this is an annual Outlook, it is subject to ongoing refinement aimed at continually improving its accuracy and relevance for those using it in their own strategic projections. Thus, results may vary from year-to-year as we incorporate new data sets and refine our model based on contemporary developments and improved insights.

AN INDEPENDENT VIEW

DNV GL was founded to safeguard life, property, and the environment more than 150 years ago. Since then we have developed a strong footing in both the fossil and renewable energy industries, and there, as in all other industries, our business is about creating trust. This, coupled with being fully owned by a foundation, allows us to take an independent and balanced view of the energy future.

As a company, we are a world-leading provider of quality assurance and risk management services in more than 100 countries. Two of our main business areas focus, respectively, on oil and gas, and on power and renewables. However, as the world's largest ship classification society, the seaborne transportation of energy as crude oil, liquefied natural gas (LNG), and coal are also key businesses for us. In fact, around 70% of DNV GL's business is related to energy in one form or another.

This Outlook therefore draws on DNV GL's broad involvement across entire energy-supply chains, spanning complex offshore infrastructure, onshore oil and gas installations, large- and small-scale wind, solar, storage, and energy-efficiency projects, electricity transmission and distribution grids, and seaborne trade in fossil fuels.

DNV GL is a knowledge-led organization, typically spending 5% of revenue on research and innovation. The core model development and research for this Outlook was conducted by a dedicated Energy Transition Outlook team in our corporate Technology & Research unit. The team relied on input from around 100 colleagues across our organization, as well as dozens of external experts whose contributions we acknowledge in the opening pages of our main report.

OUR BEST ESTIMATE

Our intention from the outset has been to construct what DNV GL sees as a central case for 'a best estimate future' for energy through to 2050. This contrasts with scenario-based approaches. Scenarios are typically set up to contrast multiple possible futures; for example, by varying the speed of the transition from the current energy mix to one dominated by renewables. Amidst a growing profusion of different energy scenarios, many customers ask us quite simply what we think is the most likely case. And it is the answer to this question that we present here.

HOW WAS THE OUTLOOK DERIVED?

MODEL-BASED

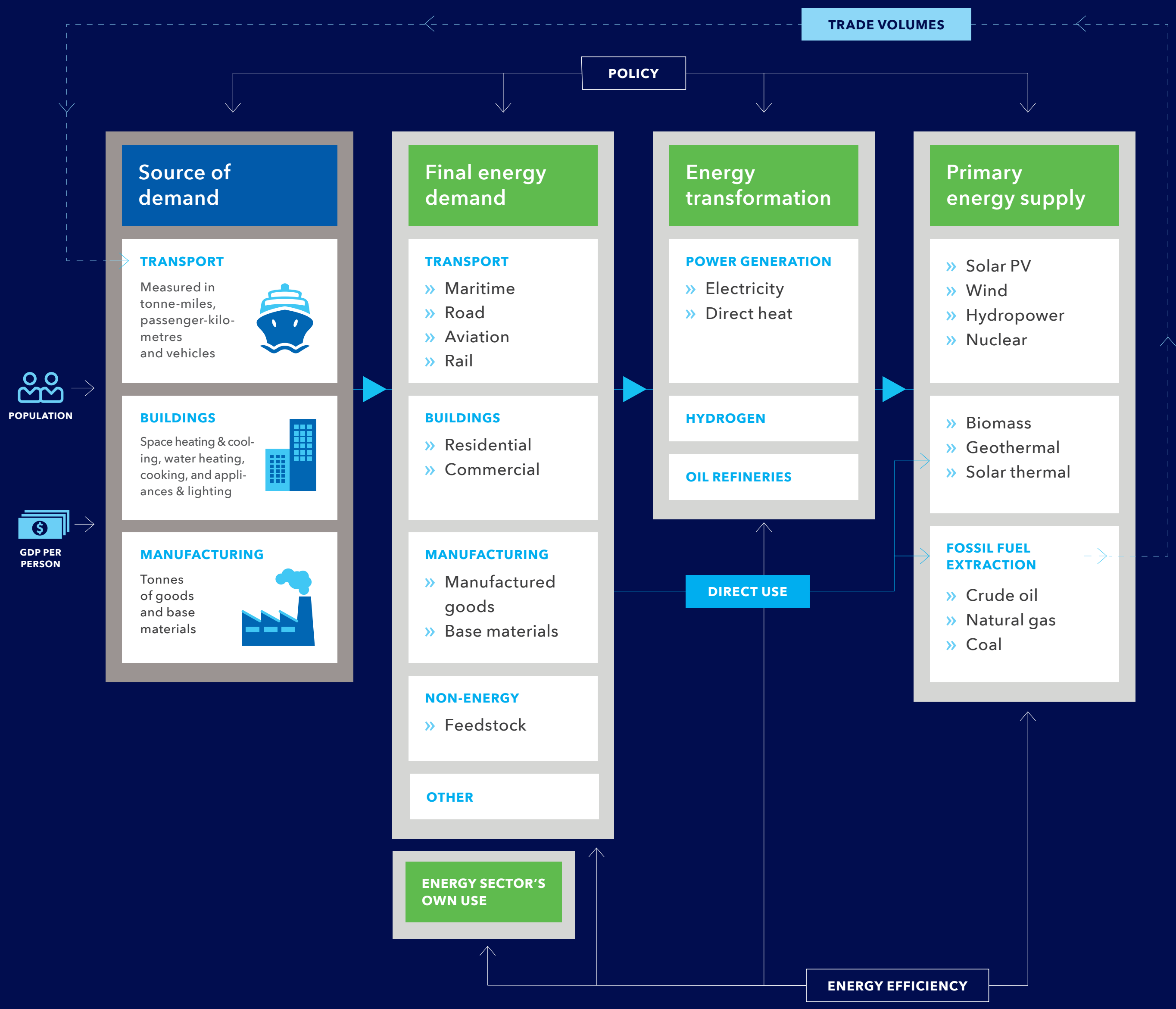
DNV GL has designed a model of the world's energy system encompassing demand and supply of energy globally, and the use and exchange of energy within and between ten world regions. The core of this is a system-dynamics feedback model, implemented in Stella software. The model incorporates the entire energy system – from source to end use – and simulates how its components interact.

The model includes all the main consumers of energy (buildings, industry, transportation and feedstock) and all sources supplying the energy (Figure 1). In several sectors, the model uses a merit order cost-based algorithm to drive the selection of energy sources. The evolution of the cost of each energy source over time is therefore critical and learning-curve effects are taken into account. Population and economic growth are the two main drivers of the demand side of the energy system in the model.

It is also important to state what we have not reflected in our model. We have no explicit energy markets with separate demand and supply determining prices; our approach concentrates on energy costs, with the assumption that, in the long run, prices will follow costs. We also do not incorporate political instability or disruptive actions that may revolutionize energy demand or supply, accepting that what constitutes 'disruption' is subjective. For example, our EV uptake model assumes a very rapid increase in the share of electric vehicles (EVs) when cost-parity is reached, with uptake following S-shaped growth. Rebound effects, where prices influence future demand, are covered to some extent in our model.

FIGURE 1

High-level view of the Energy Transition Outlook Model



The arrows in the diagram show information flows. Physical flows are in the opposite direction. Our model includes feedback loops such as that shown between the amount of fossil fuel extraction and maritime transport (tonne-miles) as a source of demand. There are other feedback loops not shown here, for example the positive feedback between cumulative installed capacity of renewables and the decline in their costs.

MODEL INPUTS

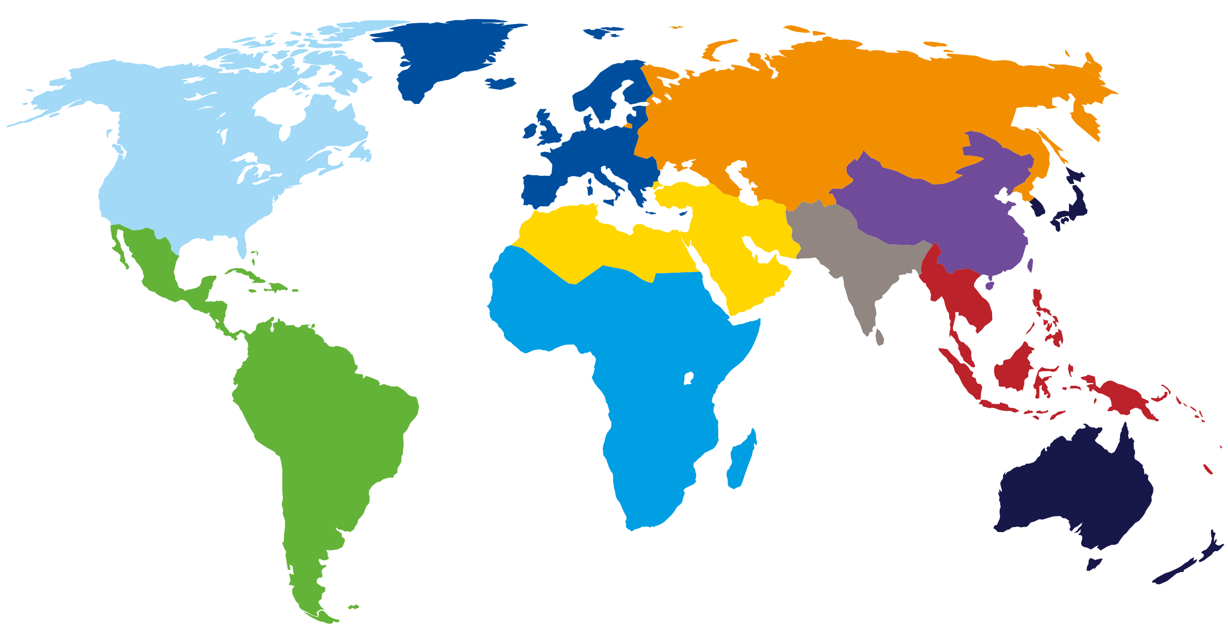
REGIONAL VARIATIONS

We find it meaningful to produce not just a global outlook, but also to explore regional energy transitions, including inter-regional energy trading relationships. This provides essential insights for any company which, like our own, operates internationally.

Countries included in each of the 10 regions (Figure 2) generally share some energy characteristics. Geographical contiguity informs our selection of regions in all but one case – 'OECD Pacific', which includes Japan, South Korea, Australia, and New Zealand.

FIGURE 2

Regional map of the 10 Outlook regions



- North America (NAM)
- Latin America (LAM)
- Europe (EUR)
- Sub-Saharan Africa (SSA)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- Indian Subcontinent (IND)
- South East Asia (SEA)
- OECD Pacific (OPA)

FUTURE ECONOMIC GROWTH PROJECTIONS

Future gross domestic product (GDP) is driven by population and productivity growth, and is a key driver for energy demand.

Energy forecasts often take the number of people worldwide as a departure point and their projections commonly rely on the World Population Prospects published biennially by the UN's Department of Economic and Social Affairs.

The UN has, however, been criticized for not taking country-specific education levels into sufficient consideration; these data are relevant for future fertility and mortality trends. Consequently, we prefer the approach used by the International Institute for Applied Systems Analysis (IIASA) at the Wittgenstein Centre for Demography and Global Human Capital in Austria, which specifically considers how urbanization and rising education levels are linked to declining fertility rates.

Using the IIASA models, but adjusting for a lower education update and faster population growth in Sub-Saharan Africa, which lags behind other regions in socio-economic development, gives us a global population in 2050 of 9.2 billion. This is some 6% lower than the 2017 UN median forecasts. In sensitivity tests, we also run our Outlook using the UN low and median population forecasts.

As the world's regions develop, they progress first through a phase dominated by primary economic activities, such as agriculture, then an industrialization phase, before the service sector becomes dominant. The potential for productivity improvement diminishes through these stages. Thus, while we see a more prosperous future planet, all regions will experience a slowdown in productivity growth.

The dual impact of slower population growth and less rapid expansion in productivity means that growth in global GDP will also decelerate.

By mid-century, even today's rapidly progressing emerging economies will experience slower growth as their economies gradually de-industrialize and become more service orientated.

The world is, however, still on track to more than double the size of its economy by mid-century. The historical growth rate of around 3%/year that we have experienced since 1980 is expected to continue towards 2030, and thereafter reduce to around 2%/year towards 2050.

Our forecast for global GDP is in line with recent projections by McKinsey and PwC. The International Energy Agency (IEA) and BP predict higher global economic development towards 2050, and that is one reason why they project greater growth in energy use than we forecast.

LEARNING CURVE EFFECTS

The premise behind the notion of 'learning curves' is that the cost of a technology decreases by a constant fraction with every doubling of installed capacity, owing to greater experience, expertise, and industrial efficiencies associated with market deployment and ongoing research and development.

Wind and solar photovoltaics (PV) have shown significant cost reductions and market growth in the last two decades. For wind, the historical cost learning rate is 18% per doubling, and we expect this to decline slightly to 16% in our forecast period. In addition, we factor in significant, but regionally uneven, public sector subsidies for new capacity, at least through the next decade.
For PV, the learning rate is historically 18% and

we expect this to continue and to drive down the cost of new installations, accepting that as installed capacity mushrooms, the rate of doubling as a function of time will slow along with cost reductions (Figure 3).

Notably, for systems dominated by variable renewables, which will be the case for several regions after 2040, storage capacity will be crucial. We account for this in our forecast by adding storage costs to the renewables' installations as they begin to dominate, which happens towards 2050 in several regions.

The learning curve for battery energy storage is expected to at least match those for wind and solar; and is set to 17% in our model. Consequently, we expect strict vehicle price/performance parity between internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) by 2024.

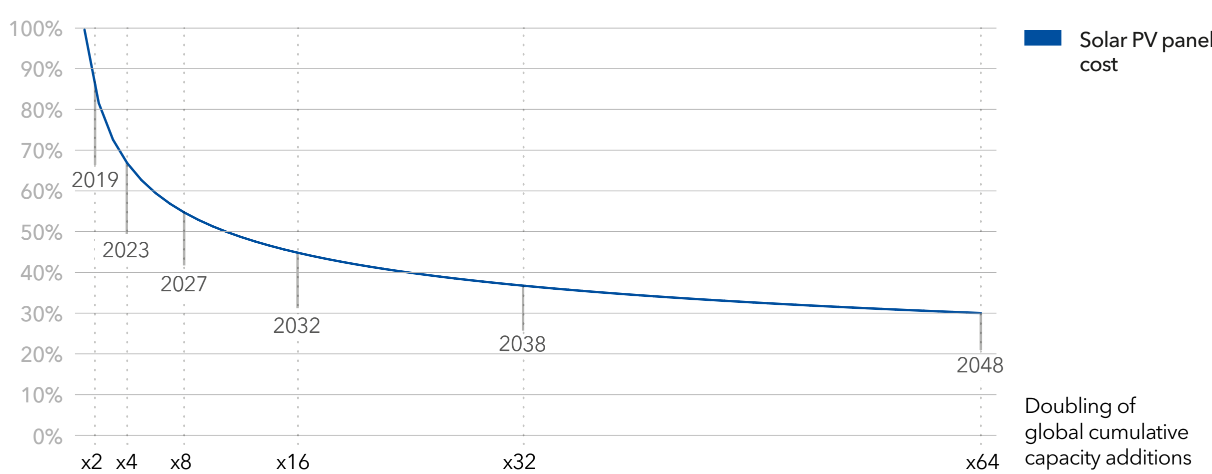
Incentives for EV infrastructure, and for wind and PV generation, will continue – albeit at steadily reducing levels – for the foreseeable future. But, after a decade or two, depending on the region, we see the energy transition acquiring a self-reinforcing momentum. This will be the main consequence of interacting cost and technology dynamics that enable low-carbon solutions to stand on their own feet.

A mixture of forces will be at play in the coming decades. There will be diverse political frameworks and policy measures to achieve climate or other policy goals and energy system change depending on a country's natural resource base, existing energy system structures, and available technology. Not all policies will seek to drive change; a cursory look at the history of carbon pricing is enough to show opposing forces at work. Indeed, our forecast assumes that the implementation of carbon-pricing schemes will remain difficult, and hence prices are generally likely to remain low and not exceed 60 USD/tonne CO_2 (in today's money) in any region before 2050.

FIGURE 3

Cost learning curve for solar PV

Units: Unit cost relative to 2016



2018 ENERGY TRANSITION OUTLOOK RESULTS

DEMAND

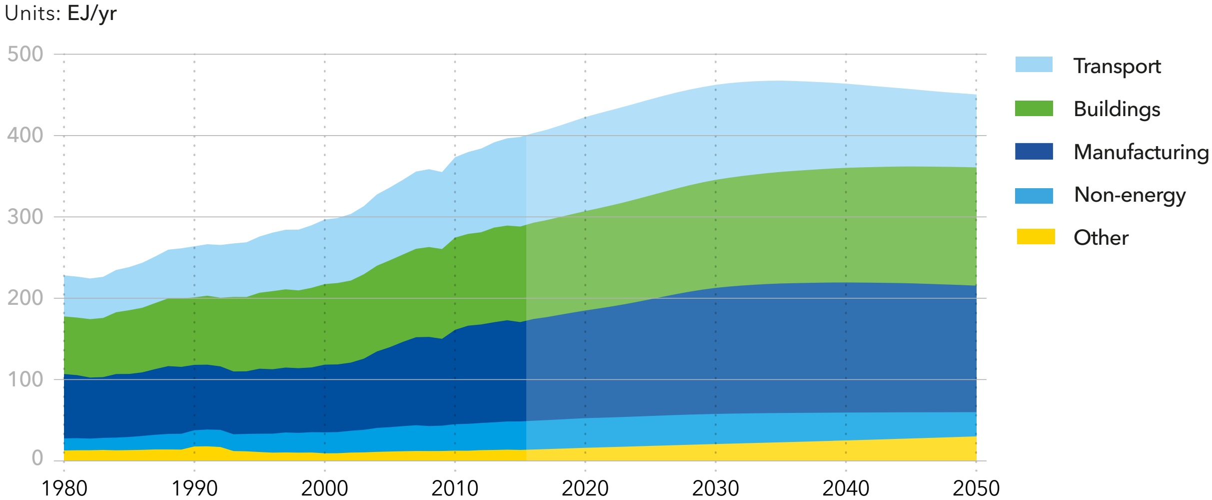
We expect global total final energy annual demand to be 450 exajoules (EJ) per year by 2050 compared with 400 EJ in 2016. Demand peaks in 2035 at 470 EJ per year (EJ/yr), then declines slightly towards mid-century. Before the peak, demand grows at 0.9% per year, but this rate slowly declines due to both energy-efficiency improvements and electrification outpacing the continued, but slowing, growth in population and productivity.

At first glance, the final energy demand chart (Figure 4) looks deceptively stable across major categories of demand. Transport shows initial growth, but plateaus at approximately 120 EJ per year over the period 2020–2030, before declining to 90 EJ per year by 2050 as mass electrification of the road sub-sector materializes. Our analysis indicates that uptake of EVs will follow an S-shaped curve, that describes the diffusion of technological innovation – examples of which include the rapid adoption last decade of flatscreen TVs, or, last century, the rapid transition from propeller to jet engines for larger aircraft. The manufacturing sector in our demand curve grows at first while later levelling off, whereas the energy demand from buildings continues to grow slowly throughout the forecast period.

FIGURE 4

World final energy demand by sector

Units: EJ/yr



WHAT IS AN EXAJOULE (EJ)?

The oil and gas industry normally presents its energy figures in millions of tonnes of oil equivalents (Mtoe), while the power industry uses terawatt-hours (TWh) and sometimes petawatt-hours (PWh) to describe large amounts of electrical energy. The SI unit for energy is, however, joules, or exajoules (EJ) when it comes to national or global energy statistics; this is also the unit that we have chosen to use in this Outlook.

So, what is a joule? In practical terms, one joule can be thought of as the energy needed to lift a 100 g smartphone 1 metre vertically; or the amount of electricity needed to power a single watt LED bulb for 1 second (1 Ws). In other words, a joule is a very small energy unit, and when talking about global energy we use EJ, which is the same as 10^{18} J, or a billion billion joules.

In this Outlook, the conversion factors we use are:

1 EJ = 23.88 Mtoe

1 EJ = 277.8 TWh


ELECTRIC

TRANSPORT

The total transport demand grows from 110 EJ today, peaking at 118 EJ in 2026 and then reduces to 90 EJ in 2050, declining from its present 27% of total energy demand to 20% in 2050.

Road transport dominates transportation energy use. The timepoint at which half of all new light vehicles (i.e. cars) sold are EVs will be 2027 for Europe, 2032 for North America, OECD Pacific, Greater China and the Indian Subcontinent, and 2037 for the rest of the world (Figure 5). The year in which half of all new cars sold globally are EVs is 2033. The pace of change is dictated by falling costs. Recent rapid advances in heavy vehicle electrification – especially in the bus and city municipal segment – leads to swift uptake of electricity here also, and half of the maximum modelled uptake of 80% is reached just after 2030 in Europe and Greater China, followed five years later by North America and OECD Pacific. Hydrogen is likely to grab a small share of this market towards mid-century.

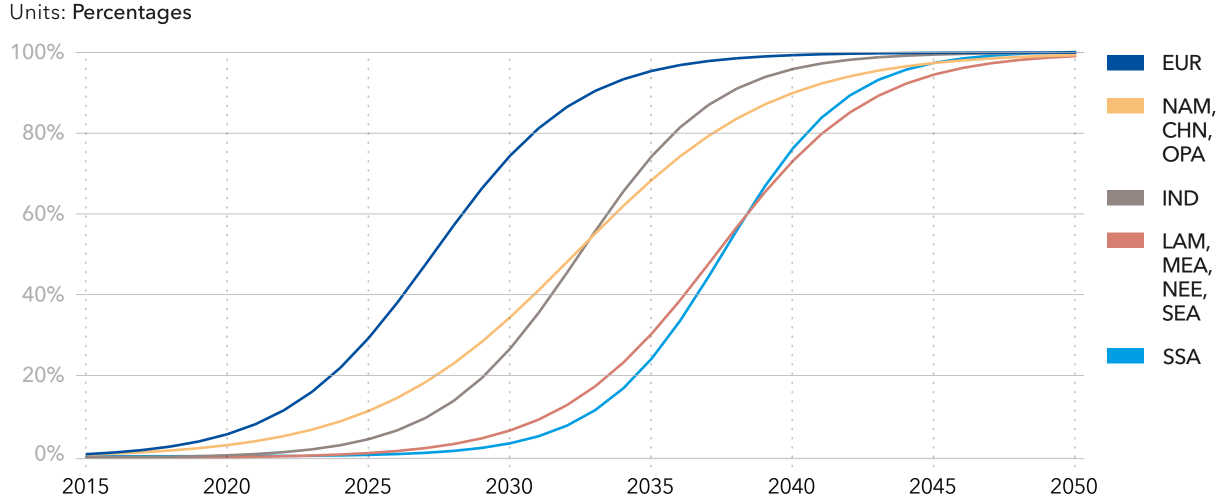
We expect growth in the maritime sector to recover by 2020. Despite an expanding fleet, energy demand in shipping is relatively flat at 11 to 13 EJ per year for the entire period, as improved engine efficiency, advanced hull designs, slow steaming methods, and new hull coatings all improve efficiency. To meet the IMO's new requirements for a 50% reduction in absolute emissions by 2050, the fuel mix in shipping changes dramatically. By 2050, biofuel will dominate followed by oil and natural gas, with electrification for some short-sea vessels and modest use of hydrogen.

Although the size of the aviation sector is expected to grow significantly, more efficient aircraft designs and engines will see energy demand largely flatten from 2030, with biofuels taking a 40% share of the fuel mix. We expect electrification of air travel to be still in its infancy by 2050. Rail electrification will continue, but rail remains a small sub-sector.

FIGURE 5

Market share of non-combustion light vehicles by region

Units: Percentages



BUILDINGS

Buildings consumed 29% of the world's energy in 2016, which amounts to 114 EJ/year. This share will grow by 0.5-1% annually, with the more vigorous growth occurring at the start of the forecast period. Overall energy use by buildings will reach 145 EJ/year in 2050 (Figure 6). There are likely to be significant changes in energy use by sub-sectors in the buildings category – namely, space heating, space cooling, water heating, cooking, and appliances & lighting. Urbanization and rural electrification in the developing world will result in a significant rise in energy demand for appliances & lighting, and space cooling. This rise in demand will occur even though energy drawn by space heating will remain relatively stable, and despite the energy savings that will result from the switch to cooking with gas and electricity in the developing world. Continued digitalization of industry and society will see an increased need for data centres and computers, but this will account for only 3 EJ or 2% of building energy demand by 2050.

MANUFACTURING

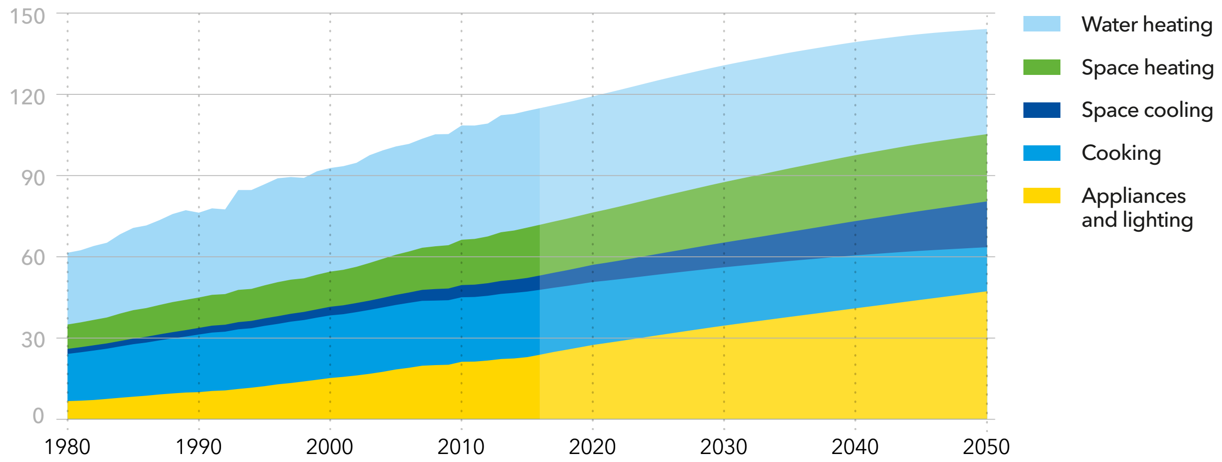
The manufacturing sector's energy demand will advance by 1.1% per year to peak at 160 EJ in 2039, and then decline slightly towards 2050. Correlated with global and regional GDP growth and regional changes in the size of the secondary sector of the economy, the global production of base materials will increase by 68%, from 29 to 51 billion tonnes, while output by weight of manufactured goods rises 130% from 13 to 30 billion tonnes during the forecast period.

Due to improved energy efficiency and increased recycling, energy demand from the manufacturing sector grows much more slowly, and even stabilizes after 2040. There is rapid displacement of coal by gas and electricity as energy carriers. Nevertheless, the dependence of China and India on coal, even in later decades, means the transition there will be slower; and, given their size, these two economic giants influence the global picture. This is despite the significant growth in China's

FIGURE 6

World buildings sector energy demand by end use

Units: EJ/yr



tertiary or service economy, which will assist in reversing the overall growth trend.

The sector non-energy use, which includes feed-stock for lubricants and plastics, asphalt, and petrochemicals, currently consumes 8.8% of the energy, and its share will slowly reduce over the forecast period to 6.6% in 2050. The final category, labelled "Other", is split between agriculture, forestry, military, and some other smaller categories.

SUPPLY

Our forecast shows an even more dynamic transition on the supply side of the equation, as electrification of industry and society accelerates towards 2050, and the primary supply mix changes dramatically with the influx of solar PV and wind, and the reduction in coal, oil, and – later – also gas.

ELECTRICITY

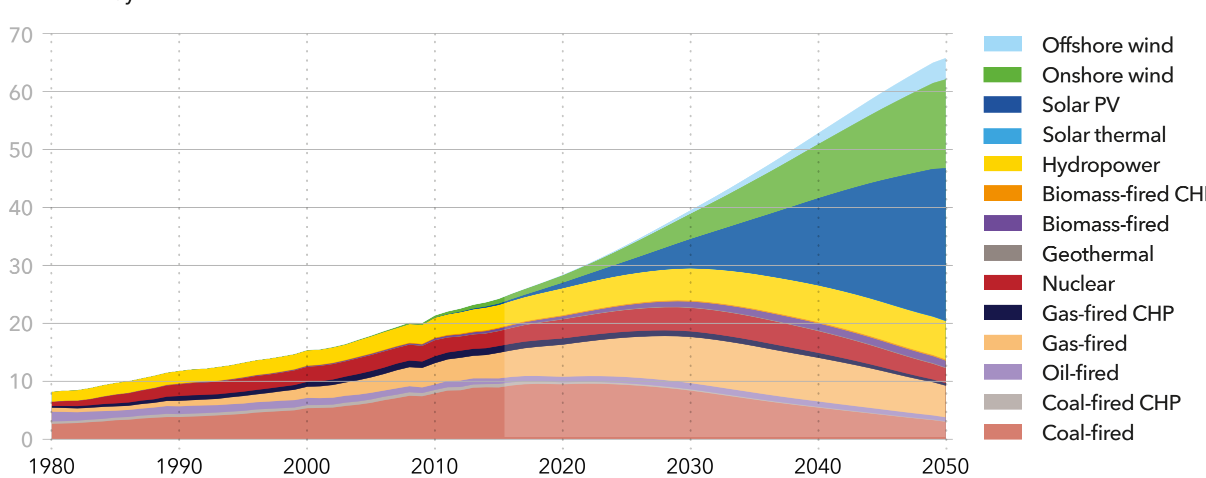
There is strong electrification across all demand categories, and we forecast global electricity supply to rise rapidly by 160% from 25 petawatt-hours per year (PWh/year) in 2016 to 66 PWh/year in 2050, thereby increasing its share of total demand from 19% to 45%.

Our model allows all potential electricity sources to compete on cost, which means that renewables also compete with each other. Renewables will increasingly dominate world electricity generation – with solar PV capturing a 40% share and wind 29% (Figure 7) by 2050. 80% of wind power will be onshore, but offshore wind will also be an important generation source. With this high amount of variable power, stability in the power network system will become crucial. The need for a comprehensive power system with increased connectivity, flexibility, storage, and demand-response will become more obvious, and is a topic we address extensively in our Power Supply

FIGURE 7

World electricity generation by power station type

Units: PWh/yr



and Use supplement. Electricity from thermal coal power stations will peak just after 2020, and gas-fired power generation will do the same in 2035.

HYDROCARBON PEAKS

Looking beyond electricity to the whole energy system, we foresee large shifts in the supply of primary energy (Figure 8). Oil and coal currently supply 29% and 28%, respectively, of global energy supply.

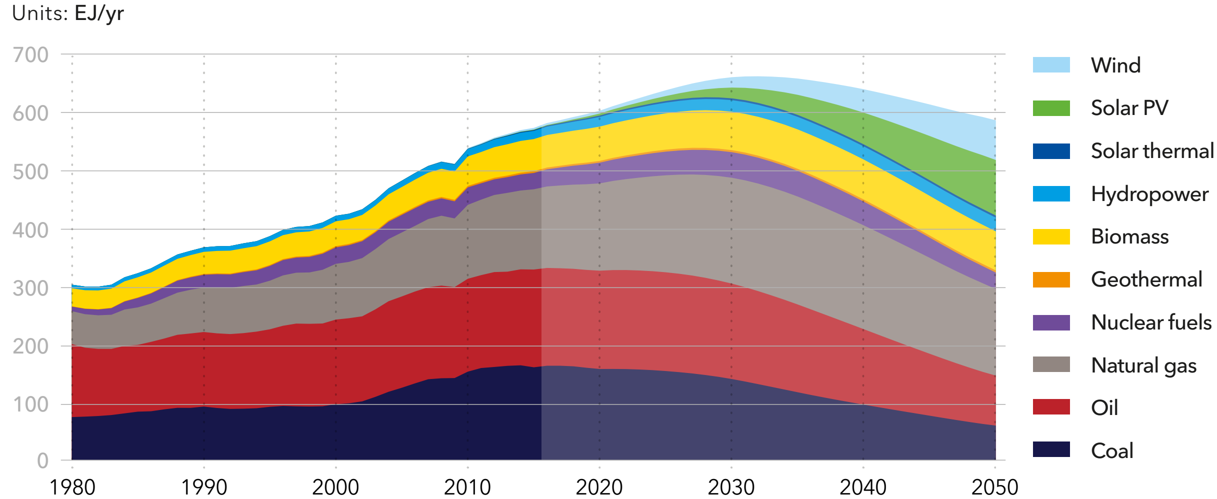
Oil will peak in the 2020s, and gas will pass oil in 2026 to become the largest energy source. The fossil share of the global primary energy supply will decline from its current position of 81% down to 50% in 2050. Biomass and hydropower will increase slowly throughout the forecast period, but nuclear will grow first and peak in the mid-2030s. Solar and wind will increase rapidly throughout the forecasting period, representing 16% and 12%, respectively, of the world primary energy supply in 2050. Hydrogen, either in fuel cells for transportation or spiked into the natural gas supply, is entering the energy mix in a few regions, but we expect uptake to be low, and to represent only 0.5% of the energy mix by 2050.

Consequently, as hydrocarbons peak, emissions from global energy use will peak, as illustrated in Figure 9. The cumulative carbon emissions from fossil fuel combustion from 2016 to 2050 are 972 Gt of CO_2.

FIGURE 8

World primary energy supply by source

Units: EJ/yr



The key result from our model of final demand peaking in 2035 and then slowly declining means the global primary energy supply required to satisfy demand will peak even more prominently within our forecast period. Final demand drops by only 17 EJ (0.25%/year) from the peak to 2050, while primary supply drops by 76 EJ (0.7%/year) due to reduced losses in power generation. DNV GL is aware that there are various ways to account for primary energy, with potential to alter this picture. This is addressed in the main report fact box on Energy counting in Chapter 4.

ENERGY EFFICIENCY

Energy efficiency is a defining feature of the energy transition. Our Outlook shows that the rapid changes in the energy system are related to large alterations in energy efficiency. The world's energy intensity – units of energy per unit of GDP – has been declining by, on average, 1.1% per year for the last two decades. We calculate that this will double, to an average annual decrease of 2.3%. The main reason for this is the accelerating electrification of the energy system, as outlined above. Simply put, using electricity rather than fossil fuels is much more efficient, with lower heat losses.

This situation is accentuated by ever-more solar PV and wind generation capacity being installed, with only negligible energy losses. This effciency trend will be further boosted by EVs becoming mainstream in automotive markets, as they consume about a quarter of the energy used by ICEVs; and the annual energy efficiency improvement in the road sector is boosted by strong electrification, to 3.4% per year over the forecast period.

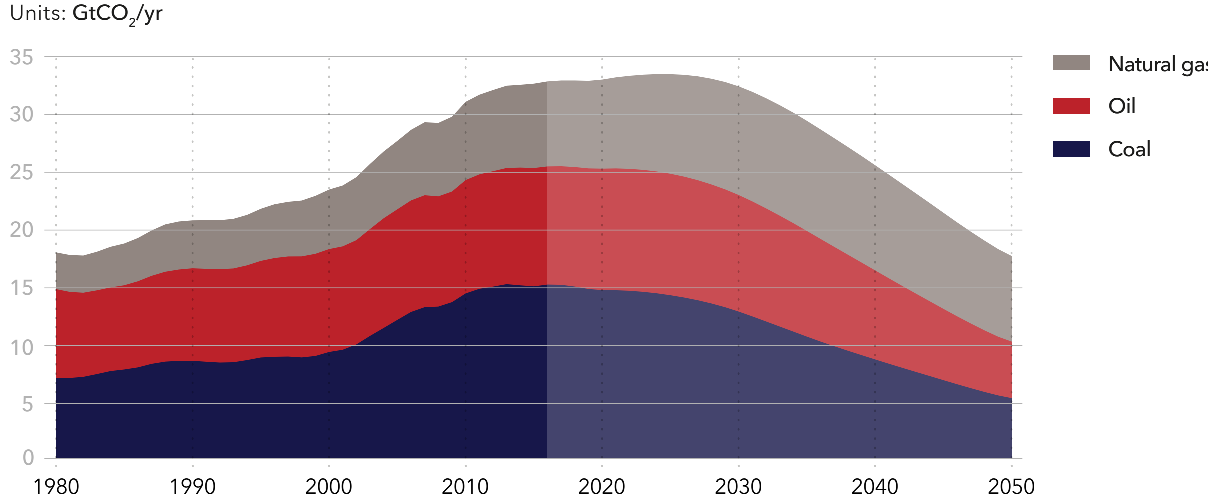
The other transport sub-sectors, and the building and manufacturing sector, will electrify more slowly than the road sector; hence they will not experience a similar additional boost in energy efficiency. Nevertheless, the average annual energy efficiency improvements vary between 0.9 and 2.0% per year for these sectors as well.

Our forecast ramp-up rates of energy efficiency are not only dependent on new combustion systems, battery developments, and other engineering innovations like 3D printing, but also on automation and digitalization as key enablers of improvements in manufacturing processes, and in the design and operation of buildings.

FIGURE 9

World energy-related CO_2 emissions from fossil fuels

Units: $GtCO_2$/yr



2018 HIGHLIGHTS – WHAT'S NEW?

In this 2018 edition of the ETO, we have refined our model further, taking into account new and more accurate sources for our model, as well as changes over the past year, including recent technology advances, revised government targets, evolving regulatory regimes and standards, additional external advisor opinions, customer and user feedback, and the actual historical developments and figures available.

With this updated input, the details in the Outlook have, as expected, changed slightly. Improving our model has resulted in the updated demand and supply pictures already presented.

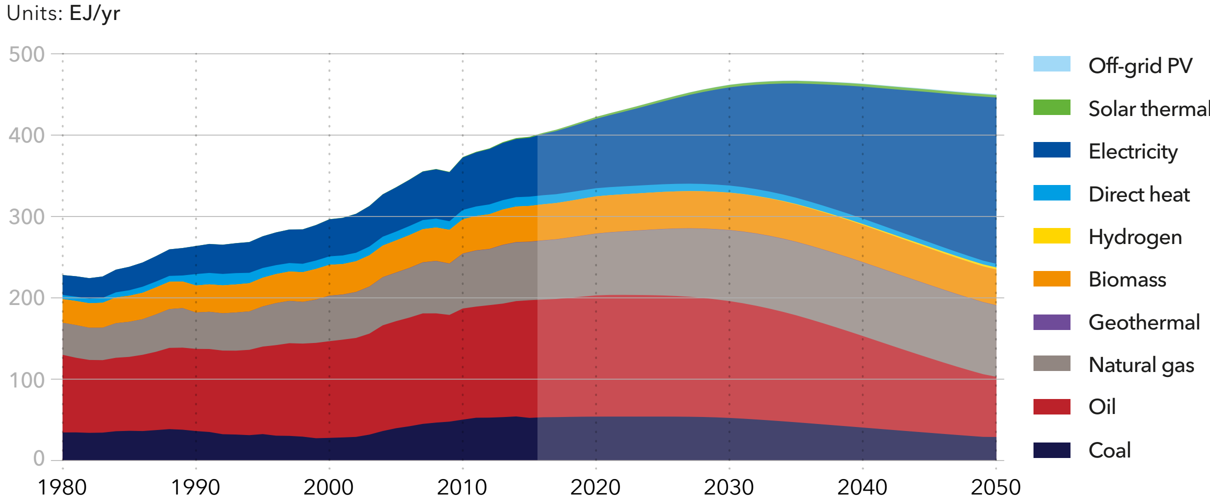
Overall, the results described are similar to those from ETO 2017, including the main conclusion – namely, a levelling off in final demand after 2030 and a peaking of primary supply to satisfy that demand (Figure 10). That being said, in this 2018 version of our Outlook, electrification is a little more aggressive (rising to 45% of energy demand by carrier, versus 40% in our 2017 project) – and total energy demand is slightly higher (6%) in 2050. Demand also grows more quickly in the first 15 years of our forecast period.

In this (2018) edition of our Outlook, energy demand for buildings by 2050 is largely unchanged, but with more nuanced results;

FIGURE 10

World final energy demand by carrier

Units: EJ/yr



manufacturing demand has increased somewhat owing to refined modelling that correlates manufacturing production with the secondary economic sector; and transport energy demand has declined slightly with increased uptake of electricity in parts of the heavy vehicle segment.

The 2050 energy mix forecast in ETO 2018 broadly resembles last year's forecast, with the share of coal a little higher, oil a little lower, and the fossil fuels and non-fossil categories each accounting for half of total energy supply. Due to higher coal and gas use, the forecast cumulative CO_2 emissions to 2050 is 10% higher than what we forecast a year ago.

In this, the second edition of our Outlook, we have extended our energy-system model in several areas, including details on grids and grid costs, an analysis of the role of hydrogen and an assessment of the impact of digitalization on the transition.

REMAINING UNCERTAINTIES

The deterministic character of a forecast, as opposed to a scenario, may give the impression that the uncertainties associated with a 'best estimates' future are small. On the contrary, there are large and significant areas of uncertainty regarding the pace and nature of the energy transition.

Our main ETO report therefore includes sensitivity analyses that highlight issues that are both uncertain and important. We also analyse uncertainties associated with assumptions that place our Outlook at odds with other forecasts.

For example, should the UN medium case for population growth prove to be correct, then the global population will be 6% higher in 2050 than we have assumed. Our model suggests that energy demand will consequently rise by slightly less (5%) than population growth, split fairly evenly between all energy sources, although solar PV growth benefits more than others.

> "Our Outlook includes sensitivity analyses that highlight issues that are both uncertain and important.

We find a similar sensitivity in productivity assumptions, where higher or lower productivity growth rates do not produce considerable changes in the pace of transition or in the energy mix. A modest increase in regional carbon prices will not alter energy demand much, but there will be a change of the energy mix and a significant reduction in emissions. The most dramatic changes in energy use come from improvements in energy efficiency.

The largest changes in the energy mix come from changing cost-learning rates for renewables.

Behavioural changes affecting, for example, the rate of uptake of EVs and electrification of buildings, are also important and can shift the pace of transition considerably.

RESOURCE LIMITATIONS

The electrification of industry and society will, of course, increase demand for associated resources, such as aluminium and copper, as well as lithium and cobalt. Most base metals are in plentiful supply, and recent concerns over lithium reserves have faded with the discovery of more ore deposits. There are plans to increase production, and although 13% average annual growth in supply is required to meet the energy transition that we forecast, we believe this is achievable. Cobalt resources remain a concern, but new battery technologies will need to evolve to address this, along with increased exploration and more sustainable extraction of cobalt reserves. Despite possible constraints, these are likely, in our view, to be overcome by technological developments, and resource limitations will therefore not impose insurmountable roadblocks for the transition we forecast.

> “Resource limitations will therefore not impose insurmountable roadblocks for the transition we forecast.

We have investigated space constraints on the energy industry that we envisage by 2050, and do not find this to be a significant issue, although it varies by region. The amount of agricultural land required to host onshore wind and solar will not represent a significant loss, especially as land can often continue to be used for farming within wind projects. Using arable land for biomass production will need careful husbandry to ensure that it does not displace food production or result in the destruction of natural habitats.

BREAKTHROUGH TECHNOLOGIES

Over the next 32 years, we may see breakthrough technologies that will significantly influence our energy future. These include nuclear fusion, superconductivity, and synthetic fuels, or radical new PV or battery technologies. As we are focusing on our best estimate, our forecast does not include any quantification of these hard-to-predict wild cards.

We do, however, discuss and quantify developments in hydrogen, which is seen by many to have game-changing potential. However, our modelling does not support hydrogen as a game-changer; high costs of storage and efficiency losses during multiple conversions will likely limit the uptake of hydrogen to just half a percent of global annual energy use by mid-century.

ENABLERS OF THE TRANSITION

ADDITIONAL INFRASTRUCTURE REQUIREMENTS

Given the energy transition we envision, where electricity takes an increasingly large share of the mix, and where gas is the dominant energy carrier, it is important to understand the infrastructure required to connect supply and demand.

There will be continued need for new pipelines joining additional gas fields to existing gas grids, and some large trunk pipelines connecting regions will be built. However, in this year's Outlook we focus on the rapidly expanding LNG trade, which will be driven largely by North American shale gas exports and Middle East oil producers' strategic emphasis on gas exports. We see a tenfold increase in liquefaction capacity in North America and a near doubling of capacity in the Middle East and North Africa. The largest expansion in regasification facilities to receive this gas will happen in China and India, as well as significant uptake in Sub-Saharan Africa.

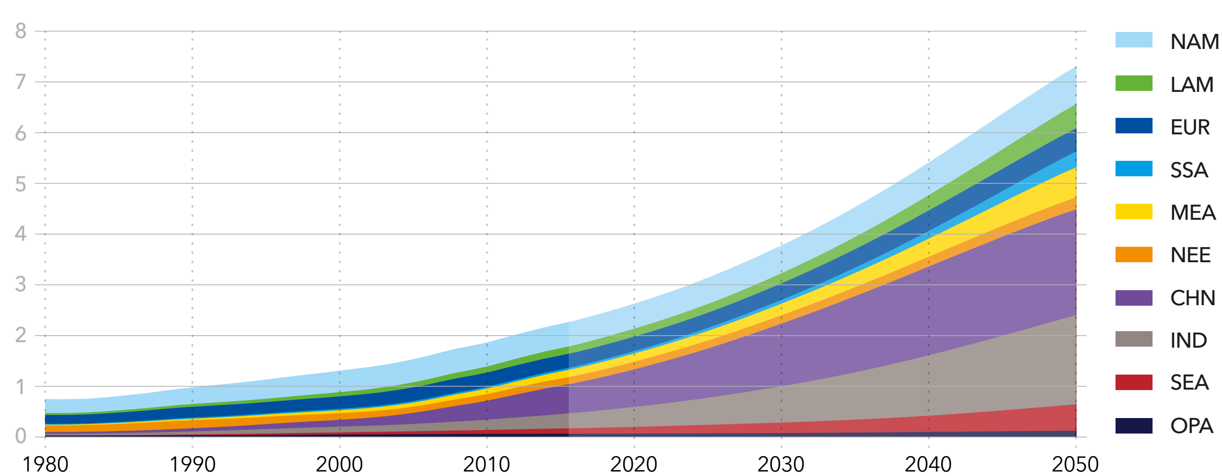
Our forecast for growth in electricity demand signals the need for a massive increase in the capacity of electricity grids (Figure 11). New renewables sites are often remote from existing generation, so that many connecting grids will need strengthening. Furthermore, ageing grids in North America and Europe require modernizing.

China and India dominate the expansion of power grids, their geographic scale also driving the need for ultra-high voltage grid systems for long-distance transmission. Section 4.4 in the main report on grids details the capacity requirements, associated grid capital expenditure (capex) and operational expenditure (opex), voltage levels, and line types (e.g., AC vs. DC), needed for each region. Our forecast of increased capacity of variable renewables also requires greater energy storage capacity and new technologies to address grid-stability issues when renewable power sources replace thermal power stations.

FIGURE 11

Capacity of power lines by region

Units: PW-km



DIGITALIZATION

Digitalization is an integral part of the present energy system, and an important instrument for the energy transition. Improved control systems, for example, driven by data from embedded sensors across the entire energy system – from generation through transmission and distribution and in end-users' plants and machinery – are critical to enabling the energy transition we envision. The power system is in the midst of digitalization; an example being demand-response, where cost-based rules may benefit both the thrifty consumer, as well as society which will see less need for upsizing the grid as electricity demand increases.

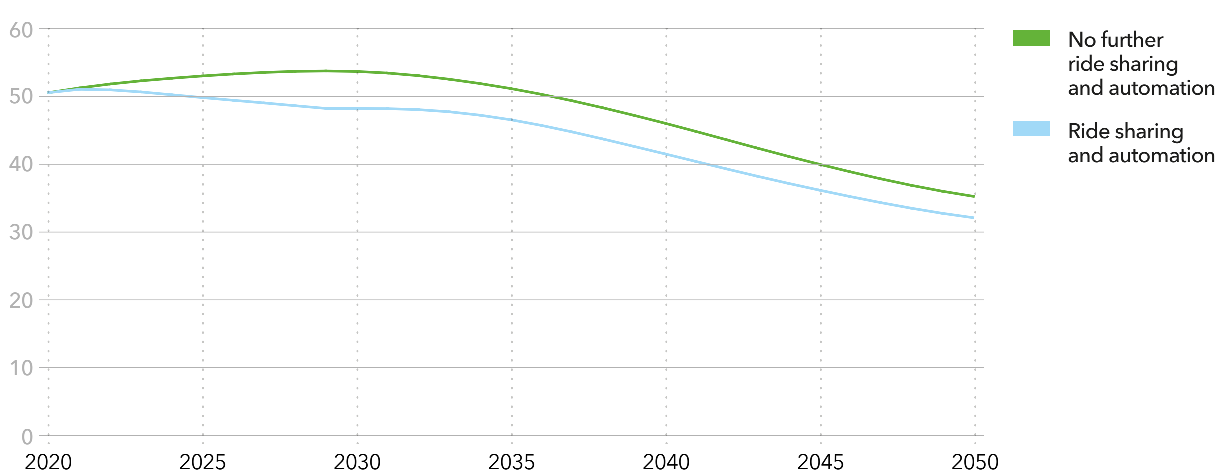
Digitalization also allows for higher asset utilization, improved energy efficiency, and the ability to implement new business models. Digitalization's impact is spread throughout the energy system, and its influence will grow with increasing application of advanced computational approaches such as machine learning.

As an example, reduced energy demand due to digitalization (in the light vehicle sub-sector) is shown in Figure 12. Digitalization enables both automated driving, and ride sharing, which allows for higher asset utilization, as privately driven cars are replaced by communal ones that may be used an order of magnitude more intensively. This results in a smaller vehicle fleet with faster car renewal. There are benefits in this for traditional combustion vehicles, which will see new fuel-efficient cars entering the fleet sooner. But for the same reason, the conversion to electric propulsion will also accelerate.

FIGURE 12

The effect on digitalization on the global light vehicle energy demand

Units: EJ/yr



FUTURE INVESTMENTS & COSTS

Given the scale of change, could the energy transition place an unbearable financial burden on society? We do not believe this to be the case.

Looking at energy-financing needs, we calculate investment in fossil fuels by considering upstream and power-related investments for oil, gas, and coal. We estimate annual global expenditures for fossil fuels to drop significantly from around USD 3.4 trillion in 2016 to USD 2.1 trillion in 2050. Non-fossil energy expenditures will exhibit a reverse trend, more than tripling from USD 0.69 trillion in 2016 to USD 2.4 trillion in 2050. Power grid expenditures will increase from USD 0.49 trillion in 2016 to USD 1.5 trillion in 2050.Global energy expenditures will increase 33%, from USD 4.5 trillion in 2016 to USD 6.0 trillion in 2050. But as GDP will grow by 130% over the same period, the energy fraction of GDP will decline from 5.5% in 2016 to 3.1% in 2050 as shown in Figure 13.

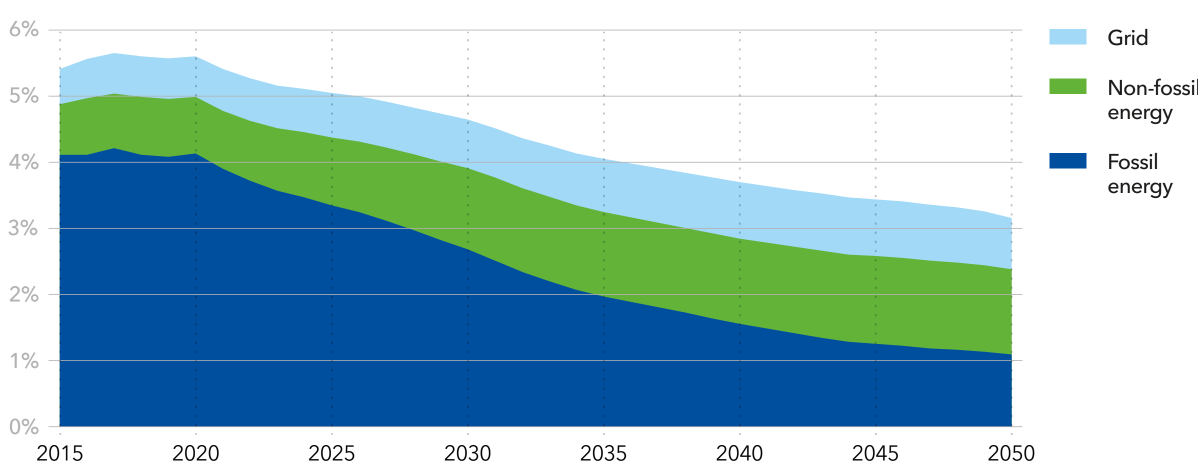
Capital expenditure (capex) on both renewable generation and grids is accelerating, and will surpass new investment in the fossil sector by 2029 onwards. By 2050, 47% of the global energy expenditures will be capex for renewables and grids, up from 17% in 2016.

The energy transition may still be financially challenging, given the heavier capex load from renewables and grids, but our forecast suggests it is unlikely to prove financially disruptive. If we chose to maintain the percentage of global GDP going to energy expenditure, then there is ample scope to accelerate the pace of change.

FIGURE 13

Energy expenditures as fraction of world GDP

Units: Percentages



INDUSTRY IMPLICATIONS

All industries will be affected by the energy transition, not least those where DNV GL has a particularly strong footprint.

Our forecast has major implications for the oil and gas industry, and for the power generation and associated infrastructure industries, and especially the renewables sub-sector. The shipping industry will feel the impact as energy-related cargoes evolve and change over time. A full discussion of our forecast and its ramifications for these sectors is the subject of the three detailed supplements to the main ETO report.

HIGHLIGHTS ARE AS FOLLOWS:

POWER SUPPLY AND USE

Major changes involving established energy industry players will spread and deepen. Established electricity utilities and electricity suppliers are looking for new roles and business models, and facing new competition from oil and gas companies moving into their sectors.

Dominant variable renewables will be a major factor in electricity markets and regulation. Solar and wind – supplying more than two thirds of world electricity by 2050 – will drive changes to electricity market fundamentals. This requires major regulatory intervention: regulatory inertia may be the dominant limit on rates of expansion. Variability on seasonal timescales will be critical in the higher latitudes. Variable renewables also drive 'sector-coupling', the use of surplus renewable electricity to produce hydrogen or other gasses or liquids, also offering opportunities for storage on longer timescales.

There will be difficulties allocating risks during massive expansion of electricity networks. Timescales for planning and constructing electricity networks may require network operators to make decisions amid considerable uncertainty. Regulators will need to make decisions about the optimum allocation of risks and costs of stranded assets.

OIL AND GAS

Significant investment is on the horizon for gas in the lead-up to mid-century. Gas will rapidly overtake oil to become the world's primary energy source in 2026. It will then remain in pole position in the lead-up to mid-century. By 2050, gas will form a quarter of the global energy mix.

While demand for hydrocarbons will decline from the mid-2020s (oil) and mid-2030s (gas), we expect industry activity to remain strong for decades to come. New fields will be required long after the peak demand years have passed, in order to continue replacing depleting reserves. These resources may be increasingly developed from smaller, more technically-challenging reservoirs, with shorter lifespans than those currently in operation.

In the midstream & downstream gas industry, we will see increasing emphasis on decarbonising the gases that we use. Greater penetration of greener gases such as biogas and hydrogen are expected by the mid 2020's.

Enhanced focus on digitalization is now needed to support a faster, leaner and cleaner oil and gas industry of the future. The industry must keep a cap on costs to compete, and we believe that the industry's digital transformation will play a significant role in achieving this.

MARITIME

Shipping will continue to grow, with an expected rise of nearly a third in seaborne-trade towards 2030, and with increases in tonne-mileage over the forecast period for all trade segments except crude oil and oil products. The largest relative growth in trade is for gas and container cargo, for which we see a tripling and doubling respectively by 2050.

As the global energy landscape changes, the pressure will continue to build on shipping to cut its emissions. Shipping will be forced to lower its environmental impact leading to a more demanding operational framework, higher expectations and higher costs. IMO's recent GHG goals for 2050 call for the whole shipping industry to step up and push for solutions to solve these challenges.

The challenge of decarbonization means the maritime industry must look to alternative low carbon or no carbon fuels. A wide range of energy-efficiency measures, alternative fuels and other emission-reduction technologies will be the focus of first research, then piloting, and finally for full scale implementation, changing the shipping fleet as we know it today. As the impact of the changes is difficult to assess, maritime assets should have a flexible "carbon robust" design.

IMPLICATIONS FOR SOCIETY

DECOUPLING

Historically, population growth and economic growth have led to a similar pattern of expansion in energy use. Our model predicts, however, that energy use will decouple from carbon emissions in the coming decades, and that energy demand and supply will peak and slowly decline, despite a continuation in population and economic growth (Figure 14). This disconnect is linked to accelerating energy efficiency gains on a global scale. These are largely driven by electricity's increasing share in the energy mix, with a large proportion of it coming from renewables.

CLIMATE CHANGE

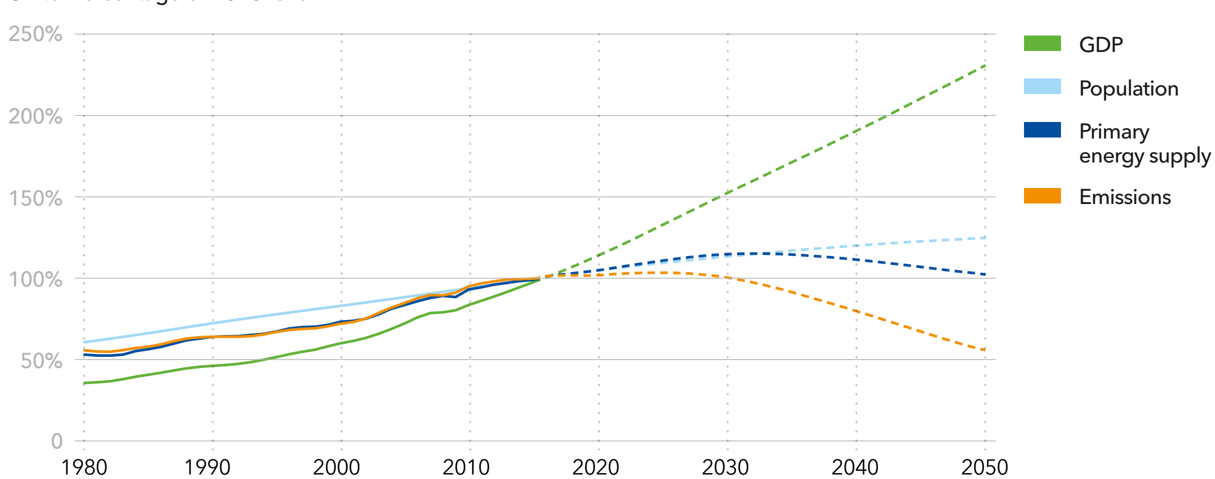
DNV GL's vision is to have a global impact for a safe and sustainable future. Thus, we support the Paris Agreement, and the efforts of almost all the world's countries to limit global warming to well below 2°C above pre-industrial levels. However, our Outlook does not see the world on track to meet the Paris Agreement climate goals. It may have been more reassuring to produce a scenario that points to a future where the risks and impacts of climate change are significantly reduced, and where dangerous anthropogenic interference with the climate system is avoided; but that is not what we forecast.

Despite our Outlook being one of the few which predicts that humanity's energy demand will peak within the next few decades and that we will collectively start using less energy, the emissions associated with our forecast still do not bring the planet within the so-called 2°C target. Although we stopped the run of our model in 2050, CO_2 emissions to the atmosphere will continue long after this. Simple extrapolation suggests that the first emission-free year will

FIGURE 14

Relationship between world population, GDP, energy supply and emissions

Units: Percentage of 2016 level



be 2090. This produces an overshoot, beyond the so-called 2°C carbon budget of some 770 gigatonnes of CO_2, illustrated in Figure 15. With an overshoot of such magnitude, the question inevitably arises: what is the level of global warming associated with our forecast?

We have reservations about citing a definitive warming figure, because there are considerable uncertainties associated with such calculations. Some are energy-related uncertainties, including the inherent uncertainties in our forecast. Others are non-energy related.

They include future agriculture, forestry, and other land use (AFOLU) emissions, unknown climate tipping points, and other non-linear earth system reactions – for example, methane stored in permafrost – that are beyond the scope of this Outlook. In addition, there is the ongoing discussion of the planet's climate sensitivity and the size of the carbon budgets as such.

Nevertheless, we hazard an estimate that our forecast points towards 2.6°C planetary warming by the end of the century.

Our prediction of failing to meet the climate target forces us to explore ways in which we might 'close the gap' between our forecast and the kind of future envisioned by parties to the Paris Agreement. For example, a much-higher carbon price may stimulate decarbonization of the energy mix and more carbon capture and storage, or further policy support could boost the growth of renewable energy.

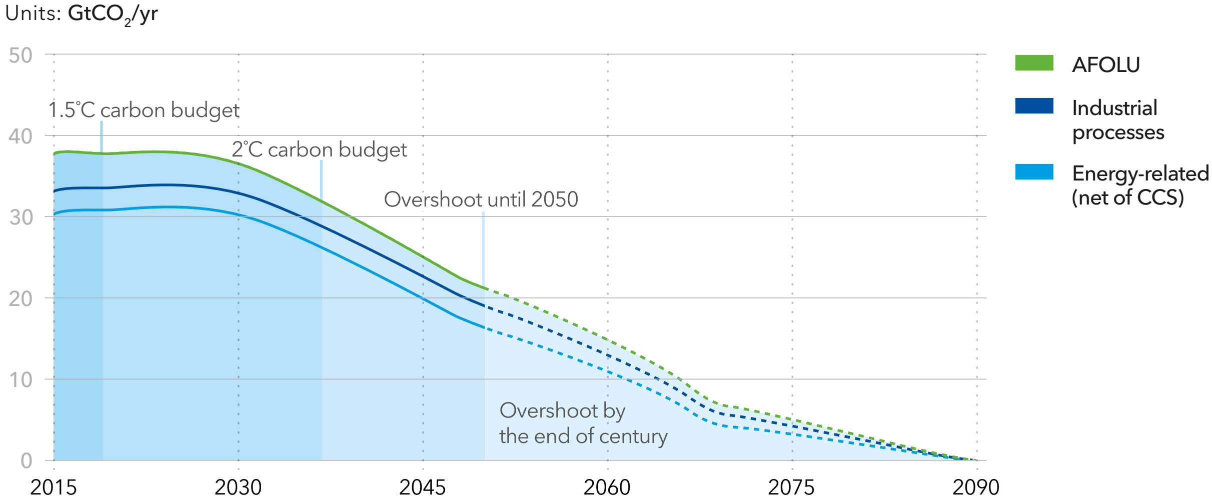
> "Only a combination of extra-ordinary measures brings the Paris Agreement within reach.

However, our main conclusion is no single measure can close the gap, only a mixture of extraordinary measures working in synchrony will enable us to reach the Paris Agreement on climate action.

FIGURE 15

Carbon emissions and budget

Units: $GtCO_2/yr$



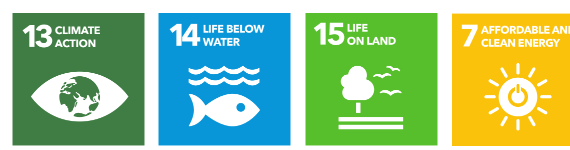
SUSTAINABLE DEVELOPMENT GOALS

The UN Sustainable Development Goals (SDGs) on Climate Action (#13), Life Below Water (#14), and Life on Land (#15) set the planetary boundaries for all other SDGs. Succeeding with a rapid energy transition that decouples CO_2 emissions from economic development is the key to fulfilment of all the goals that constitute the UN's Agenda 2030. This ambition must be balanced with SDG #7, ensuring access to affordable, reliable, sustainable, and modern energy for all.

The future we forecast is one where humanity's energy use peaks in 2032, and then slowly declines towards 2050. We foresee this happening, even as the world makes steady positive progress with SDG #7, addressing the energy poverty that afflicts more than one billion people today. Energy demand declines mainly because the energy intensity of economic activity is decelerating; less energy is required per person. Note however, that it is final energy demand that reduces, not the services it provides; for example, a family may install several solar-powered LED lights, replacing a single kerosene lamp. The result is much more light, with orders of magnitude less energy used.

We forecast that SDG target 7.3 – doubling the rate of improvement in energy efficiency by 2030 – will not be met, but we are approaching the right levels. Our forecast of 2.0% annual reduction in energy intensity per year in 2015–2030 is not a doubling of the historic 1.3% per year in 2000–2015. The SDG target 7.1: "By 2030, ensure universal access to affordable, reliable and modern energy services", will largely be met for all regions except Sub-Saharan Africa regarding access to electricity, while access to modern cooking and modern water heating will improve, but will not be universal across Sub-Saharan Africa, the Indian Subcontinent, and South East Asia.

Despite these near-misses in the run-up to 2030, we emphasize, once again, that energy efficiency is the defining feature of the coming energy transition. Over the next few decades, the role played by energy efficiency will be even more decisive than shifts in the mix of energy sources.



CHAPTER 1

INTRODUCTION

1. INTRODUCTION

This publication presents DNV GL's outlook through to 2050 for the entire world energy system, and includes regional outlooks for 10 global regions. Together with this main publication, we have issued three supplementary 'Industry Implications' reports, examining in greater depth the implications of our forecast for the following sectors:

– Oil and gas

– Maritime

– Power supply and use

ABOUT DNV GL

DNV GL was founded more than 150 years ago to safeguard life, property, and the environment. Today, we are a world-leading provider of quality assurance and risk management in more than 100 countries.

DNV GL has a strong footing in both the fossil and renewable energy industries, with around 70% of our business related to energy in one form or another. This, we think, brings a balance to our view on the energy future, and the fact that we are fully owned by a foundation means that our outlook is independent of shareholders' interests.

This Outlook draws on DNV GL's broad involvement across entire energy supply chains, spanning complex offshore infrastructure, onshore oil and gas installations, large and small- scale wind, solar, and energy efficiency projects, and electricity transmission and distribution grids.

The energy transition is unfolding as a daily reality for many of our customers. In some sectors and industries such as power supply and in road transport, the transition is already advancing rapidly. In others, it is slower, and there are also sectors where the future trends are not yet visible.

DNV GL is involved across this continuum of change, with advanced R&D and specific projects at the forefront of the transition. As technical advisors, we help our customers to manage the transition to a safe and sustainable future. In many other areas, we work to safeguard existing, established businesses. We are a knowledge-led organization, typically spending 5% of revenue on research and innovation.

DNV GL is in the business of building trust, not only into systems and processes, but between parties. Given the urgent need for the global economy to decarbonize, much is riding on the pace and outcome of the energy transition in terms of enterprise risk, technical risk, and societal risk. DNV GL thus feels compelled to contribute, where we can, to rational, informed discussion of the energy future in the coming decades.

> "This Outlook draws on DNV GL's broad involvement across entire energy supply chains.

OUR APPROACH

This Outlook gives an independent view from DNV GL of what we consider our best estimate for the future - or the central case - for energy demand and supply as it unfolds to 2050.

DNV GL forecasts one likely future. This contrasts with the more common scenario-based approach used by many energy analysts, involving the presentation of two or more internally consistent and plausible descriptions of possible future states of the world's energy system. Scenarios can usefully illustrate the effect of different assumptions and the uncertainty inherent in projections, but they often are not intended to reflect the forecasters' best estimates. Where one has a proliferation of scenarios, as is the case with the energy transition, each additional scenario may add to the perceived uncertainty and cause confusion.

To avoid such confusion, we have decided to focus on a single outlook which we judge to be our best estimate, based on extensive research and modelling. We also perform sensitivity analyses to determine how predictions are influenced by various factors. This approach has the advantage of revealing critical assumptions and highlighting which results are more or less sensitive to uncertainties. The latter is important when forecasts are to be used as a basis for decision making.

As a leading risk management firm, DNV GL, has a long history of constructing evidence-based and model-driven projections. Given our wide exposure to the energy industry – from well (or wind farm) to socket –our customers have looked to us for our best estimate of the energy future. And addressing that question is what we have attempted to do with this Outlook, which is based on our own extensive modelling efforts. We reiterate, therefore, that in this publication we present a *forecast* of the world's energy system through to 2050, not a range of scenarios.

Of course, we are aware that the future energy mix will not be exactly as we describe it here, and we therefore acknowledge significant uncertainties in our forecast. To assess their impact, we have subjected our forecast to sensitivity tests. In Chapter 4, we show how adjustments are made to main assumptions to test sensitivities. Over time, we will extend these sensitivity tests to allow for fruitful discussion of alternative views.

> “In this publication we present a *forecast* of the world's energy system through to 2050, not a range of scenarios.

The core model development and research for this Outlook has been conducted by a dedicated team in our Energy Transition research programme, part of the Group Technology and Research unit. The team has worked with around 100 colleagues across our organization, and dozens of external experts, on topics such as technology, economics, and policy, and on their interconnectedness.

A FOCUS ON TRANSITION

This Outlook considers the energy system from source to end-use. It thus encompasses the entire energy system and how its components work together. It includes all main consumers of energy – buildings, industry, and transportation – and all sources supplying the energy. We focus on technologies already in use and for which we have been able to calibrate uptake – and decline – rates, and how these are interlinked. Some of these technologies are not yet firmly established, but, in our estimation, show many signs of becoming mainstream. We are more cautious with the consideration and inclusion in our model of uncertain, potentially breakthrough technologies.

Our forecast reveals a mixture of continuity – for example the important role of natural gas in the world's energy system through to 2050 - and change.

The most important characteristic of the transition is decarbonization, with renewable energy adding to and, over time, replacing fossil energy.

Other changes are unfolding in parallel to the renewable energy transition, and we include these in the term 'energy transition' as used in this outlook:

- The world is electrifying
- In the oil and gas industry, shale-based production is fast becoming dominant in North America and is spreading internationally
- Off-grid and mini-grid systems are developing locally, adding to the existing connected grid system, and a more distributed power system is emerging

WHAT IS NOT COVERED BY THE DNV GL OUTLOOK?

- The focus of this Outlook on long-term transition means short-term changes — both cyclical and one-off impacts, for example from policies, conflicts, and strategic moves by industry players — receive less attention, and are generally not covered.
- The Outlook presents regional energy costs as unit variable costs and levelized cost of electricity (LCOE). It also presents break-even costs for oil and gas development. But the Outlook does not reflect fluctuating energy prices caused by demand and supply imbalances, which, in the real world, and at certain times, may be quite different from costs.
- The Outlook is built up by energy demand and supply considerations focusing on yearly averages. This approach does not in itself fully reflect the differential nature of variable energy sources. We do not model daily or seasonal variations, nor do we model grid stability or other short-term renewable energy dynamics. Instead, we add storage and back-up capacity to energy value chains with large shares of variable renewables. We regard the costs of these additions as part of the overall cost of renewables.
- Technologies which in our view are marginal are typically not included, but we do include those new technologies which we expect to scale. Breakthrough, emerging technologies are discussed, but not included in the model forecast. The exception is hydrogen, which is modelled and discussed.
- Changing consumer behaviour, evolving travel and work patterns, social media and other sociological trends are discussed, but are only included and quantified in a few areas in our forecast.

PERSPECTIVE ON CHANGE

DRIVERS AND BARRIERS

We present here our selection of key drivers of the energy transition, as well as barriers hindering the transition. These opposing forces suggest that the transition will not occur without friction, or, as Austrian economist Joseph Schumpeter (1942) termed it, "creative destruction" when new technologies diverge from and destabilize old.

So much for the nature of the transition; what about its pace? There are ardent proponents of both a slow and a fast transition, and both camps cite historical evidence to validate their positions. Our view is that the historical evidence is inconclusive – and that the coming transition is likely to be experienced as both fast and slow; that is to say, the pace of change will vary by sector and geography.

> "The coming transition is likely to be experienced as both fast and slow.

A confluence of factors – policy, technology and economics – is propelling the pace of the transition.

The UN Sustainable Development Goals and the Paris Agreement have unquestionably created a shared sense of mission. A global mindset has set most governments and many businesses on the same course. The transition is increasingly seen as a strategic opportunity for business and as a pathway for sustained economic growth. The energy transition is increasingly being viewed as a shift from a centralized to a more decentralized energy value chain enabled by advances in technology and the digital revolution.

The cost learning curves associated with renewable energy technologies are crossing performance and cost thresholds, triggering widespread global uptake. We caution, however, that cost is not the sole arbiter of change.

Digital technologies, emerging from outside the domain of energy industry, are altering the competitive landscape and affecting all energy sectors, and the interactions between them. The digital revolution imparts a synergistic boost to the transition – enabling smarter management of many complex systems, efficiency and productivity gains in industry, facilitating the influx of renewable power and siphoning customers away from traditional firms with the rise of self- or locally generated power.

Digitalization is at the heart of what the Global Future Council on Energy has called the 'innovation tsunami', which "… has the potential to wash over the world's energy systems … some firms and industries fear survival while others foresee riding these powerful waves into new markets" (WEF 2018a).

There is solid evidence for rapid change in end use technologies. EVs, with hardly any vehicle diversity in the beginning of the decade, have seen a proliferation of light vehicle models, now rapidly encompassing heavier vehicles. Our view is that EV adoption will follow the so-called S-curve pattern, with significant potential for disruption – reducing the demand for oil, stimulating electrification and driving down vehicle and battery costs, as well as energy storage costs.

Developments in e-mobility, solar PV and wind are consistent with what Professor Andrew Hargadon (2015) at UC Davis Graduate School of Management calls a ‘Long Fuse, Big Bang’ technological dynamic – summarized in the statement: “Things take longer to happen than you think they will and then they happen faster than you thought they could.”

There are a number of barriers that prevent change, and hamper or delay the energy transition giving elements of the transition a 'long fuse'.

New energy technologies rise in the face of legacy systems, competing with powerful industry players and energy infrastructures that have stood the test of time and have a built-in resilience in the form of increasing returns to scale on the physical infrastructures as well as the organisations that perpetuate them (Unruh et al. 2006). New entrants must, in parallel, scale production, maintain reliability and profitability, while facing uncertainties from competitors, investors and consumer choices to unknown rules of the game and public policies that are predictably unpredictable (C2ES 2011).

There are therefore many drivers and barriers influencing the energy transition, and they create uncertainty. The drivers and barriers described in the rest of this chapter reflect our current thinking; they are likely to play out differently, and that in turn will influence the pace of the transition and hence our forecast. Irrespective of accuracy, we believe repositioning and re-invention are the watchwords for navigating the unfolding energy transition.

DRIVERS OF THE ENERGY TRANSITION

POLICY AND GOVERNANCE DRIVERS

ENERGY SECURITY

The combination of energy efficiency, technology advances, and the falling costs of renewables, provides governments with mature, affordable, and clean options for energy security.

- Renewables largely exploit domestic wind, solar and hydro resources and, to the extent they substitute imported fossil fuels, renewables improve security, create employment and reduce exposure to price hikes and foreign exchange requirements and fluctuations.
- Improving energy efficiency and demand response programmes also helps energy security by reducing demand and import requirements.
- Distributed energy systems and renewables matched with flexibility and storage options offer a decarbonized pathway to energy security, and are more resilient to extreme weather events and other grid disruptions.

GOVERNMENT POLICY AND THE COURTS

Nearly all countries have national policies on decarbonization and the energy transition. In addition, court systems will play a role in climate and energy policy and the implementation of policy commitments – both concentrating attention and propelling transition.

- All Paris Agreement signatories or ratifiers have at least one law addressing climate change or the transition to a low-carbon economy.
- More than 170 countries have renewable energy targets, and nearly 150 have enacted policies, incentives and mandates to catalyse investments. At least 128 countries have policies for renewable power, 70 for transport and 24 for heating and cooling, and 57 countries have 100% renewable electricity targets (IRENA 2017, REN21 2018)
- Policy and government support will continue to be instrumental to increasing technology uptake and bring low carbon options to cost parity.
- The falling costs of renewables will give governments reassurance that fiscal incentives should be designed only temporarily.
- A rise in litigation cases – filed by NGOs, individuals, and subnational governments – will push courts to examine whether governments and corporations/major carbon emitters should be held accountable for climate change related damages. This may result in international ambitions and obligations being brought into domestic courts (LSE-Grantham 2018, Renssen 2016).

CITIES LEAD THE WAY

Urbanization is a global trend and cities are front-line players in the energy transition, as implementers of green solutions to pressing problems.

- Urban areas consume about 75% of global primary energy (UN-Habitat 2018) and will attempt to tackle urban air quality, congestion delays, and health impacts in order to attract people and investments.
- They will act as testbeds for energy innovation and experimentation from which best practices and solutions will diffuse, through global networks such as C40 and the Covenant of Mayors, and scale up to the national level (DNV GL 2018f, HBS 2018).
- Leading cities are pursuing improved energy efficiency in buildings, smart technology, and infrastructure. They encourage zero-emission transport and set climate-neutral targets.

ECONOMIC AND MARKET DRIVERS

COST CURVES DIVERGE

The long-term cost curves of extractive fossil energy and renewables will cross and diverge.

- As wind and solar PV scale up rapidly, their costs will keep falling.
- In contrast, fossil producers have traditionally picked the 'easiest barrels first', and may also be limited by restrictions on extraction.
- Oil and gas industry cost reductions, driven by learning curves shaped by technology developments and digitalization gains, and lower-cost unconventionals, will delay the divergence.

CORPORATES SETTING TARGETS

Energy is climbing up the corporate agenda, and major energy users and companies are choosing to power their operations with clean energy.

- Companies will set more ambitious targets for the share of renewables in their energy supply, and for responsible corporate sourcing.
- Buyer alliances will engage with utilities and developers to advance renewable energy purchase agreements (WRI 2017).
- Members of the RE100 initiative are from both mature and emerging economies. The trend is expected to diffuse, following the manufacturing and operations sites of global corporates. Apple's announcement of a USD 300M Clean Energy Fund to boost the use of renewable energy in its supply chain in China, is one example.

SHIFTS IN INVESTOR AND INSURANCE FOCUS

An increasing number of investors and insurers are backing away from high carbon sectors, citing risks of being locked into stranded energy or low return assets.

- Changes to regulations and emerging clean technologies are likely to reduce the value of carbon-intensive assets.
- Financial liabilities for abandonment and clean-up of renewables sites are lower than for fossil and nuclear energy sites.
- Assessing and pricing environmental risks is mainstreaming. Green finance, climate-aligned bonds and sustainable investing reached USD 22.9 trillion at the start of 2016.
- For these sources of green finance, investment in renewable energy is the most common use of funds – and allocations to green buildings, energy efficiency and low carbon transport are increasing in volume (Climate Bonds Initiative 2018).
- Insurance companies are taking steps to manage carbon-related sustainability risks (Insurance Journal 2018).

SOCIAL / SOCIETAL DRIVERS

LOCAL ACTION

The local benefits of a more renewable, often decentralized energy system are numerous and sufficient to trigger local action.

- Local authorities will play a key role in enacting energy efficiency standards, setting building codes, planning for district heating and cooling systems, and transitioning public car fleets.
- Public concerns about air quality from transport and industrial pollution along with the water demands of thermal power plants and unconventional hydrocarbons will force local authorities to accelerate the transition to cleaner alternatives.
- Distributed affordable energy from nearby renewables creates local economic opportunities, health and environmental benefits, gives communities power over energy, and reduces outlay on sourcing and transporting fuel.
- Energy projects that unlock local potential will foster civic engagement and acceptability, with increased local employment in the energy industry helping stabilize communities.
- Socially-conscious millennials will dominate workforces during the 2020s, and will seek out responsibly-sourced products and pursue opportunities in ‘good causes’ at the local level.

HYPER-TRANSPARENCY

Pressure is rising to assign all costs – economic, environmental, social – to energy and fuels, assisting renewables in challenging fossil energy.

- Enabled by the ICT revolution, groups and individuals demand greater disclosure, accountability, and incorporation of social and environmental impacts into corporate activities and decision making.
- Innovations in data gathering (satellite and sensors), 'datafication' of corporate ESG (environmental, social and governance) performance and the growing sophistication of valuation techniques are revealing the value implications of sustainability performance/ investments in unprecedented ways.
- Digital ledgers such as blockchain technology will enable accountability by tracking the origin and movement of products and recording transactions transparently and reliably.
- The ability of consumers to access more reliable data on the impacts of products and services will impact purchase decisions.

TECHNOLOGY AND INNOVATION DRIVERS

RAPID TECHNOLOGICAL PROGRESS

Technological progress raises productivity, increases energy efficiency and changes the dynamics of supply and demand in energy sectors.

- Learning rates and improved technologies continue to bring down the cost of renewables, without even considering the societal costs of fossil energy. The same dynamic characterizes the shale revolution.
- Different sizes of units, scales of deployment, and chemistries in energy storage technologies will continue to evolve, enabling dispatchable renewable power systems and improving the driving ranges of electric vehicles (EV).
- The complementary effects of ever-increasing deployment, continued innovation (e.g. the Mission Innovation, 2018) and material advances, will stimulate technological learning rates and further cost reductions.
- Initiatives like The Breakthrough Energy Coalition – a group of more than 20 billionaires investing in early-stage clean tech – point to a more active R&D and innovation arena with private sector engagement.
- Increased computational power enables more simulation in design resulting in better systems in operation and increasing feedback from operations to create better next-gen products.
- Deployment of Industry 4.0 technologies will lead to energy efficiency gains and energy savings in manufacturing.

OPPORTUNITY AND INNOVATION IN CLEAN TECH

Recognition of the value at risk from climate change (EIU 2015) combined with the documentation of enormous economic opportunities is pushing a shift from the “brown to the green economy” as coined by UNEP (2011).

- Nations and communities increasingly promote clean tech innovation addressing climate change, energy security, social wellbeing, environmental health, and to boost economic competitiveness.
- The UN Sustainable Development Goals (SDGs) are getting down to business with SDG-related market opportunities forecast to be worth at least USD 12 trillion a year in business revenue and savings, of which USD 4.3 trillion are in energy and materials (BSDC 2017). More capital is becoming available because the economic opportunity is measured.
- Company-level engagements in environmental and social issues are a powerful opportunity to differentiate, innovate, and drive corporate growth. Industries that alleviate unsustainability by reducing use of energy, raw materials, and water, will be favoured by markets.

THE WAVE OF DECENTRALIZATION

A trend towards decentralization of the energy system is strengthened by advances in technology.

- High shares of variable renewables, grid-scale storage and an ever-increasing number of distributed assets are being commissioned.
- Digital technologies support the decentralization through analysis of large amounts of sensor data and determination of optimal settings for the control software systems.
- In mature energy systems, end users become an active part of the energy sector with smart homes and appliances, EVs, domestic storage, and in-house electricity generation enabling them to sell back any surplus to the grid.
- In developing regions, distributed renewable energy solutions (standalone and mini-grids) – particularly significant for regions such as Sub-Saharan Africa and India – will be incrementally added to enhance energy access, also enabling the leapfrogging of under-served energy communities over traditional centralized systems.

DIGITAL TECHNOLOGY AND BUSINESS MODELS

The merger of operational technology with information technology is cross-cutting and affects all energy supply and demand sectors.

- Digital technologies will be key to effective asset management with smart grids enabling the balancing of demand and supply. ICT will support optimization of generation, energy-consuming devices and demand management based on energy price signals and the physical state of the grid.
- Many utilities are likely to use digitalization to reinvent their business models toward tailored service offerings, becoming owners of large-scale renewable plants, and investing and operating the grid infrastructure to turn the threat of revenue erosion from loss of kilowatt hour sales into opportunity (Fratzscher 2015).
- The digital wave will increase asset utilization and optimization in all sectors, and will drive sharing models and automation in the transportation sector, which in turn will lead to a reduction in energy demand.

ENVIRONMENTAL DRIVERS

A PLANET TURNING ON US

The planet itself will force change. Deteriorating environmental conditions and extreme weather events will force a rethink in land use decisions and investments in energy supply or infrastructure.

- Scientific evidence is robust regarding the realities of global challenges. Two thirds of ecosystems worldwide are degraded and in decline, and human activity oversteps recommended safe planetary boundaries (Steffen et al. 2015).
- A planet being pushed to the edge will inevitably become less hospitable to human livelihood, economic development and business operation (Lambertini 2017).
- Costs associated with the effects of climate change will strain public budgets. Business as-usual economic and technological trends will increasingly create turbulent conditions for government, business and society alike (Randers 2012).
- Decision makers will be forced to move resource management to the centre of decision making to prevent the rush towards planetary resource limits.

BARRIERS TO THE ENERGY TRANSITION

POLICY AND GOVERNANCE BARRIERS

INTERMITTENT PUBLIC POLICY AND FOCUS

Long-term investment requires stable political targets and schedules for the energy transition and related support.

- Regulatory environments are uncertain, with frequent rollbacks in public policy and election cycles restricting planning horizons.
- Voters and politicians are geared to short-term benefits, and inward orientation and populism obstruct interconnected markets and the rapid travel of best practice, and also put a brake on energy system change to safeguard current jobs in fossil energy.
- Unstable enthusiasm for technologies, coupled with lack of institutional support during difficult development phases before technologies reach market competitiveness, hinder transition efforts and undermine the credibility of policy makers.

OUTDATED ELECTRICITY MARKET DESIGNS

The organization of the electricity sector varies significantly around the globe, but one feature tends to be common: market designs are tailored for a different era, when centralized electricity generation provided significant economies of scale.

- Decentralized generation requires arrangements for decentralized decision making. There is an urgent need for more market and less central planning and decision making in the electricity sector.
- In order to balance the electricity system, we need to unleash currently under-utilised sources of flexibility. Markets for flexibility, that efficiently reward resources for stabilising and optimizing network operation are emerging in Europe and the US.
- Volatility of prices is a key enabler for innovation and actions to cope with volatility in supply. Merit-order wholesale markets must be supplemented with additional markets with finer granularity in time and space.
- Market design must provide transparent and efficient price signals and promote contracts for efficient risk sharing.

ECONOMIC AND MARKET BARRIERS

SUBSIDIES AND LACK OF EXTERNALITY PRICING

Addressing climate risk, and advancing the energy transition, requires an end to fossil fuel subsidies and a price on carbon (IMF 2015). Yet entanglements of government, businesses and individuals with the productions and consumption of fossil fuels is stalling reform.

- A 2016 study estimated that implied global fossil fuel subsidies were USD 5.3 trillion per year, representing 6.5% of global GDP (Coady et al. 2017), including undercharging for costs such as global warming impacts and air pollution.
- Fossil fuels still receive four times the subsidies given to renewables (IRENA, IEA and REN21, 2018).
- The inadequate pricing of fossils fuels distorts competition between energy technologies.

SHORTAGE OF SKILLS

There is a widespread skills shortage of engineers and technicians in all parts of the renewable energy industry. Human capital development will be critical to keep up with the energy transition.

- Lack of skilled workers prevents positioning in, and deployment of, clean energy technologies, and hinders rapid transfer to new geographical areas where skills are not available.
- There is a particular need for qualified engineers in energy technologies, and similarly for skilled craft workers for project development, construction, and installation, and also for operation and maintenance activities.
- Educational and training systems need to respond swiftly to the emerging requirement for particular skills for the energy transition.

SHORT-TERM THINKING

Businesses display short-term thinking linked to quarterly performance reporting and shareholder primacy.

- Actions maximizing value and share prices today disregard future risks and costs to repair the damage resulting from environmental problems.
- Financial short-sightedness creates hurdles, as do cost structures.
- High upfront capital costs and capital-intensity in renewables, and perceived performance risks, translate into perceptions of riskiness. This results in access to capital being more difficult and expensive, particularly in developing countries.
- Uncertainty risks due to discontinuity of support schemes and lack of long-term policy visibility translate into risk premiums (Hu et al. 2018).

SOCIAL AND SOCIETAL BARRIERS

PUBLIC OPPOSITION

Community acceptance is vital for energy projects in many countries.

- Renewable energy projects are not immune to public opposition on various grounds: land use, related grid expansion, trade-offs between economic benefits and environmental costs, visual amenity, biodiversity, or just plain 'not-in-my-backyard'.
- Public opposition results in costs, delays, and cancellation of projects.
- Similar concerns exist for nuclear power and unconventional oil and gas. Winning community consent and public acceptance can be a challenge.

INSUFFICIENT AWARENESS DESPITE INFORMATION OVERLOAD

A deluge of misinformation and disinformation inhibits fact-based decision making.

- When energy leaves the pump, socket, or gas source, consumers are typically unaware of the environmental and climate-change consequences of buying and using it.
- Some authority figures deny climate change or say it has nothing to do with human activity.
- The Internet enables knowledge sharing but spreads disinformation and sows doubt about climate change and renewable energy. Trust in information is low: dispelling myths is difficult.

TECHNOLOGY AND INNOVATION BARRIERS

TRANSITION HEADACHES

Structural shifts in energy systems carry transition costs and affect careers, entire industries, and their supply chains.

- Lack of effective relocation, retraining, and transition programmes in response to job losses in fossil-fuel dependent communities can hinder political and public support for the energy transition.
- Infrastructure constraints such as insufficient upgrades to transmission and distribution grids hinder integration of renewables. Absence of charging infrastructure obstructs EV uptake.

INNOVATION GAPS

There are inherent uncertainties in the stages of technical development from R&D to market scaling.

- The potential and perceived value of new energy technologies is affected by public policy, consumer preferences, and market acceptance of competing alternatives.
- Companies and individuals are risk-averse and avoid making decisions until performance and technology are proven and costs have fallen. Zero-emission vehicle adoption, for example, is hindered by high 'off-the-shelf costs' in most countries, lack of charging stations, and scepticism about driving range compromising ease-of-use.
- Critical areas and gaps by sector, application, and technology still need to be overcome, while government spending in energy R&D has declined. From growing steadily between the mid-1990s until 2012, almost returning to the levels of the post-oil crisis peak of 1980, public energy R&D budgets has declined overall since 2012. In IEA member countries, energy's share of spending declined from over 10% in the early 1980s to about 4% in 2015 (UNFCCC 2017, IEAs RD&D database 2018).

LOCK-IN INERTIA

Change is difficult. Finding alternative investment options for the trillions of dollars invested in the established energy industry is challenging; concerns regarding asset stranding could lead to lobbying efforts that may hamper switching to cleaner alternatives.

- Entrenched positions on fossil fuel extraction, centralized energy systems, and other vested interests, both industrial and unionized labour, will prefer the status quo, rendering the timing of the transition uncertain.
- Inertia is amplified by the 'ecosystem' of workers, research efforts, funding and supportive public administrations which makes existing systems less responsive to outside pressures and change.

THE SUSTAINABLE DEVELOPMENT GOALS

- **The 17 Sustainable Development Goals (SDGs)**, adopted by UN and 193 nations in September 2015 describe in detail the future humanity wishes to achieve by 2030.
- **Two of the goals (#7 on Affordable and Clean Energy and #13 on Climate Action) deal directly with energy**, but many of the other goals involve aspects of energy and energy transition, including the challenges of energy poverty, with close to one billion people lacking access to electricity, and around 2.3 billion people without access to modern cooking facilities.
- **DNV GL delivered a detailed study of the SDGs in the report "Future of Spaceship Earth"** (DNV GL 2016). One of the report's conclusions was that climate action is a prerequisite for reaching many of the other goals, and that succeeding with a rapid energy transition is the single most important action that humanity can undertake in its quest to achieve all 17 goals. The co-benefits of an energy transition for other SDGs targeting renewable growth, good health and wellbeing are significant.
- **In this year's Outlook, we have quantified energy access as part of our assessment**, finding that that the world makes progress but does not manage to meet the goal in all regions by 2030. This is detailed in the Infographic on Energy Access in Section 4.1.
- **The SDGs have gained considerable government and private sector momentum**, where business can contribute to the new development agenda by way of sustainable business solutions. As such, the SDGs play an important role in the energy transition. Individual goals and targets for areas like economic growth, deforestation, biodiversity, sustainable transportation and availability of agricultural land are all important influencers on the energy future. Balancing priorities will shape national energy strategies and decisions on energy solutions.

THE 17 SUSTAINABLE DEVELOPMENT GOALS

COP21 AND THE PARIS AGREEMENT

- **At the 21st Conference of the Parties to UNFCCC in Paris in December 2015, 193 countries agreed on what is being called the Paris Agreement.** On the 4th of November 2016, the agreement entered into force. The Paris Agreement is complicated in the sense that the sum of what the individual countries promise to do in their pledges (the Nationally Determined Contributions) is collectively far from sufficient to meet the target of: "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".
- **The Agreement contains a plan to renew and increase the pledges every five years**, in the hope that humanity will approach the target over time.
- **In order to ensure full operationalization of the Paris Agreement by 2020**, the parties agreed that the Paris Agreement rulebook would be agreed upon during COP24, December 2018.
- **In our assumptions and model, we have put some weight on the NDCs.** They are, after all, the stated intention of sovereign nations. Moreover, our earlier analysis (DNV GL 2016) shows that the sum of pledges will in themselves be delivered by means of the on-going momentum in the energy transition. Unlike the IEA's New Policies Scenario (NPS), however, we do not envisage a future where all countries deliver on their pledges. Some countries – e.g. China and India – are likely to overfulfil their current pledges. Other countries have conditional pledges that will not easily be met. The present NDCs also have the limitations that they generally stop at 2030, while our forecast continues to 2050.
- **Despite these caveats, the Paris Agreement and the NDCs do constitute a very important framework** for understanding and deriving government policy and will provide relevant signals to market.


VIKING LADY
HAUGESUND
RESCUE ZONE

CHAPTER

2

CONTEXT AND BACKGROUND

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2.1 TEN REGIONS

This Outlook divides the world into 10 geographical regions. They are chosen on the basis of geographical location, resource richness, extent of economic development and energy characteristics.

Each region's input and results are the sum of all countries in the region. Typically, weighted averages are used; countries with the largest populations, energy use, and so on, are assigned more weight when calculating averages for relevant parameters.

Prominent characteristics of certain countries – nuclear dominance in France, for example – are averaged over the entire region. In some cases, we comment on this. More detailed country-specific issues may be included in future analyses.

Detailed discussions, results, and characteristics of regional energy transitions are included in the regional sections in Chapter 5 of this Outlook.

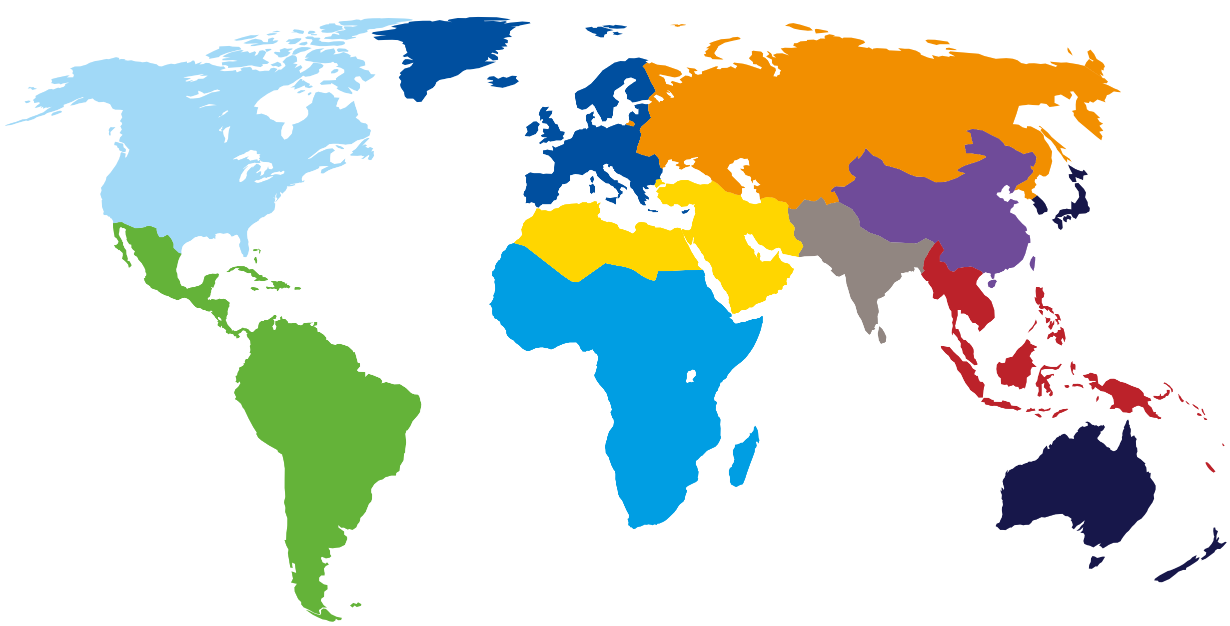

FIGURE 2.1.1

- North America (NAM)
- Latin America (LAM)
- Europe (EUR)
- Sub-Saharan Africa (SSA)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- Indian Subcontinent (IND)
- South East Asia (SEA)
- OECD Pacific (OPA)

2.2 POPULATION

A typical energy forecast starts by considering the number of people that need energy. Although energy consumption per person varies considerably, and will continue to do so, everyone needs access to it in one form or another.

The most frequently used source for population data and projections is the UN Department of Economic and Social Affairs (United Nations 2017), which publishes its World Population Prospects every other year. The forecast in the latest update, in June 2017, runs to 2100, and although the UN does not itself produce energy outlooks as such, its population projections are often used to cover the population dimension of such forecasts.

Entities that separately produce population forecasts include the US Census Bureau and the Wittgenstein Centre for Demography and Global Human Capital in Austria. The Wittgenstein Centre goes beyond the UN's analysis to also consider how future education levels, particularly among women, will influence fertility. As noted by Lutz (2014), urbanization in developing countries will reduce fertility rates; having many children is a greater economic burden in cities than in traditional, rural agricultural settings. Furthermore, evidence reveals that higher levels of education among women give a lower total fertility rate (Canning et al. 2015).

In Sub-Saharan Africa (SSA), the reduction in fertility is slower than in other parts of the world. In some countries, the rate of decline has even slowed recently.

SSA lags other world regions in the expansion of education and in socio-economic development. However, we assume that eventually, although lagging the rest of the world, urbanization and improved education levels of women will also accelerate the decline in fertility rates in Africa.

It is likely that SDG#4 Quality education and SDG#5 Gender Equality will give further impetus to female education, which again gives many other co-benefits. Consequently, we follow the Wittgenstein Centre's fast-track education assumptions for all regions except SSA, where a constant enrolment ratio is chosen.

The Wittgenstein Centre also uses several scenarios related to the five different 'story lines' developed in the context of the Intergovernmental Panel on Climate Change, IPCC (van Vuuren et al. 2011). The IPCC calls these story lines Shared Socioeconomic Pathways (SSPs). In this Outlook, we follow the central scenario (SSP2) for population, and use it as a source of inspiration for other forecast input.

The combination of SSP2 and the education assumptions described above lead to our 2050 population forecast of 9.2 billion, with Africa still contributing to limited global population growth of 0.3% per year by mid-century. As a sensitivity test in Section 4.9, we have also run our Outlook using the UN's median and low population forecasts.


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HOW MUCH ENERGY DOES THE AVERAGE PERSON NEED?

In 2014, the US Department of Energy released an engaging podcast 'Direct Current' addressing the issue of how much energy the 'average person' in the US consumes (US DoE 2014). The answer they gave was some 157 gigajoules (GJ) of energy consumed per US citizen per year, which the podcasters then converted into the energy equivalent of burritos, sticks of dynamite and even the amount of energy required to send 'Marty' in the film *Back to the Future* back into time. They also noted that, "If coal powered everything, every few days you would consume your body weight in coal". Importantly they compared energy consumption across the various states, finding that Alaskans had the highest per capita energy use per year (the energy equivalent of 70,228 burritos per year) compared with sunny California (at 24,418 burritos).

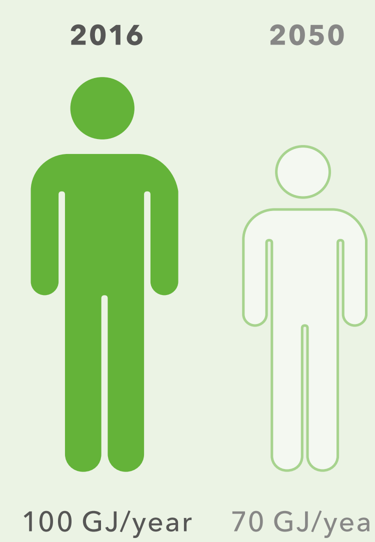
The World Bank also publishes a list of countries by energy consumption per capita (World Bank 2016). They measure not just the end-use consumption of energy, e.g. for transport and heating, but all the energy required as input to produce fuel and electricity for end-users – in other words, the total primary energy supply per person. For the USA in 2016, the World Bank cites a figure of 290 GJ per person per year – very close to our own figures.

But the question we address here is: how much energy does a person *actually* need?

In its 2016 study, "A better life with a healthier planet", Royal Dutch Shell PLC estimated that in order to have a decent quality of life, a person requires access to 100 GJ of energy per year.

With a global population of 7.5 billion, that implies a global energy consumption of 750 exajoules (EJ) per year. However, we estimate global energy consumption in 2016 to be 400 EJ, implying that a great many people lack access to sufficient energy – especially considering that some nations, like the US, consume well above average. According to the UN, one billion people lack access to electricity, and more than three billion still cook with dirty, inefficient fuels.

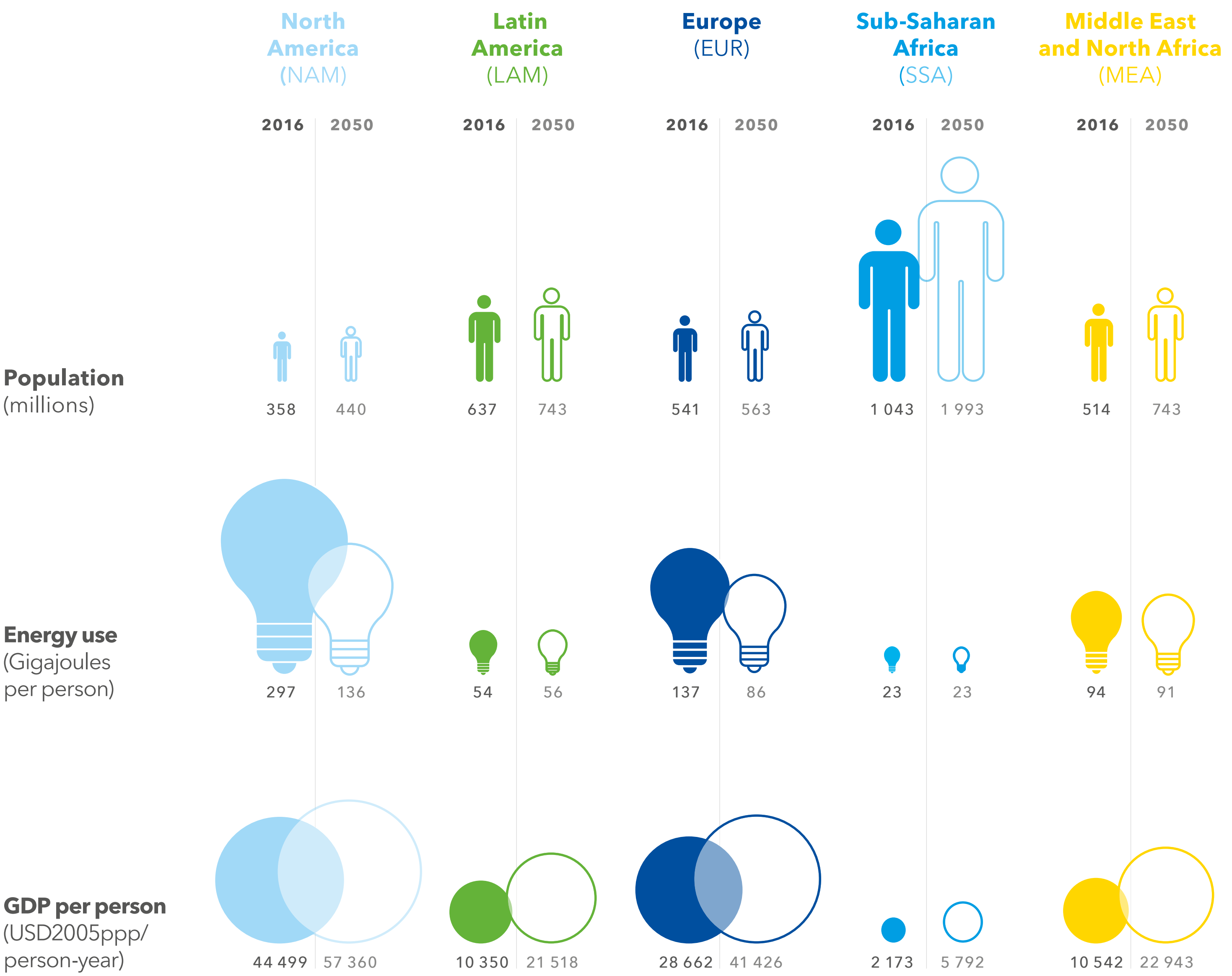
What gives reason for optimism is that, owing to rapid efficiency gains, a decent quality of life will be sustained by a lot less energy by 2050. In fact, we place this figure at around some 70 GJ per person per year. Nevertheless, we acknowledge that access to clean and affordable energy for all (SDG#7) remains a formidable challenge.

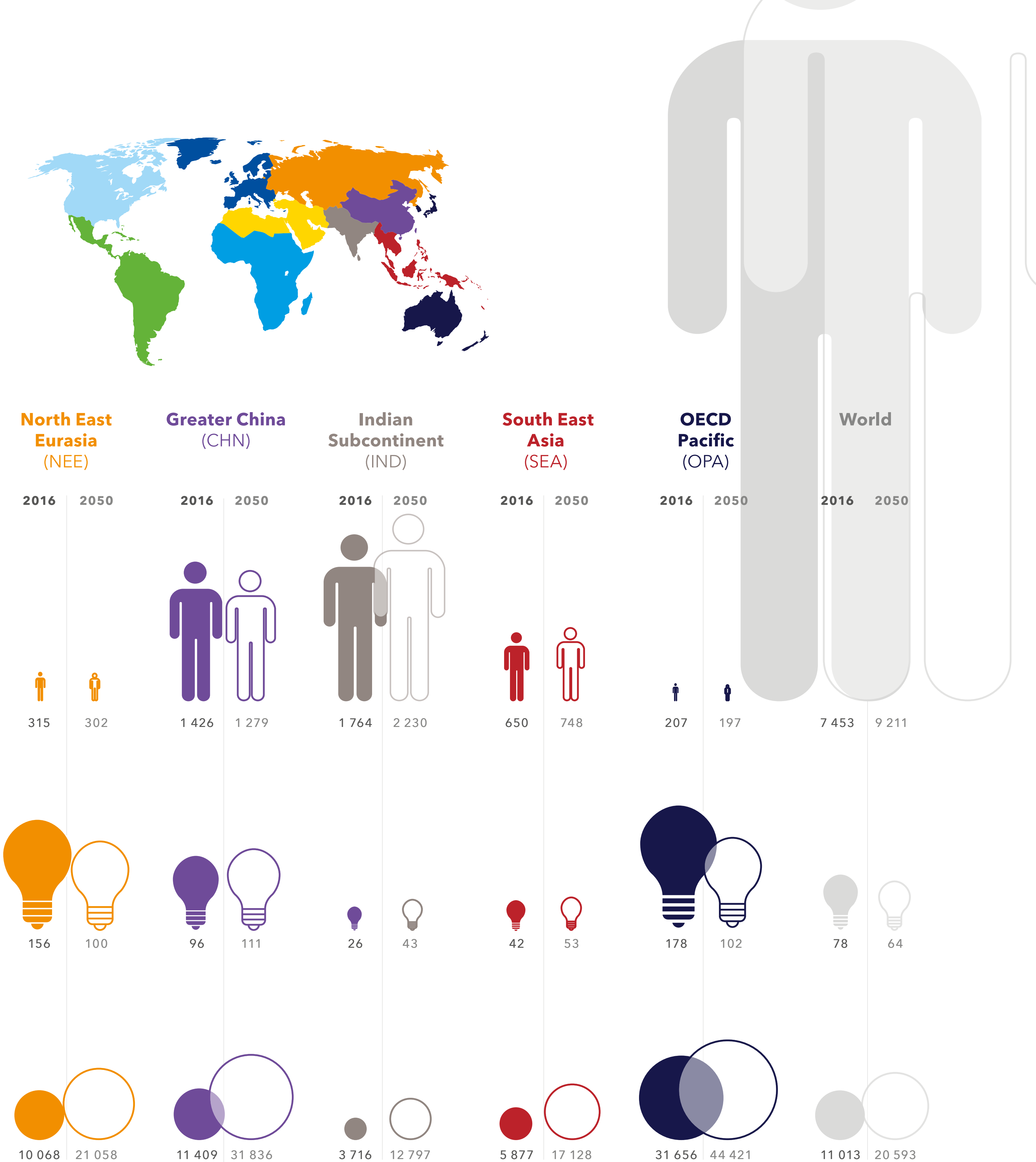


PEOPLE, ENERGY AND GDP ACROSS OUR 10 OUTLOOK REGIONS

2016-2050 OVERVIEW

This illustration shows, for each region considered in this Outlook, a comparison between population, per capita energy use and GDP (2016 and forecast figures for 2050).



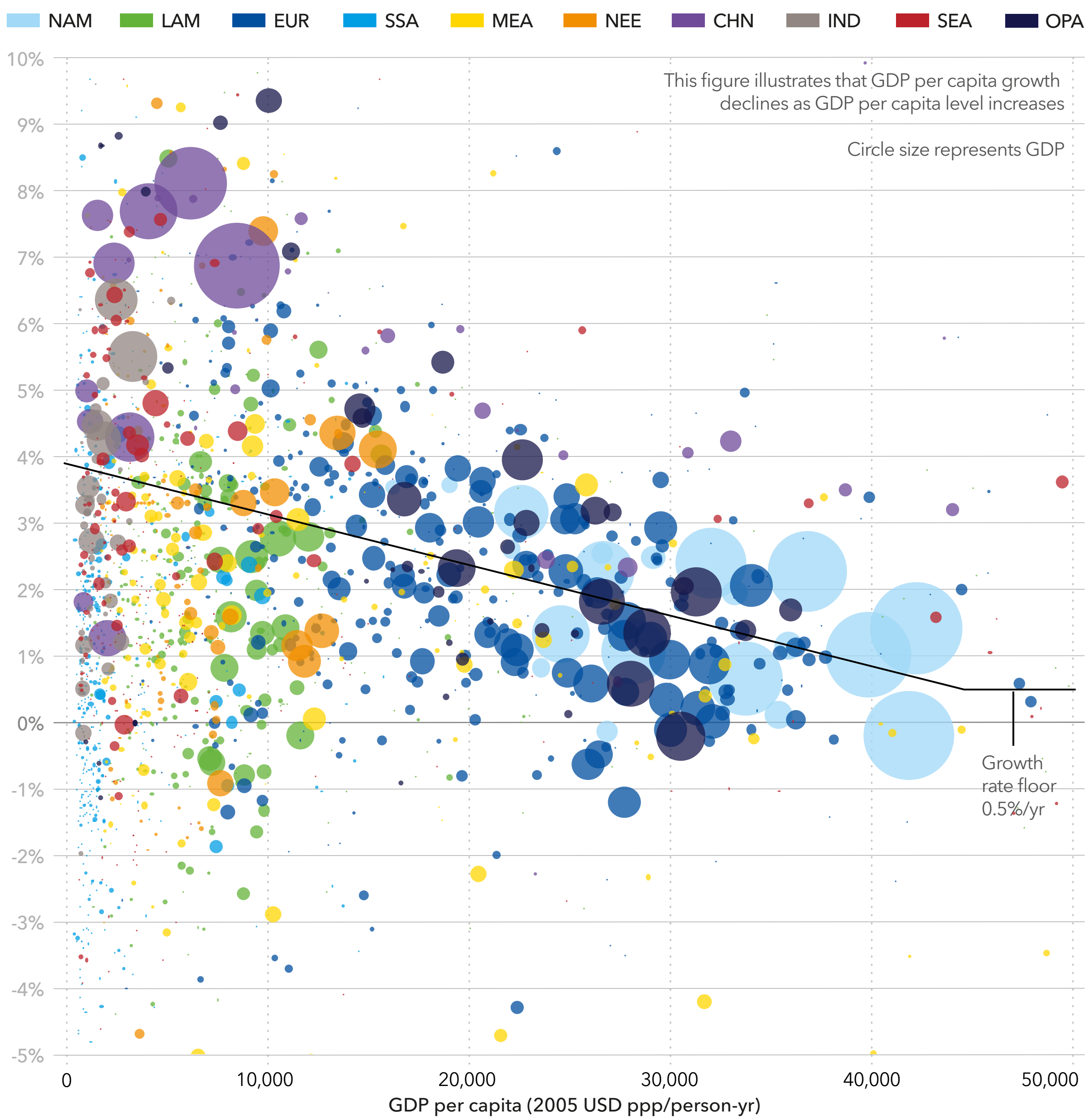

North East Eurasia (NEE)
2016 2050
315 302
156 100
10 068 21 058
Greater China (CHN)
2016 2050
1 426 1 279
96 111
11 409 31 836
Indian Subcontinent (IND)
2016 2050
1 764 2 230
26 43
3 716 12 797
South East Asia (SEA)
2016 2050
650 748
42 53
5 877 17 128
OECD Pacific (OPA)
2016 2050
207 197
178 102
31 656 44 421
World
2016 2050
7 453 9 211
78 64
11 013 20 593

2.3 PRODUCTIVITY

FIGURE 2.3.1

Annual GDP per capita growth as a function of a country's level of economic development

Units: Percentages/yr



Each circle represents 5-year average GDP value for a country. Data range 1965-2015. Source: Gapminder

Productivity is the output achieved per worker and is measured in Gross Domestic Product (GDP) per capita. We have assumed that the current employment fraction does not change, and consequently output per capita is a very close proxy for productivity, as documented e.g in (DNV GL 2016). While the productivity growth of a poor nation tends to increase as it becomes more prosperous, productivity growth of an advanced economy slows down as its standard of living improves, as shown in Figure 2.3.1.

The dynamics of productivity growth are straightforward: An increase in standard of living in a poor country comes first from productivity improvements in the primary sector, and then from productivity improvements in the secondary sector, when an increased share of GDP is devoted to industrialization. In both sectors, the move from manual to industrial processes carries vast potential for productivity improvements.

However, mature economies employ increasing shares of their GDP in services (the tertiary sector). Although services such as financial services and health care benefit from technology uptake, productivity improvements tend to increase quality rather than the amount of output. This implies that productivity growth will slow down as economies approach maturity.

We base our productivity assumptions on the trend shown in Figure 2.3.1, where we assume regions will converge to growth rates indicated by the line in 15 years' time. As we consider it likely that high income regions with dominant tertiary sectors will also manage to have some productivity growth, we have amended the forecast and truncated the trend line at 0.5% per year productivity growth for standard of living higher than 45,000 USD/person-year.

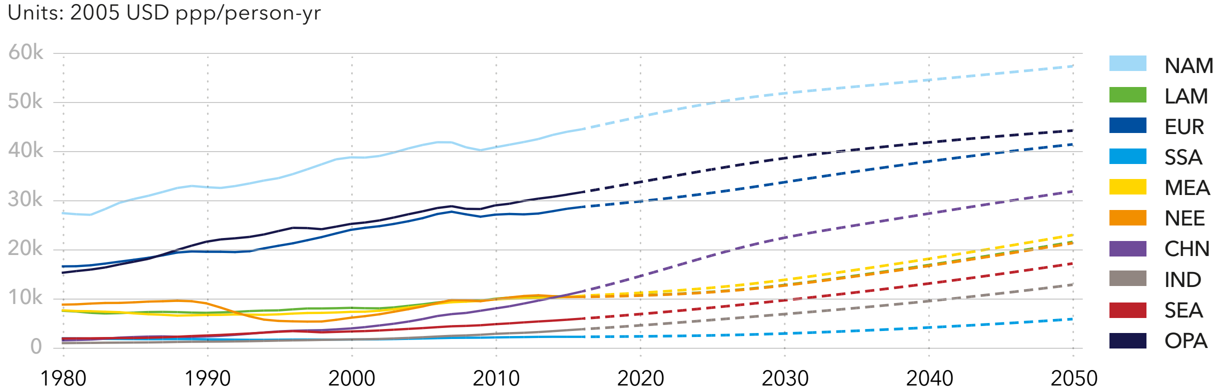
Greater China's productivity growth has been much stronger than the trendline in Figure 2.3.1 suggests. However, we forecast that it will slow down towards the trend over the next 15 years, just as those regions below the trend line will catch up with it over the same period.

Figure 2.3.2 shows the resulting productivity forecast. We find productivity growth in OECD and Greater China regions slowing down, while other developing economies will experience higher growth, but their growth will also slow down as their economies mature.

FIGURE 2.3.2

GDP per capita by region

Units: 2005 USD ppp/person-yr



2.4 GROSS DOMESTIC PRODUCT (GDP)

GDP is the product of population and GDP/capita.

Unlike population statistics, there is no central or main source for global GDP forecasts. The IMF and World Bank, much quoted sources for economic growth, produce only short-term forecasts covering the next few years, and have no 2050 forecasts. We therefore produce our own GDP forecasts, based on the productivity figures outlined in the previous section.

There are multiple ways to measure the gross domestic product of a country. To allow comparison between regions and over time, we use real GDP data that are adjusted for differences in cost of living between countries (purchasing power parity). Our historical GDP data is from Gapminder (2014), a comprehensive data source for various global indicators, and is given in international USD in 2005 prices.

Using the methodology above, multiplying regional productivity dynamics with respective population forecasts, we see a 130% global increase in global GDP from 2016 to 2050 (CAGR 2.5%/yr), reaching USD 190 trillion by mid-century. The growth rate is not constant, but reduces over time, as shown in Table 2.4.1.

TABLE 2.4.1
Ten year GDP growth rates

Period	Average GDP growth in the period [%/yr]	Global GDP at end of the period [USD tn/yr]
2010–2020	3.2	93
2021–2030	2.9	125
2031–2040	2.3	156
2041–2050	2.0	190

Our forecast for Global GDP is in line with recent projections by McKinsey (2015) and PwC (2017). Some energy forecasters, however, use higher GDP growth figures, resulting in higher energy consumption estimates. The difference is partly due to them using the UN median population forecast, which is 9.8 bn for 2050, 6% higher than our population forecast. Moreover, a stronger belief in a reversal of the well-established decline in productivity rates in the OECD, explains why others typically end up with higher GDP figures in 2050.

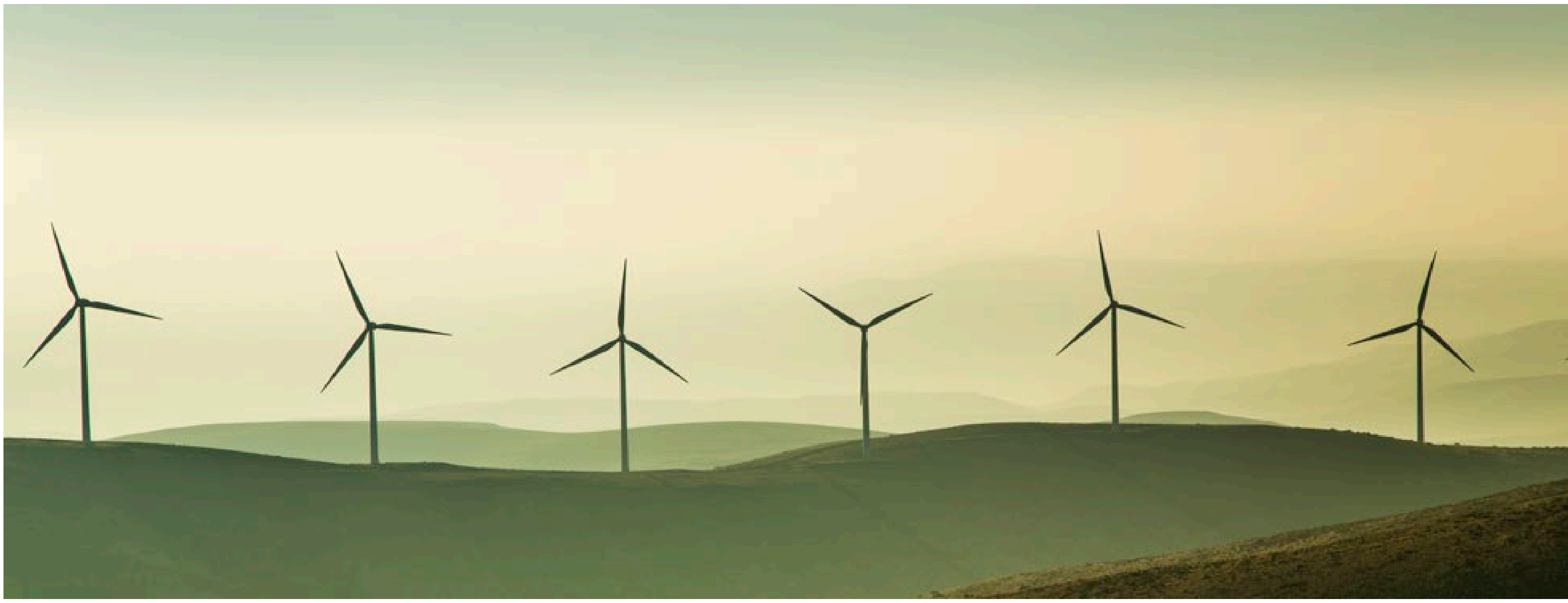
2.5 TECHNOLOGY AND COST LEARNING CURVES

Technology is central to enabling us to meet the world's energy and development needs, and influences both energy supply and demand. Although new technologies hold the potential for decreasing energy use, the converse is also possible.

The premise behind the notion of 'learning curves' is that the cost of a technology decreases by a constant fraction with every doubling of installed capacity, owing to the growth in experience, expertise and industrial efficiencies associated with market deployment and ongoing R&D. As the installed base increases, the learning rate as a function of time will abate.

Wind and solar PV have shown significant cost reductions and market growth in recent years, with investment unit costs declining rapidly, and showing little signs of slowing down. Germany, Denmark, and Spain as early movers in wind, and Germany, the US, and Japan in solar, carried a considerable load of the early learning curve dynamics. Their advances have helped to mature the technology and the industry, and those countries have in turn gained, through renewable technology deployment, an important source of clean energy and employment. Electric vehicles (EVs) and battery technologies are also areas that hold considerable downward cost potential, with the latter also assisting renewable power proliferation.

Over the last few years, exploration and drilling in the oil and gas industry have also experienced rapid downward cost trends, notably in shale technologies. While the 2014-2017 oil price drop itself has accelerated this dynamic, technological advances have also made considerable impact. Parts of such technologies may also spread to related production processes, positively influencing cost dynamics in conventional and offshore oil and gas production.



Technology needs market exposure to demonstrate and develop its commercial potential – the classic chicken-and-egg dilemma. Entrant technologies frequently need an initial boost, and that is a rationale for policy measures aimed at triggering investments flows and hence learning curve dynamics. However, the need for policy measures to support development and deployment for these technologies will change and diminish over time, and be dynamically adjusted to reflect maturity and cost-competitiveness levels reached.

Other technology areas, such as carbon capture and storage (CCS) and hydrogen, are still at an early state of deployment, and will require massive technological learning and scale-up. CCS requires coordination, policy signals, and support schemes to stimulate investments, launch projects, and support learning curve developments.

WIND POWER

Humanity was harnessing wind energy well before the industrial revolution, but wind as an energy source was largely forgotten until three decades ago, when the energy security, climate, environmental and health disadvantages associated with conventional fuel combustion began to be more fully appreciated. Since then, OECD governments have favoured solar and wind-based power, both onshore and offshore. In the latter case, there has been a symbiosis with offshore wind and offshore oil and gas technology developments.

As of today, the wind power industry has evolved to a point where it is increasingly less reliant on preferential treatment for its sustainable future. History has shown significant stability in cost learning rates, measured in the rate at which costs decline as accumulated production doubles. The market for wind technology is global, and therefore the cost learning rates are identical across regions while the resource will depend on the actual location. The historical cost learning rate for the base turbine and associated technologies in onshore wind has been around 18%. In line with the views of several wind experts, we expect the future learning rate to be 16% per doubling of installed global capacity through to 2050 (Wiser et al. 2016a) as a factor that applies to most of the unit investment costs, while for unit operation and maintenance costs, onshore wind will experience two thirds of that rate (11%), and offshore wind slightly higher with three quarters (12%) of the investment cost learning rate. Over and above the learning curve effect, we also factor in significant public sector support that lowers the installation or use costs for new wind installations

Future cost dynamics are presented in Figure 2.5.1 and Figure 2.5.2 indicating that onshore wind in 2050 will be available at about two thirds of the current costs. Yet, these figures only tell part of the story. Just as offshore oil and gas has flourished in a world with cheaper onshore production, we forecast offshore wind to grab a sizable portion of the growing wind market. First, the average capacity factor is much higher offshore so the difference is much less in term of levelized cost of electricity (LCOE) than in installed cost. However, as noted in the technology-specific discussions in Chapter 4, offshore wind connection costs are often subsidised by the rest of the power system and/or by other regulatory mechanisms that favour offshore.

FIGURE 2.5.1

Onshore wind average unit investment cost, before support

Units: USD/kW installed

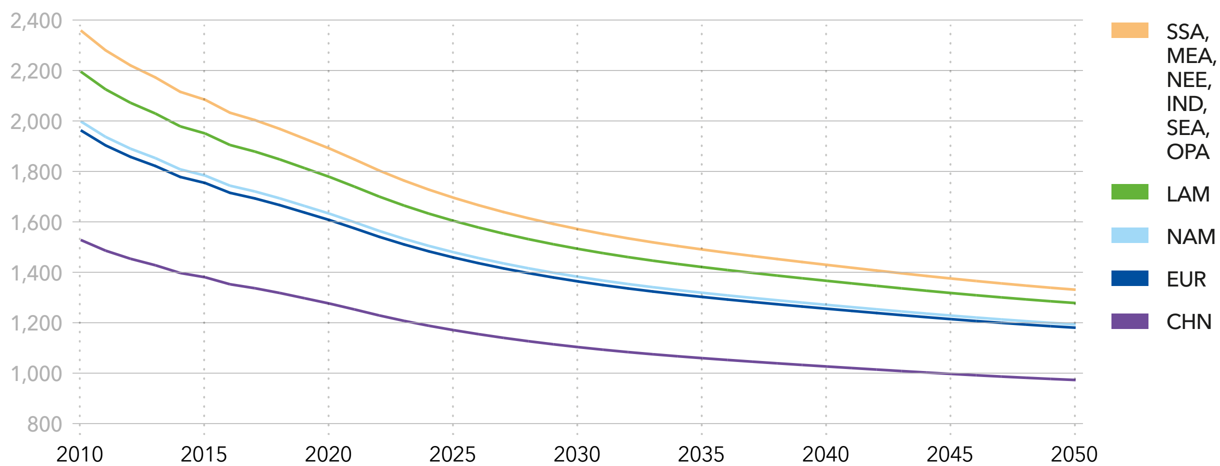
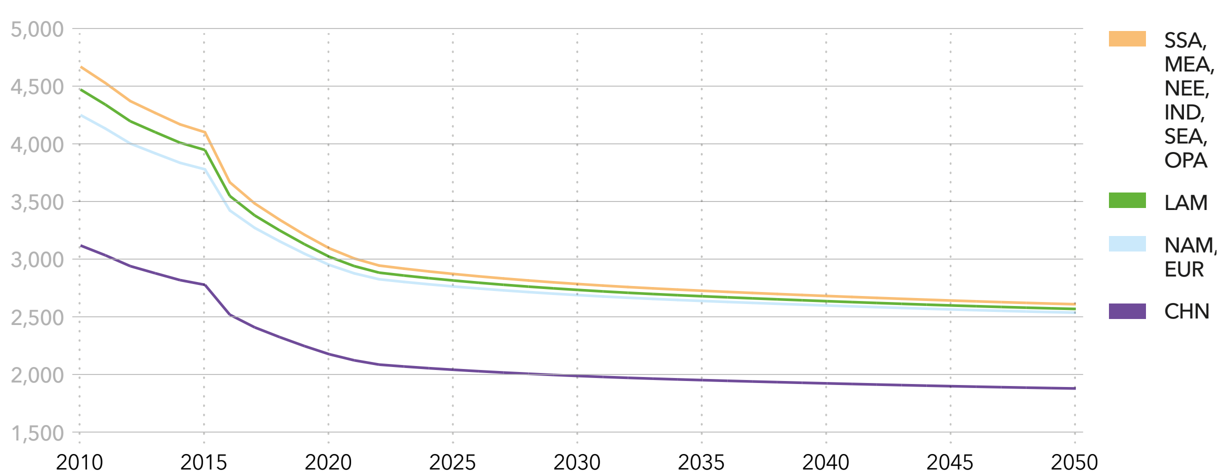


FIGURE 2.5.2

Offshore wind average unit investment cost, before support

Units: USD/kW installed



SOLAR PV

We have averaged all types of PV technologies and installation categories, such as utility, commercial and industrial, as well as residential power systems into one. Of its various integrated hardware elements, solar PV panels have been experiencing the fastest decline in unit costs. Past cost learning rates have been 18% (Sivaram & Kann 2016).

We forecast this cost learning rate to continue, and are using 18% all the way through to 2050. Extrapolating from insights in related technologies, we have applied this rate to investment/unit installation costs, with operating costs experiencing a learning rate which is half of that, i.e. 9%. Figure 2.5.3 shows the resulting PV instalment costs.

Even with peaking plants, demand-response, and other arrangements to stabilize the power system, a system dominated by variable renewables (which will be the case for several regions after 2040), needs storage capabilities. We account for this by adding storage costs to the renewables installations as they are added to the grid. This means that, although the cost of the technology itself declines, the experienced wind and solar PV unit installations costs would increase in several regions after 2040. In addition, there is a host of other measures to ensure flexibility and balance, such as battery storage, bespoke oil and gas fuelled backup power plants, and increased connectivity through grid fortification to ensure that electricity can be dispatched from areas with abundant supply to those in demand. These amendments to the power system are however typically 'socialized' as system costs and borne by all, not any of the specific power providers.

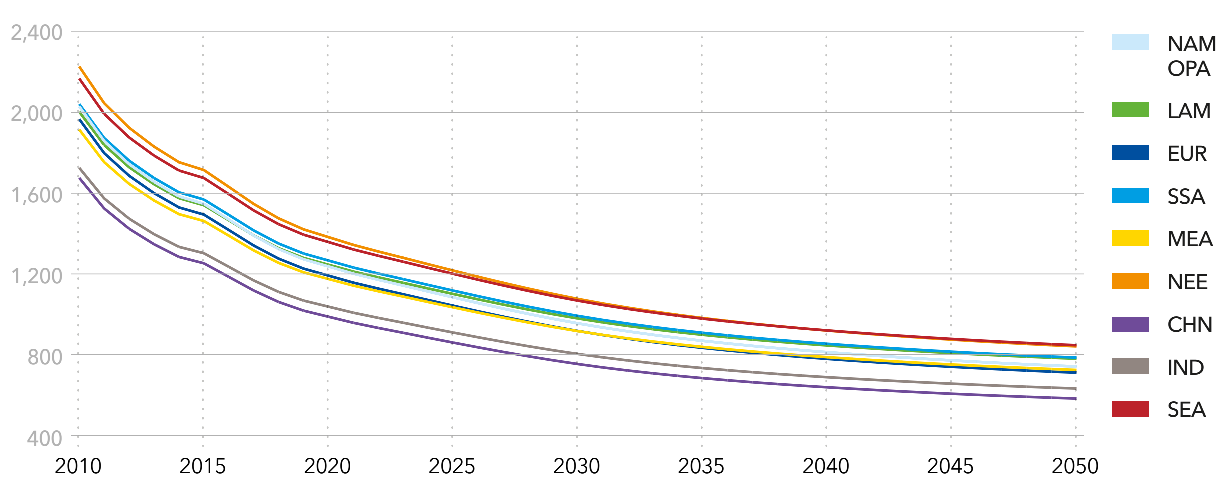
ELECTRIC VEHICLES

Compared with internal combustion vehicles (ICEVs), battery electric vehicles (BEVs) have smaller, simpler, lighter weight (although batteries are heavy), and thus less expensive electric

FIGURE 2.5.3

Solar PV average unit investment cost, before support

Units: USD/kW installed



engines. We are assuming average light vehicle batteries to store 30 kWh, and heavy vehicles 200 kWh. Consequently, current unit costs of BEVs are significantly higher than for a similar range ICEV model. Battery cost learning rates of about 20% have recently been observed for doubling accumulated global capacity. We expect this rate to continue. Fuel cell electric vehicles are another type of EV. These have more complex drive trains, and we do not forecast them to be cost competitive for light vehicles. Yet we do foresee a long-haul niche for them in regions where their energy carrier, hydrogen, will see a supply chain emerging for the heating of buildings.

OIL AND GAS EXTRACTION

Extraction of oil and gas is subject to two counter-acting cost forces. As in the sectors described above, extraction is subject to cost learning as production volumes increase. Disruptive technologies with significant potential for cost reduction also come in to play occasionally, with shale oil and gas as prime examples. However, oil and gas are finite resources, and, as with any extractive industry, the counteracting force is one of increasing costs as production empties reserves. The lowest hanging fruit tends to be picked first, and the chase for the other resources, typically, starts later. To take the offshore oil example: only now, with the North Sea fields in the phase of being depleted, is the chase for resources in the cold climate Barents Sea and further offshore commencing. Ever-improving technologies also contribute to this move towards more distant and challenging conditions.

Based on DNV GL sector and technology-specific expertise, the expected net result of opposing forces in all regions is a decline in investment costs per barrel of oil and cubic meter of gas. This does not represent individual fields, but the average dynamics of an entire region.

Although oil extraction costs differ significantly across the world, cost learning rates do not and are applied uniformly. Differences between production technologies exist, however: Emerging technologies, such as unconventional oil production, have seen their costs decline rapidly by 20% per capacity doubling within North America. Such technologies, with related know-how, can be transfered to other regions and it can be expected that improvements will continue unabated. Offshore oil is more mature and has less potential for further improvements, and we have estimated a cost decline per capacity doubling of 12% globally, whereas conventional onshore production – typically the cheapest technology in all regions – is estimated to fall by 10% per capacity doubling.

Gas extraction is also subject to net learning rates, and estimates of 10%, 15%, and 30% respectively for conventional onshore, offshore, and unconventional onshore production have been applied. LNG liquefaction and regasification plants play an increasing role in our estimate, driven also by cost considerations

In our companion publication for Oil and Gas (DNV GL 2018b) we give more detail on oil and gas extraction.

CARBON CAPTURE AND STORAGE (CCS)

Long seen as an essential decarbonization factor, carbon capture and storage (CCS) has yet to play any transformational role. CCS technologies are still awaiting an initial push in the form of government support for pilot installations and storage infrastructure. But as there finally are several such pilot plants and storage plans in the pipeline, we forecast a dozen or so to come to fruition before 2025.

CCS is used for two purposes. Currently, most applications result in enhanced oil recovery and this is profitable in regions with significant carbon costs for oil producers. The climate benefits in such cases are a side-effect. The second application of CCS is when it is used solely to reduce the carbon footprint of large point sources in fossil energy production and in industrial processes. Emerging technologies for re-use of CO_2 to produce building materials-, or chemicals are being discussed, but are currently not a key factor.

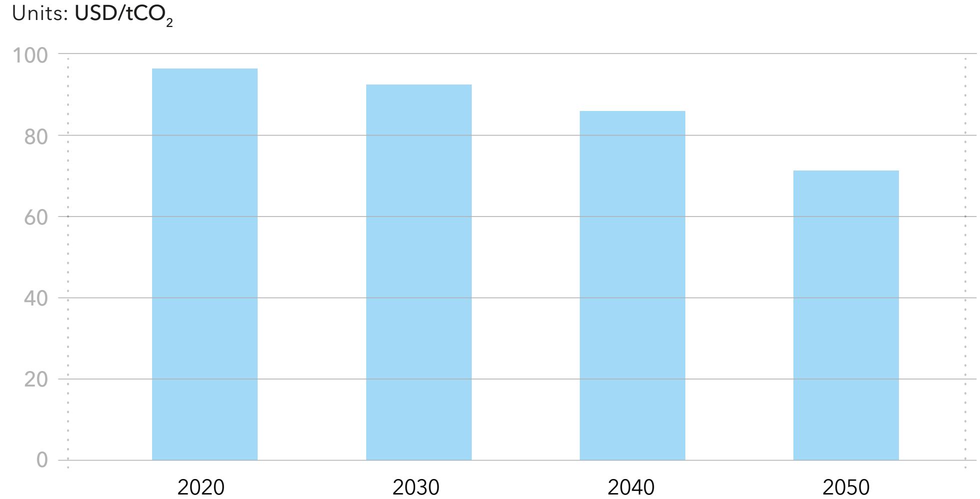
Estimating learning curves for CCS is not straightforward, owing to limited capacity additions. We have therefore studied a similar capture technology, that of sulphur dioxide and nitrogen oxide control technologies at coal-fired power plants. These have shown cost learning rates of 11% for capital costs, and 5% for operation and maintenance costs (Rubin et al. 2015).

We expect increasing average carbon pricing across all regions (Figure 2.6.1), but carbon prices are lower than the CCS costs for the first decades (Figure 2.5.4). Towards the end of the forecast period, these costs and carbon prices will approach each other, and CCS uptake will start increasing rapidly. The effect on climate-influencing emissions will not be felt before the end of this forecast period. But since its growth curve is so steep, it bodes well for CCS in later periods. CCS uptake is extremely sensitive to carbon prices. Increasing them by 33%, expands uptake seven-fold as we show in this report's sensitivity discussion (Chapter 4). In a separate study of what it would take for EU to comply with the Paris Agreement, a carbon price doubling to EUR 90 per tonne is sufficient to reach 100% CCS uptake in Europe (WindEurope 2018).

FIGURE 2.5.4

CCS Costs, assuming limited uptake

Units: USD/tCO_2



Estimating learning curves for CCS is not straightforward, as the history of capacity additions is very short

2.6 GOVERNMENT AND POLICY IN THE ENERGY TRANSITION

Government action and policies are a crucial and integral part of the world energy system, affecting how the energy transition unfolds. Predicting policy over the coming decades is tough in a world dominated by short political attention spans and election cycles. We look first at the context that will shape decisions and investments to spur the transition, then highlight five dynamics of the visible hand of governments. Carbon pricing and fossil fuel subsidies are then discussed as key factors in determining the competitiveness of energy solutions. Sectoral policy dynamics are discussed in Chapter 4 addressing both supply and demand.

DNV GL's understanding of policy and its implications for the energy transition is informed by our work with governments and regulators in helping to shape better policies, and our advisory work with industries on how to respond to such policies. We have also been helped by the experts in our Energy Transition Collaboration Network.

We foresee further intensification in efforts promoting decarbonization and structural changes in the energy sector. Decarbonization overlaps with the goal of reducing local air pollution, a pressing social, political and economic concern across the globe. Clean air policies are familiar in Europe; major European cities like Rome, Paris, Copenhagen, London and Madrid have announced or consider diesel bans and internal combustion engine (ICE) restrictions by 2020 and onwards. Britain, France, Norway and the Netherlands have announced their intention to end sales of ICE vehicles between 2025 and 2040. China is reducing coal use near Beijing and other cities, and developing a plan to ban the production and sale of ICE cars, and restricting car use in cities. New Delhi and Mexico City have followed suit. Energy policies everywhere are rooted in domestic issues and public concerns that are both local and global.

We recognise there will be setbacks and regulatory failures as well as push-back from vested interests that for ideological or financial reasons, seek the dismantling of environmental regulation, and to influence policies in their favour. Still we see economics and technology advances as progressively driving the transition, which combined with the impetus by business and investments towards low-carbon solutions are propelling a dynamic that policy making can delay but not stop. The global energy transition has taken hold. Hence overall, we foresee a world with policies and government action at the global, regional, national and local levels providing direction, promoting research, innovation and investment, and stimulating job creation, market development and the uptake of clean energy technologies – consistent with environmental and economic objectives.

CLIMATE CHANGE ON THE GLOBAL AGENDA

Governments are well underway with implementing the first set of the Nationally Determined Contributions (NDCs) outlining the strategies for emissions reduction and adaptation efforts to meet the objectives of the historic 2015 Paris Agreement and framework for action. While the US announced its intention to withdraw from the Agreement, we see no indication that others will not uphold their pledges. The EU and China have stepped up their climate action leadership, and more collaboration to further the clean energy transition is in the works (Guerra 2018); also, the follow-up climate change summit in Paris marking the second anniversary of the Paris Agreement

– One Planet Summit in December 2017 – hosted an array of business, international organisations and political leaders that are engaged and moving forward. Upholding pressure and progress on the completion of the Paris Agreement 'rulebook' will be important to ensure that emission reduction pledges are implemented as planned, and to prevent lax interpretations of pledges.

Though current state pledges are insufficient to limit warming in line with the goals of the Agreement (UNEP 2017) and are typically only defined until 2030, we expect NDCs to influence energy policy beyond then, especially as new NDCs will be submitted for the post-2030 period. Some nations will strengthen their contributions over time, as the Agreement intends with the timeline for the ratchet mechanism starting in 2018 to prepare for the next round of pledges in 2020. IRENA (2017) concluded that renewable energy targets in NDCs are often less ambitious than targets that countries have already established in national energy plans and strategies. We expect countries to progressively reflect their national renewable energy targets in their NDCs. Analysis and tracking of NDCs will be ongoing to ensure progress, and to prevent the backpedalling of governments from commitments.

CONNECTING CLIMATE AND SUSTAINABLE DEVELOPMENT GOALS

Climate and sustainability goals, and economic growth or prosperity, are interdependent and will increasingly be pursued together. Emerging economies continue to embrace sustainability as it underpins growth and development. Consequently, we foresee developing and emerging economies adopting less resource-intensive development models than those historically pursued by industrialized countries. This is enabled by technological progress – the combination of energy efficiency and falling costs of renewable energy technologies, meaning that the provision of energy services requires less primary energy, and the share of renewables in the supply of primary energy grows. Policies will seek to link the two and leverage their synergies, helping to decouple economic growth from the growth in global energy demand and emissions. Countries not entrenched in a fossil fuel energy system or depending on revenue from traditional energy sources are better placed to see economic benefits from developing renewable energy-related business.

Domestic policies will become more geared to developing energy systems that optimize benefits such as energy provision, job creation, air quality and health. This will be supported by development partners and financial institutions, private and governmental, incorporating sustainability criteria in investment decisions. Recently, the European Commission has proposed regulation to ensure the financial sector contributes towards combating climate change, and that asset managers and institutional investors disclose how environmental risks are factored into investment decisions (European Commission 2018). We have also seen that attention to the financial impacts of climate risks have come to the fore with the recommendations of the Financial Stability Board's Task Force on Climate-Related Financial Disclosure – considering physical and economic losses from unmitigated climate change but also the climate policy and transition risks that increase the risk of economic dislocation and asset stranding (Campiglio et al. 2018). Climate-related financial risks and opportunities will continue the ascent on the agenda of the financial world. Risks will be priced, managed and will influence the cost of both financing investments and mandates on funds. This in turn will affect the deployment of capital and blended finance with an expected upswing in allocations to clean sectors, thereby accelerating decarbonization and the transition.

Countries will seek a reliable supply of energy as part of meeting development needs and safeguarding economic growth. The energy trilemma demonstrates a need for policy to balance requirements for security of supply, affordability, and sustainability. The universal aspiration to deliver the UN 2030 Agenda and Sustainable Development Goals is expected to continue guiding politically-focused efforts, supported by innovative business solutions and technology developments. Achieving SDG goal #7 — to ensure access to affordable, reliable, sustainable and modern energy for all — becomes even more realistic with cost reductions. Cheaper wind and solar energy, coupled with smart infrastructure and storage technology, will improve the economics of sustainable energy paths. We expect that at the national level, there will be growing policy effort to link NDC and SDG plans and actions on the ground. Issues will be addressed in tandem to realize positive synergies, and balance competing priorities such as species and habitat protection, water for multiple uses, land use for food- and energy production.

SECURITY OF SUPPLY

Energy policies have always been tightly linked to access to natural resources, and to their implications for economic development, technology opportunities, and foreign affairs. In modern times, few countries have had indigenous energy supply and fossil energy resource bases large enough to secure energy self-sufficiency. Some dependence on imports has been common. Given awareness of geopolitical risks and fears of disruption to energy supply, diversification and energy security will remain key concerns and drivers of policy. This is seen in fast-growing economies such as China and India, due to the sheer pace of growth in demand, but also in the European Union where over half of energy needs are met by imports. The rapid expansion of the LNG market allows the EU to draw upon global, as opposed to regional, supply of gas, and infrastructure projects such as the Southern Gas Corridor have the goal of reducing Europe's dependency by expanding the number of supply sources.

Security of supply and putative job preservation are used as arguments for continued exploitation of domestic fossil fuel endowments such as coal resources, as seen for example in the case of Poland and the EU Commission's acceptance of state aid to coal power and recently in the US with policy efforts by the Trump administration to keep coal power up and running. However, energy import dependence will increasingly be alleviated by the growing decentralization of energy systems. We forecast new energy sources, with advancements in technology, to be produced locally to progressively reduce import reliance and create jobs. Denmark's drive for wind energy, UK offshore wind ventures, Mexico's clean energy generation targets, and Chile's effort to reduce dependency on oil and coal and exploit abundant solar and wind energy, illustrate this.

Energy systems will increasingly rely on renewables – with flexibility and storage options to accommodate short-term volatilities in supply – which by their physical nature will be mostly indigenous. In other words, 'home grown' as relying predominantly on sun and wind thereby allowing countries to escape the price, foreign exchange, and political volatilities commonly associated with hydrocarbons extracted from a limited array of geologically advantaged countries.

CRITICAL SUPPORTING RESOURCES

The rise of renewable energy is raising concerns about the materials critical to exponentially growing technologies and infrastructures, such as wind, solar, batteries, electric vehicles, and grids. We expect that more global coordination across industry players, traceability of materials along value chains as well as technology developments will emerge to overcome bottlenecks and balance supply with the demand needs of the energy transition, while also addressing the political, social and environmental challenges linked to the production of e.g. metal ores. We discuss the potential for resources limitations to influence the pace of the energy transition in more detail at the end of this chapter.

SEIZING THE POTENTIAL

New technologies and models of economic activity will also sway the agendas of policy makers. The change from linear to circular material flows through a combination of extended product life cycles, intelligent product design, reuse, recycling and remanufacturing (IRP UNEP 2017), are all instrumental strategies to

reducing environmental and resource pressures, and with implications for the energy sector.

For example, increasing the share of secondary production (from recycled metals) in the total supply of metals (as opposed to primary production from ores) reduces energy use substantially. Hence, we see that circular is merging with the decarbonization- and energy transition agendas. China and the EU, already have circular economy-related roadmaps and legislation; we expect that policy attention and efforts will grow, also helped by analyses like the Circularity Gap report (2018).

Technological advances in combination with business model changes will continue to transform the energy sector. For example, in buildings, with digitalization and 'smart' energy management systems, in manufacturing with the impact of circular strategies; in power with the role of digital technology in intelligently managing power systems, and in mobility being hit by concurrent major shifts – sharing, autonomous, lightweight materials, together with the switch to EVs. Common to all is that the speed of uptake will be mediated by the behaviour of consumers and regulatory frameworks set by governments, affecting development, testing and deployment, and as such, the future shape of the energy system.

HOW DO WE SEE THE POLICY SPACE UNFOLDING TOWARDS 2050?

At the country level, diverse institutional environments, political economies and governance styles as well as varying economic maturity and priorities, will result in a wide range of approaches adopted by major economies in the world towards energy transition and decarbonization. This diversity will pose a challenge to effective cross-border coordination at the scale needed. The energy sector will continue to be heavily influenced by policy, though decarbonization in the energy system will become progressively less dependent on public policy and support as technology advances and wind and solar costs continue to decline. The energy transition that we foresee is rapid and disruptive. Governments would be well advised to plan proactively for a future transitioning away from fossil fuels, facilitating an orderly transition and ensuring that communities and the people affected are properly supported and retrained, with a view to energy segments on the rise as the engines of job creation.

The pace of the energy transition will also be affected by the political feasibility of dealing with barriers to the uptake of competing innovative technologies — for example lock-in effects, both technical in the form of incumbent systems and physical infrastructures along with the political clout of the incumbent industry. Considering the high dependence of the global energy system on fossil fuels – from energy intensive industries to households — carbon pricing and fossil fuel subsidy reform are essential for decarbonization and for addressing negative impacts, such as on health due to air pollution. That governments properly manage the fiscal gains of these policies to smooth impacts, such as through compensated retraining programmes, or targeted short-term assistance to affected low-income households, will be vital to build support.

> "The energy transition we foresee is rapid and disruptive. Governments would be well advised to plan proactively.

THE VISIBLE HAND OF GOVERNMENT – FIVE DYNAMICS

1. A new phase of government facilitation:
Regulatory approaches will evolve to cope with features of novel technologies. These will seek to accommodate;

- the growing share of renewables and decentralized components;
- new business models such as for shared, autonomous mobility or circular value chains; and
- the fundamentally different characteristics of future energy systems, such as offshore grids and interconnection, which need coordinated network planning.

Policies supporting and capitalizing on electrification will vary, but seem to be shifting towards hesitant reliance on market forces. Regulatory bodies will evolve electricity market designs for the required system integration and to manage variability in power systems that comes from greater reliance on variable wind and solar. This involves valuing flexibility, adjusting demand to better follow supply, and also providing a stable investment environment for flexibility resources and new energy technologies that are more capital intensive. Governments will increasingly facilitate such shifts and are likely to harness resources beyond the public sector to enhance the effectiveness of innovation and transition efforts, and to mobilize private capital.

2. Multiple objectives motivate transformation of energy systems:
Policy decisions on energy will not be straightforward. The main, often competing, considerations will include:

- security of energy supply,
- technology, innovation and industry development,
- job creation or destruction,
- improvements to local livelihoods and health,
- conservation of the natural environment and scarce resources,
- climate change mitigation and adaptation, and
- not least, cost to the end consumer.

Energy policy measures, planning and target-setting will continue to attempt to balance trade-offs and/or win-wins between these multiple objectives.

3. Positioning and competitiveness:
Driven by the decarbonization agenda and the goals of the Paris Agreement, governments worldwide will juggle the competitiveness of domestic industries and the need to promote secure, affordable and sustainable energy mixes. Public stimuli will take many forms in a race to lead in clean energy technologies and capture positive economic spin-offs through establishing industries, building competences, and exporting technology. Maximizing industrial opportunities in a transforming energy technology landscape will be a dominant aspiration for governments.

4. Government 'push':
Government will be geared towards stimulating the private and academic sectors to 'push' or originate new technology alternatives and solutions, and investments in energy efficiency improvements and infrastructure. Examples of technology-push instruments are: energy technology plans, financing mechanisms such as reduced taxes, loan guarantees, direct public funding and capital grants to R&D

activities. The share of government energy R&D spending on mitigation technologies, such as renewables and energy efficiency, has risen significantly while the shares going to nuclear and fossil fuels have fallen (UNFCCC 2017). Support of collaborative arenas will also remain important. As an example, the 2015 launch of the Mission Innovation initiative, involving 22 nations and the EU, is committed to doubling public investment in clean energy R&D over five years to accelerate innovation.

5. Government 'pull':
Governments will seek to stimulate new energy technologies and low-carbon solutions by pulling through demand to encourage uptake and deployment, thereby stimulating market- as well as job creation. Examples of technology-pull instruments are: renewable obligations, capacity targets and auctions, feed-in tariffs/premium payment, vehicle fleet efficiency standards, consumer-oriented labelling, and public procurement policies – which will remain important for investments in new markets and for energy access.

Support will be progressively phased out as technologies mature and become competitive. Renewable energy technologies are becoming less dependent on support and more immune to unpredictable government policies. This applies especially to the power sector. In others – notably buildings (heating, cooling) and transport – policy will continue to play a key role in accelerating the uptake of technologies and new practices.

CARBON PRICING

For many years, many actors in government, academia, and civil society have advocated carbon pricing that both reflects the true societal costs of energy and emissions, and is set at a level high enough to influence investment and consumption decisions, but to little effect up until now. Carbon pricing is difficult to sell politically, and it raises concerns about the competitiveness of domestic industry. Nonetheless, carbon pricing continues to gain traction, as seen at the One Planet Summit in Paris where leaders and countries across the Americas vowed to step up carbon pricing and launched the Carbon Pricing in the Americas cooperative framework. We expect similar initiatives to spread globally with guidance provided by the Paris 'rulebook' on the operationalization of Article 6 – carbon market provisions – of the Paris Agreement. On the other hand, we think it unlikely that the impact of the initiatives will be such that the costs of climate change will be borne fully by emitters.

As of the first half of 2018, 45 national jurisdictions and 25 cities, states, and regions were pricing carbon or had carbon pricing initiatives scheduled for implementation. The relatively brief history of carbon pricing shows a tripling in coverage over time from 5% of global emissions in 2005 to 15% in the beginning of 2018 (7.4 $GtCO_2e$), and coverage will be raised to about 20% with scheduled initiatives (World Bank et al. 2018). In other words, 85 % of global emissions are presently unpriced, and about three quarters of the emissions that are covered by a carbon price are priced below USD 10/tCO_2. Hence the status of achievement on carbon pricing is modest, and in stark contrast to the recommendations of the High-Level Commission on Carbon Prices, which concluded that the explicit carbon-price level consistent with achieving the Paris temperature target be at least USD 40–80/tCO_2 by 2020 and USD 50–100/tCO_2 by 2030, provided a supportive policy environment is in place (CPLC 2017).

With 88 countries, representing 56% of global GHG emissions, stating the intent to utilize carbon pricing as a tool to meet commitments to the Paris Agreement in their nationally determined contributions (World Bank et al. 2018), we expect that countries will continue to pursue a mix of emission trading schemes, taxes or hybrid approaches imposed on different parts of their energy sectors. However, there will be great variation in terms of the values and sectoral applications, and regions will move at varied speeds, mediated by the national and economic interests linked to existing technical systems, and energy resource endowments (Bang et al. 2015).

The competence and experience gained from carbon pricing systems will increase and support a more effective policy response. Already there has been significant learning across emission trading schemes to avoid repeating mistakes made by others (Wettestad et al. 2018). As an indicator of climate action, carbon prices will slowly escalate from today's symbolic level (not referring to the levels of the Nordic countries and France that have more substance) but are not expected to reach a consistent price level to stimulate emission reductions in line with the Paris Agreement, such as through rapid implementation of CCS.

With modest price signals and little predictability in terms of future carbon pricing policies/level, we foresee a continued reliance on other policies (performance standards, mandates, technology investments, renewable support) to achieve the desired level of emissions reduction.

The political effort to strengthen the carbon-related price signals will also be supplemented by voluntary corporate actions. Many corporations already have internal investment guidelines incorporating higher future carbon prices to integrate climate risk into business planning (CDP 2017).

In our forecast, we have – based on the above – included the average carbon prices to be applied per region. These will be significant but will remain lower than USD 60/t CO_2 before 2050 (Figure 2.6.1). We further discuss our model's results for carbon prices in the sensitivity section in Chapter 4.

REMOVAL OF FOSSIL FUEL SUBSIDIES

Subsidies, taxation and other policies favouring production and consumption of fossil fuels have contributed to their establishment and expansion. Fossil fuel support artificially lowers the price of fossil fuel energy – by lowering the cost of production or by lowering the price paid by energy consumers – thereby distorting the competition between energy technologies and directing investments and decisions towards carbon-intensive modes of production and consumption. This delays the energy transition. Support to fossil fuels runs counter to decarbonization policies, and is counterproductive to efforts to tackle local air pollution and other environmental damage resulting from their production and use.

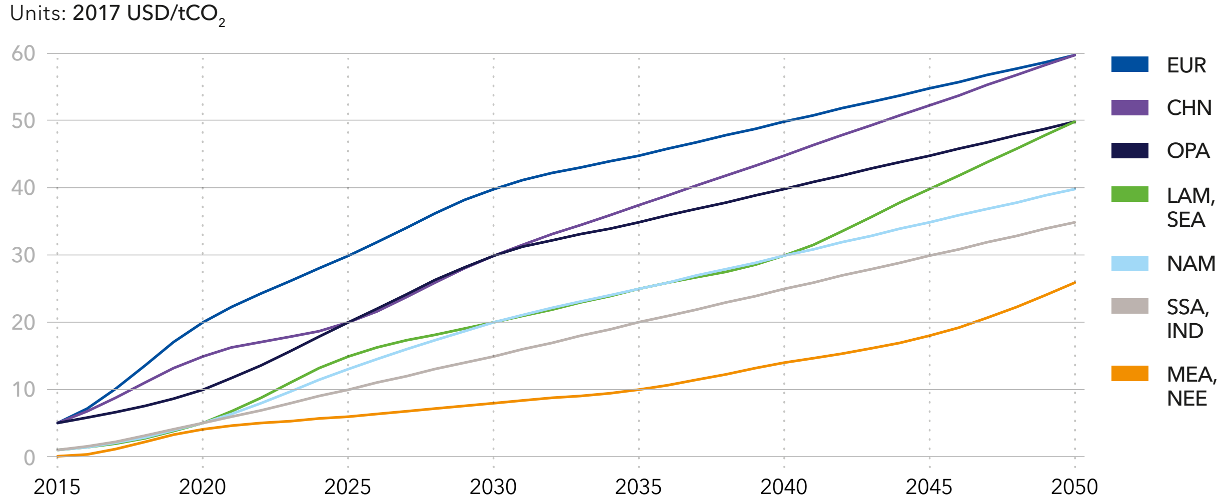
Measures and definitions of 'fossil fuels support' vary, but generally consist of the following categories:

- Production measures that make it less costly for producers to develop resources; examples include tax breaks for capital investment, public finance specifically given to fossil fuel production and investment by state-owned enterprises (SOEs).

FIGURE 2.6.1

Carbon price by region

Units: 2017 USD/tCO_2



– Consumption measures that reduce the price of energy to consumers, and it could, for example, be through government controls on the price of petrol/gasoline and diesel. The aim of these subsidies is often to increase energy access by lowering transport, heating, lighting and cooking bills.
– Externalities that constitute support to fossil fuels to the extent that they fail to factor in the full cost of fossil fuel production and use into the price of fuels/energy, such as increased health care costs due to poor air quality.

Depending on how 'subsidies' are defined, estimates of annual global fossil fuel support range from USD 373-617 billion (OECD 2018) to USD 5.3 trillion, the latter representing 6.5% of global GDP in 2015 (IMF 2015, Coady et al. 2017, Asmelash 2017). The lower estimate largely only incorporates consumption support while the higher estimates include consumption and production support as well as the cost of externalities. The International Monetary Fund (IMF) goes beyond the consumption and production-side subsidy definitions arguing that the cost of carbon and environmental damage should be included in the definition of fossil fuel support.

Momentum for fossil-fuel subsidy reform has been building for years, but despite long-standing pledges to phase-out fossil fuel subsidies, repeated since 2009 and the Pittsburgh Declaration of the G20 countries to 'rationalise and phase-out of subsidies', there is a failure to match words with action. Lack of transparency and different country definitions of support are challenging progress and common steps for reform. Currently, the only legally binding definition of subsidies, accepted by 164 WTO Member States including all G20 countries, is the Agreement on Subsidies and Countervailing Measures (ASCM) of the World Trade Organisation. ASCM defines a subsidy as a financial contribution by a government that confers a benefit to the recipient (WTO 1994 in Asmelash 2017).

Given the centrality of G20 countries in putting the topic on the global agenda, and since G20 countries account for 80 percent of the world's total primary energy consumption and 82 percent of global energy-related CO_2 emissions (Roehrkasten et al. 2016), phase out and action by this group of countries will remain important. We see signs that the matter will be advanced by smaller groups of like-minded countries, such as through The Friends of Fossil Fuel Subsidy Reform (FFFSR).

In our forecast, fossil fuel support is not modelled explicitly due to the lack of common definition of subsidies, and limited transparency in historical data. Eliminating fossil fuel subsidies faces strong opposition from both consumer and producer beneficiaries, who often carry political weight (WEF 2018b). However, we foresee that preferential treatment of fossil fuels will decline. It will be phased out at a varying pace globally owing to diverse motives and domestic economic factors, such as fiscal deficits, climate change goals, differing public views on urban pollution, and as the continual reduction in the cost of renewable energy technologies make public finance support for fossil fuel options increasingly unjustifiable. A gradual, regionally specific, phasing out of subsidies in the various sectors is therefore taken into account in our forecast.

2.7 RESOURCE LIMITATIONS

Exponential growth in renewables, EVs and an electrification of energy demand will combine to significantly change the energy industry landscape. Is this change possible and will there be enough physical resources available? We have investigated physical land mass demands from our Outlook, and the associated requirements for potentially scarce materials linked to exponentially growing technologies.

The ETO Model derives oil and gas output from considerations that duly reflect resource reserves and their depletion. However, the model assumes no constraints on the availability of other raw materials needed to support the energy transition. We therefore, developed a separate model assessing the demands from exponentially growing technologies like wind, solar PV, battery storage and electric vehicles.

MATERIALS

Several recent studies have pointed to raw materials that risk depletion (Arrobas et al. 2017, UNEP 2016, HCSS 2017, Olivetti 2017) when transitioning into a less carbon intensive future. Using those findings, we then used a risk based approach based on conservative estimates: For those cases where demand might challenge raw materials supply, we have evaluated the resource in more detail.

Demand for rare earth metals, as well as nickel, manganese, chromium and copper will grow significantly in the future. However, based on existing and evaluated reserves (USGS 2018), our analysis suggests that there are sufficient reserves to support our projected growth.

However, lithium and cobalt could be in critically short supply in the near term driven by exponentially growing demand from battery storage technologies. Both metals are currently used in cellular phone, laptop and other mobile device batteries. In our forecast, lithium and cobalt are key materials for the development of grid storage and a core component for batteries in EVs. However, we also see a potential competing future demand from drones, robots, sensors and other devices supporting the IoT, which has not been evaluated.

Lithium production must grow by at least 13% annually to support the demand forecast until 2050. The industry appears to be supporting the growth with several large-scale mining projects announced for the immediate future, and existing reserves are capable of supporting demand in the longer term.

Cobalt is a more challenging story: Even accounting for future battery chemistries using 30% less cobalt from 2025, 9% annual growth in cobalt supply will be needed to meet our forecast. Demand just from EVs and grid battery storage would equal the total 2016 supply levels already in the mid 2020s and then continue to rise over the coming decades. As cobalt is mostly a by-product of copper and nickel production, the expansion of those metals will heavily determine availability in the future. The largest recognised cobalt reserves are in the Democratic Republic of Congo (over 50%), so there is significant political risk, increased export taxes and supply chain breakdowns from this dominant supplier, alongside sustainability, social and environmental supply chain challenges.

Since the battery industry is well aware of future cobalt constraints, intense research is ongoing to further reduce cobalt intensity of batteries. Tesla claims to have significantly reduced cobalt use in their batteries. This, in addition to the possibility of new battery technologies, such as solids state or super capacitors, lead us to believe that there will be solutions to the cobalt challenge, and that lack of cobalt or other raw materials will not be a roadblock for the forecast energy transition.

COMPETITION FOR LAND AND OCEAN UTILISATION

In the future, with a growing population, there will be a pressing need for housing, food, recreational space and infrastructure. This raises the question of whether society can afford, or even have the available space to develop, solar PV farms, wind turbine arrays and significant biofuels production competing with food production.

We have used a conservative value of 30 - 50 MW of solar PV panels per each square km. Our 65-fold increase from 2016 to 2050 implies a global solar PV capacity of 19.1 TW. Of these around 30% will be placed on buildings. The remaining 70%, or 13.3 TW, will occupy 0.3% of global land area, about 400,000 square km. Breaking this analysis down, we see that often the competition is between agricultural or arable land (used for only growing crops and not animal grazing) and energy projects; in this case our estimates show 0.8%/2.9% respectively would be necessary for solar PV as a fraction of available agricultural/arable land.

We do not consider these figures overly challenging; there are often possibilities to use the PV farms for pasture or grazing between the panels when space is an issue, to place the PV farms on arid and desert lands, to place it offshore (as done e.g. on Indian lakes), or double occupancy placing it at pavements or roads. Regionally we find that the Indian Subcontinent, using almost 2% of total land mass, will have the biggest share of solar PV per available land. Between 3.5% and 4.6% of agriculture and arable land will be used for solar PV. Even though these figures are higher than the global average, they are of similar size as land use for urban areas. So, although challenging to develop we believe this to be feasible, taking the solutions mentioned above into account.

Wind turbine capacity will grow 15-fold to 2050 and requires space in-between each turbine in order to operate efficiently, avoiding wake for adjacent turbines. This means that onshore turbines, even though projected to need an area of 2 million square km, are compatible with crop growing, grazing and forestry and not simply arid or desert land. While cognizant of the challenges of urban populations and their concerns on visual and noise pollution and conflicts with nature conservationist, we believe our forecast of 6.1 TW onshore wind to be feasible.

Placing wind turbines several kilometres from shore can make them more accepted, at least by urban populations. In our forecast, we have also investigated the impact regionally of our forecast quantity of offshore wind.

Region Greater China, for example, needs approximately 20% of its coastline populated with wind turbine arrays. The configuration would require a 50-km-deep array of 25 modern 10 – 15 MW offshore wind turbines installed along parts of the coastline. In North America, there would be about 4% of the east and west coast populated with wind turbines arrays. Mass installation of offshore wind will clearly need coordination with fishing, shipping and other offshore economic and recreational activities, although there are also co-benefit proposals such as marine farming and artificial reefs within wind arrays. Based on our forecast, we do not think the amount of installed wind onshore or offshore poses an insoluble challenge, assuming proper stakeholder involvement, similar to other large scale infrastructure installations.

BIOMASS VERSUS FOOD

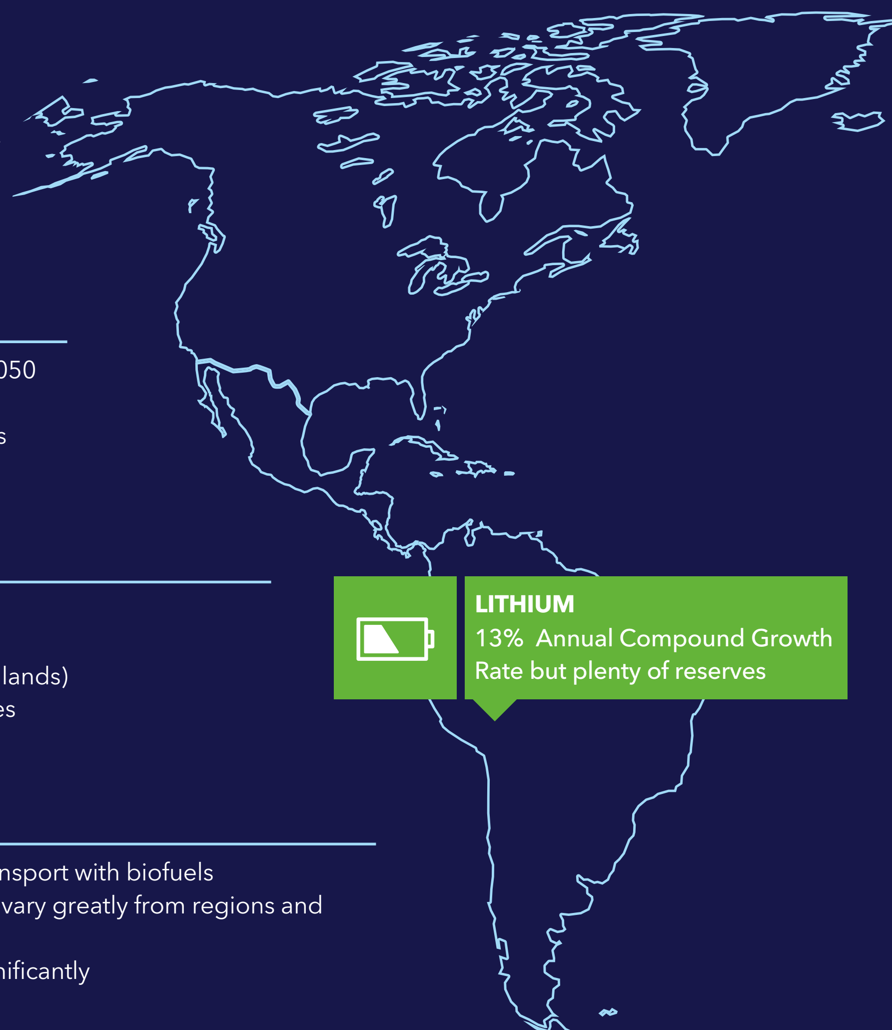
Biomass used for energy (principally transport) is often a direct competitor with food production. Biofuels have a wide range of sourcing materials from corn and sugar cane to waste materials from the agriculture and forestry industries. In the future, offshore production is also likely.

We have used current second and third generation biofuel types to evaluate the land needed to supply the anticipated amount of energy sourced from biofuels in 2050 for the transport sector. Since the production and yield of biofuels is local, and the values vary greatly between regions and even within each region, it is difficult to arrive at accurate average numbers. However, using conservative figures, we have estimated that the potential land mass in 2050 needed would be around 0.5 - 1 million square kilometres or 0.8% of global land area. The most critical region seems to be Greater China with anticipated significant growth in biofuel demand. The necessary area to produce biofuels to support Greater China would be 237,000 km² or approximately 2.5% of their total land area. This might be a challenge, but biofuel can easily be traded globally, and we expect more constrained regions to import from other regions with less constraints.

Future generations of biofuels using, for example algae, will need to meet tougher sustainability criteria and produce a higher amount of energy per square kilometre than current levels.

RESOURCE LIMITATIONS?

We expect exponential growth in renewables, EVs and grid storage. These changes combined will significantly change the energy industry landscape. Will sufficient physical resources be available?



SOLAR x 65

– 65-fold increase of global PV capacity to 19 TW by 2050
– 30% of installed capacity on buildings
– 70% or 13.3 TW will occupy 0.3% of global land mass

WIND x 15

– 15-fold increase to 7.2 TW
– Onshore wind occupy 2 million square kilometres (can fit together with crop growing, grazing and arid lands)
– Offshore wind will need increasing share of shorelines

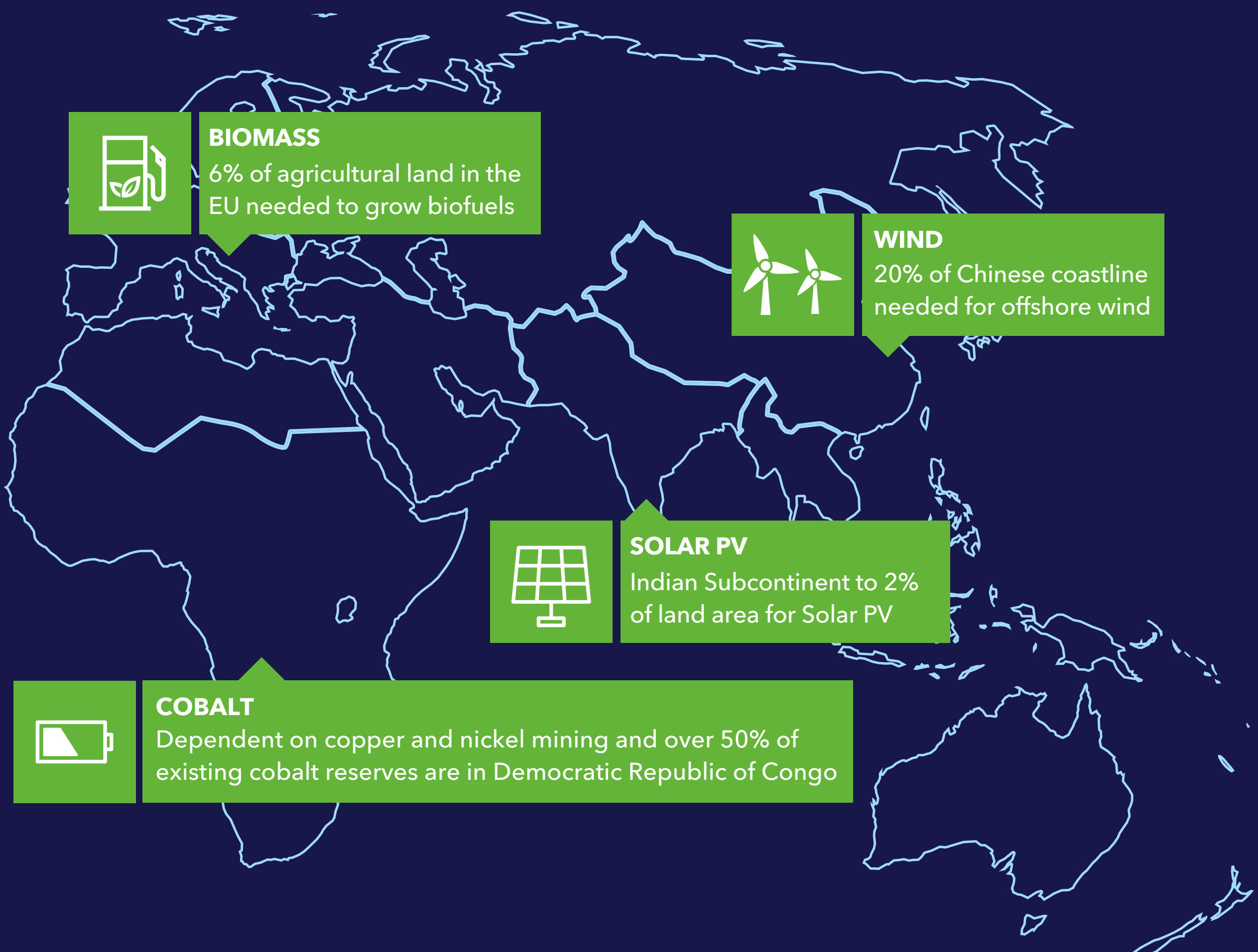
BIOMASS

– 0.5 to 1 million km^2 land mass needed to support transport with biofuels
– Production and yield of biofuels are local and values vary greatly from regions and within each region influencing the result
– Ocean biomass and algae could increase supply significantly

LITHIUM

– 13% annual average growth to supply growing battery demand
– Industry responding with mining projects
– Existing reserves capable of supporting long term demand

Apart from cobalt, there appears to be sufficient resources to supply the materials and land area necessary for the forecast energy transition.
There will be temporary local and global supply bottlenecks, and prices will be affected on a short to medium term basis. However we believe these will even out over time.



COBALT

- 9% annual average growth to supply growing battery demand
- EV and Grid storage demand reach global capacity of supply in 2025
- Forecast demand outstrips all terrestrial reserves available by a factor of 4

Cobalt – running the numbers

*Reserves: are an inventory of economically extractable commodity based on current prices and technology available.
**Resources: are the total amount of possible to extract material currently identified.

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

Our Energy Transition Outlook Model (ETOM) is a system dynamics simulation model that reflects relationships between aspects of the world energy system, and informs expert opinion on the energy system's past and future. Its data and logic enables the forecast in this report.

Each sector of the energy system (see Figure 3.1) is modelled by modules representing:

- final energy demand (buildings, manufacturing, transport, feedstock and other),
- energy supply (coal, gas and oil production),
- transformations (power generation, oil refineries, hydrogen production),
- and other relevant developments (grids, CCS, energy markets, trade volumes, emissions).

The modules exchange information about demand, cost, trade volumes and other parameters to provide a coherent forecast. A detailed documentation of the model is provided elsewhere (DNV GL 2018d).

MODELLING PROCESS

The equations and parameters in the ETOM are based on academic papers, external databases, commercial reports and expert judgement within and outside DNV GL. Examples of external databases used include IEA *Energy Balances*, IRENA *Capacity & Generation Database*, Platts *World Electric Power Plants Database*, and Clarkson's *Shipping Intelligence Network*.
For reliable forecasting, we have run dozens of workshops and discussions with DNV GL industry experts. Nearly 100 people have been involved in this work, acting as conduits to historical data sources in the many domains, quality assurers of model sectors and interrelationships, and as expert assessors of end results.

BEYOND 2050

Our Outlook and model forecast stop at 2050. Looking 32 years into the future involves large uncertainties which increase with longer horizons.

We are confident that the decarbonization and electrification megatrends will continue after 2050, gradually shifting energy to renewable sources. Longer horizons increase the probability of technological breakthroughs or scaling of sources that we do not yet understand.

Consequently, this Outlook does not include any forecast or quantification of what may happen beyond 2050. The only exception has to do with climate implications, where we give an indication of the global temperature increase in 2100 if our 2050 forecast proves correct.

TIME SCALE

The ETOM covers the period 1980–2050. Historical simulation outputs are used to test the model's ability to replicate historical developments, and hence increase the credibility of our forecast.

The ETOM is a continuous-time model with years as the base time unit: it is designed to reflect dynamics happening only at the yearly scale or longer. Dynamics such as within-year seasonality of energy demand, and daily changes in renewable electricity production, are implied in annual parameters and not directly reflected in the model.

Timescale is important in interpreting the model results. With the ETOM deliberately ignoring short-term fluctuations occurring over months or even a few years, the Outlook has low reliability over shorter time periods. For example, while readers can confidently compare the average growth rate of gas demand over 10-year intervals, analysing the rate for 2019–2020 in isolation would not yield meaningful insights.

GEOGRAPHICAL SCALE

The spatial resolution of the model is limited to 10 world regions. Regions interact directly through trade in energy carriers, and indirectly by affecting and being influenced by global parameters, such as the cost of wind turbines, which is a function of global capacity additions. Although we do not explicitly model each country or state within regions, we account for variability through statistical distributions of the parameters we are using. For example, the investment cost of a biomass-fired power station in Europe is modelled as a normally distributed parameter to reflect differences between countries and sub-technologies. This allows the model to reflect that capacity additions might occur in some countries despite the possibility that the average cost of a given technology may be uncompetitively high.

MODELLING PRINCIPLES

All models are abstractions of reality that focus more on certain features of the real system than on others. Our main priorities when designing the ETOM were to include three key characteristics of the world energy system: interconnectedness, inertia, and non-linearity.

Interconnectedness is the most important of these. What happens in solar PV technology influences power generation demand for coal, which in turn affects shipping volumes for bulk carriers, and oil demand for the maritime sector.

Inertia is present in all parts of the energy system – from household appliances to oil refineries – and slows energy transitions. Also, many processes are non-linear: a unit increase in a factor does not always have the same effect on another variable.

One important distinguishing property of the ETOM is that it is not an equilibrium model. Many econometric models assume equilibrium conditions, such as supply and demand being equal all the time. The ETOM explicitly reflects the delays in reaching a desired state, and is consequently able to forecast the path and speed of energy transitions.

Our model does not assume optimality or rationality as a prerequisite. Its methodology is strongly influenced by behavioural economics, where, given the particularities of a given decision situation, decision making can be predicted (Thaler 2015), but the decisions themselves are not necessarily rational in the utility-maximizing sense of the term. Fortunately, we have much historical evidence as to how decision makers tend to react under varying conditions of, for example, energy abundance or shortfall.

The ETOM is not stochastic, but deterministic. We have used past data and our best judgment to provide expected values for all input parameters, and each run of the model gives an exact output as there is no randomness in the model. Of course, there are multiple sources of uncertainty in the outputs, and the ETOM cannot provide confidence levels for these. To partially address this, we run sensitivity tests to understand how model results change when selected input parameters are adjusted. Furthermore, some assumptions we make may be controversial, or differ from those presented in other forecasts. In such cases, it is can be useful to discuss the associated sensitivities.

In this Outlook, we are transparent in our assumptions, inputs and models. Although the exact calculations emerge from a complex model and therefore are not amenable to simple hand-checking with a calculator, we are clear about the parameters used and how they are related. Our aim is to present a transparent model, not a black box. In that way, we believe that it simplifies discussion of the results, and if one wishes to test the consequence of an alternative assumption or disagree with a value chosen, that is easily done.

MODEL STRUCTURE

The world energy system is a collection of independent and linked physical flows and decision making. A high-level depiction of the ETOM is provided in Figure 3.1. In each of 10 regions, we establish five demand sectors: transport, buildings, manufacturing, non-energy and others – each with sub-sectors. Population and productivity are the main drivers of energy demand. Others, such as household size, heating and cooling degree days are also used.

DEMAND DRIVERS

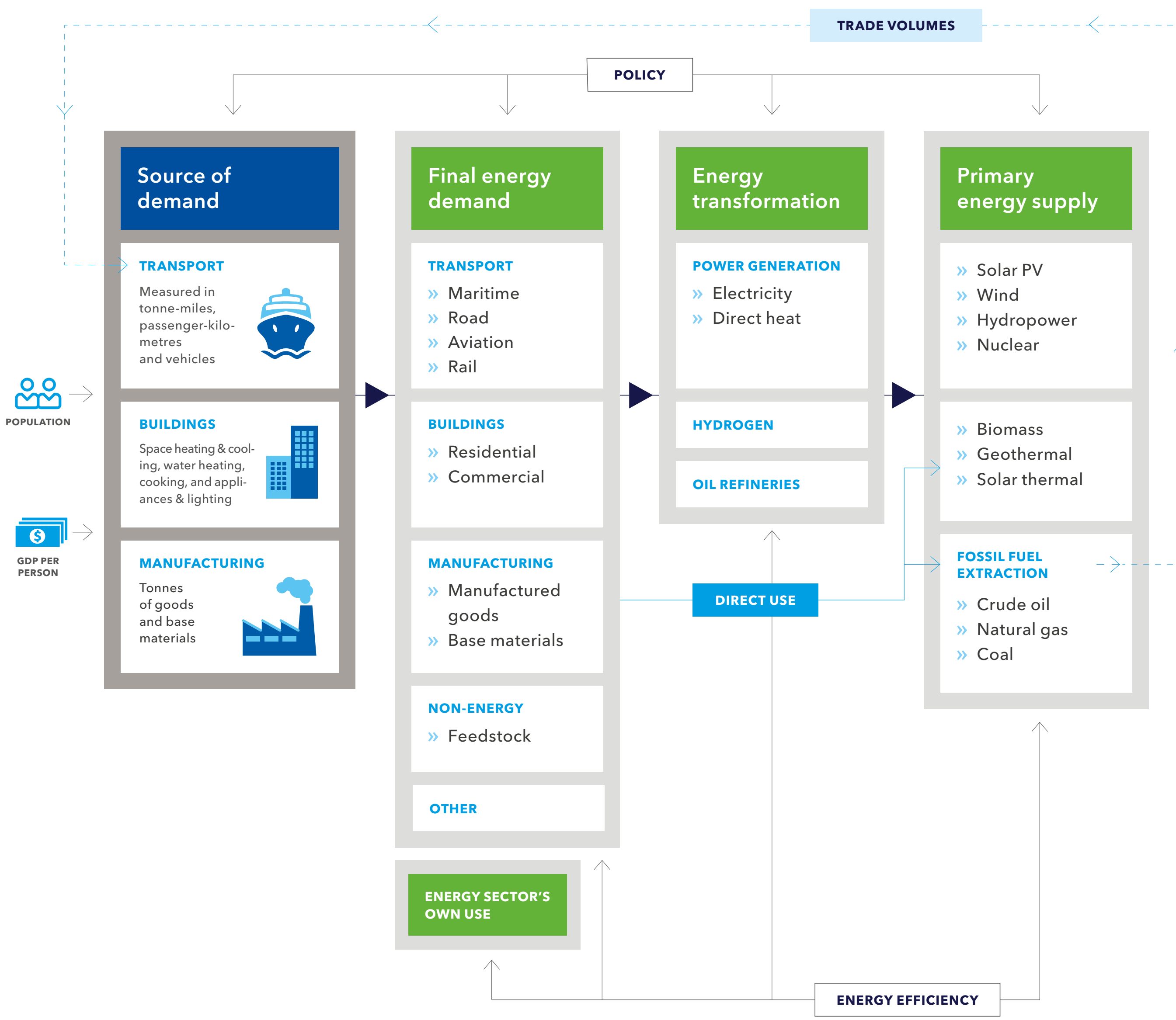
We use policy and behavioural effects explicitly, as in the effect of increased recycling on plastics demand; and, implicitly such as the impact of expected electricity prices on electrification of heating. Generally, we estimate sectoral energy demand in two stages. First, we estimate the sectoral 'output', such as passenger-kilometres of transport, tonnes of manufacturing, and useful heat for water heating. Then, we use parameters on energy efficiency and energy mix dynamics to forecast the final energy demand by sector and by energy carrier.

Our forecasts for the energy efficiency and energy mix of the demand sectors are derived from extrapolating past usage trends into the future. These trends have been subject to expert judgement in our workshops, and adjustments have been made where deemed appropriate. Factors considered during those sessions include: our understanding of the role of governments and policy, reflected in Chapter 2 and technology-specific sections in Chapter 4; and, publicized energy sector efficiency and decarbonization plans, like future fuel standards for vehicles.

> “We are clear about the parameters used and how they are related. Our aim is to present a transparent model, not a black box.

FIGURE 3.1

High-level view of the Energy Transition Outlook Model



The arrows in the diagram show information flows. Physical flows are in the opposite direction. Our model includes feedback loops such as that shown between the amount of fossil fuel extraction and maritime transport (tonne-miles) as a source of demand. There are other feedback loops not shown here, for example the positive feedback between cumulative installed capacity of renewables and the decline in their costs.

FROM PRIMARY ENERGY SUPPLY TO FINAL ENERGY DEMAND

An energy carrier is either a substance or a phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes (ISO 1997). Our ETOM encompasses 10 energy carriers:

Primary energy sources:

- Biomass (including wood, charcoal, waste, biogases and biofuels)
- Coal (including peat and derived fuels)
- Direct solar (thermal energy from solar water heaters)
- Direct geothermal
- Off-grid photovoltaic (electricity from solar panels not connected to the grid)
- Natural gas, including natural gas liquids;
- Oil

Secondary energy sources:

- Electricity
- Direct heat (thermal energy produced by power stations)
- Hydrogen

We model the flow of energy carriers from primary energy supply to final energy consumption, which is the point where energy carriers are in their final tradable form. This means, for example, that we account for how much fuel is used by vehicles, but do not calculate the mechanical work done by these vehicles.

Among the 10 energy carriers we model, seven are also primary energy sources, i.e. they can be used without any conversion or transformation process. The others – electricity, direct heat, and hydrogen –are secondary forms of energy obtained from primary sources. We model the conversion of primary energy sources to electricity and direct heat in the power generation module. Hydrogen is modelled separately. Figure 3.2 shows the global energy flows for 2016 and 2050.

TRANSFORMATIONS

We place special emphasis on electricity generation, both because it is one of largest energy carriers in final energy demand, and also because of its prominence in the energy transition. Using 14 different power station types, we employ a cost-based selection algorithm to forecast changes to a regional electricity mix. As our estimate of the required additional electricity capacity is based on increased electricity demand and estimated capacity retirements, we determine the mix of capacity additions based on a probabilistic model that makes use of the levelized cost of electricity.

In the model, the lower cost will win, though we acknowledge that in the real world other factors are at play, such as geopolitics, and energy and job security. Yet, because we use statistical distributions to reflect not just the average cost, but the varying costs within a certain technology and region, capacity additions do not only come from the lowest average cost technology, but from a mix.

We explicitly estimate the effect of renewable subsidies, carbon price, and the cost of CCS if it becomes economical, as well as the additional cost of batteries for variable renewables. We also recognize that capacity additions happen on a very different timescale. Putting rooftop solar PV in place might have a decision cycle of less than a year, while new nuclear capacity may take more than a decade between first initiatives and full operation.

The role of direct heat is a diminishing one. Consequently, we use a simple extrapolation to estimate regional mixes of direct heat supply. Hydrogen is introduced as a new energy carrier in this year's model and is expected to have a growing share towards 2050 in some regions. As very little data is available, we use input from DNV GL experts to forecast the demand sectors where it will become significant. We assume that hydrogen will be supplied by electrolysis relying on electricity curtailment from variable renewables and dedicated fossil fuel-based hydrogen production facilities.

FOSSIL FUEL PRODUCTION

When it comes to the supply of energy from primary sources, the ETOM focuses on the production of oil, natural gas, and coal. For oil and gas, we again use a cost-based approach to determine regional production dynamics. On the crude oil supply side, we model production capacity as a cost-driven global competition between regions and in three field types: offshore, onshore, and unconventional. Since transportation is typically less than 10% of the final crude oil cost, we use total breakeven prices of prospective fields to estimate the location and type of future oil production.

We model regional gas production slightly differently from crude oil. We first estimate the fraction of gas demand to be supplied from the region's own sources. This varies between regions due to economic, geographic, and political differences, and over time. Then, to determine the development of new fields, constrained by resource limitations, we set three field types to compete on breakeven prices on a regional scale. Regional refinery capacities are also part of the ETOM.

Coal production is modelled by distinguishing between hard coal and brown coal. Each region's hard coal supply reflects its mining capacity, which expands as demand increases and is limited by its geologically-available reserves. For brown coal, we assume most regions to be self-sufficient.

TRADE

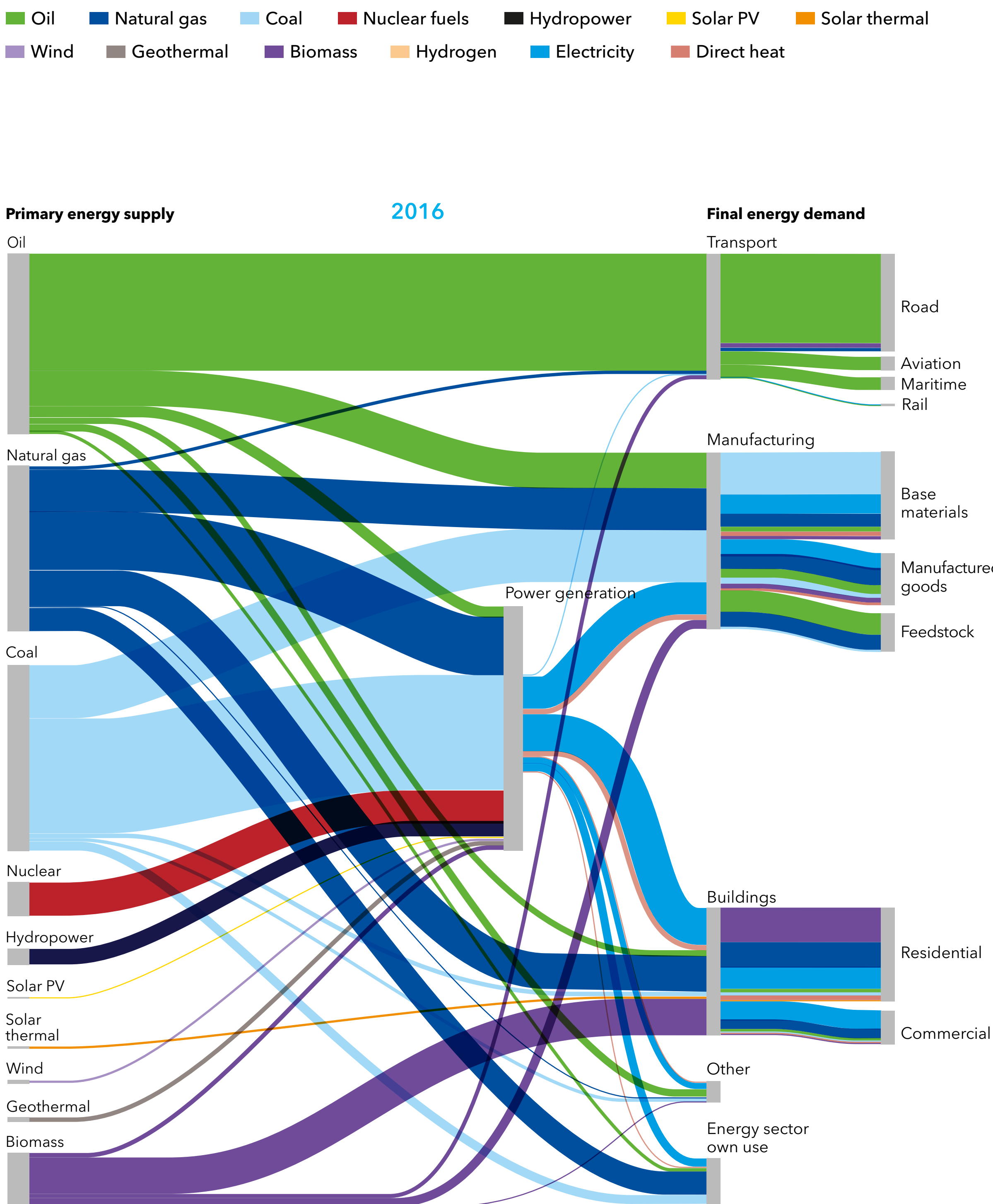
Trade, and especially seaborne trade of energy carriers, is an important component of the ETOM. For crude oil, the gap between a region's production and refinery input determines the surplus for export or a deficit to be met by imports, which is mainly transported on keel. For natural gas, any shortfall in meeting demand from regional production is allocated to exporting regions according to their current shares as gas trading partners. Intra-regional trade is determined as a constant multiplier of regional gas demand. For coal, as for natural gas, we assume a stable mix and shares of trade partners. Regions with domestic shortfalls import coal from exporting regions. Our manufacturing sector provides a baseline for non-energy commodity trade of raw materials and manufactured goods.

CONTINUAL IMPROVEMENT

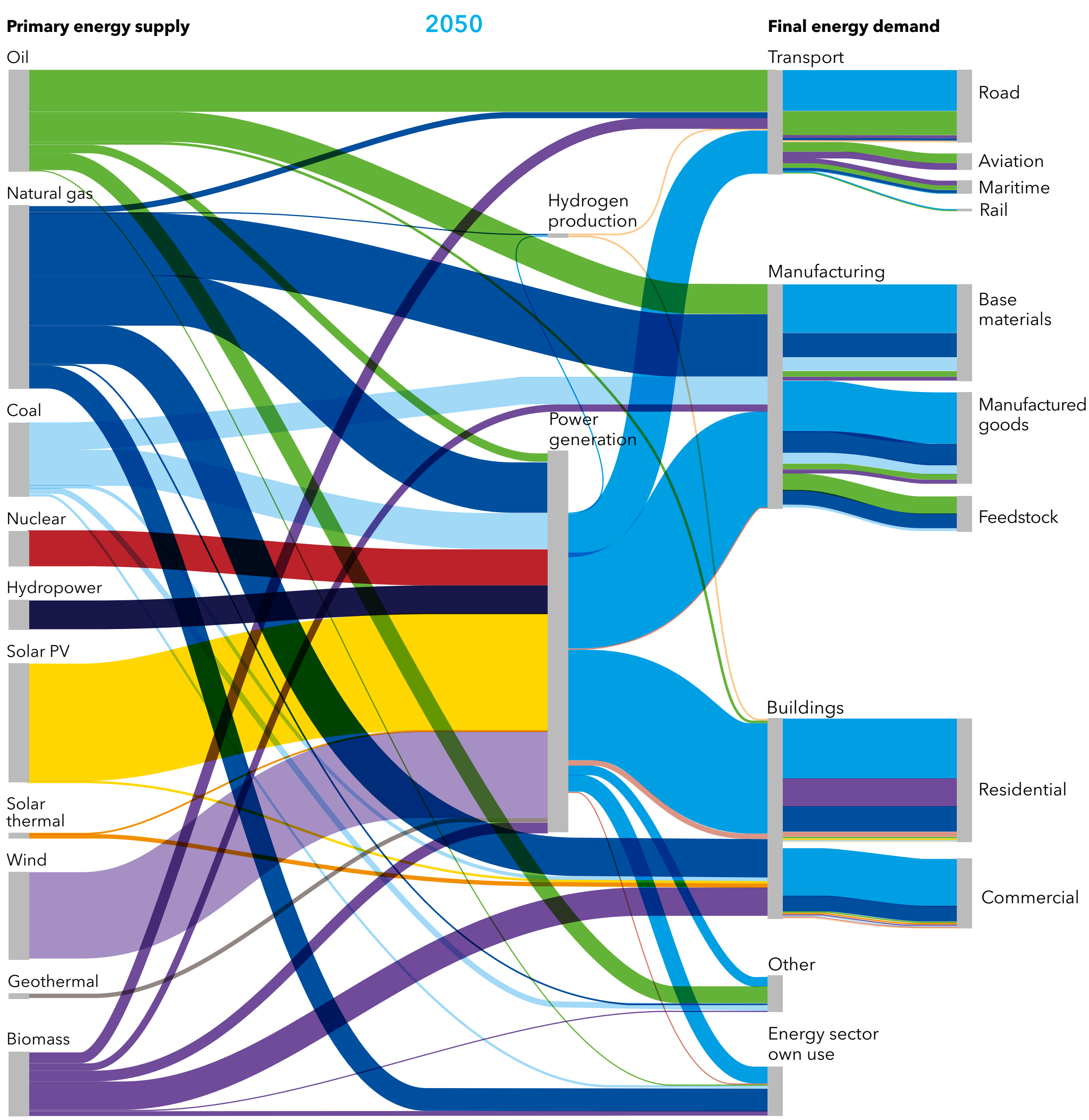
The structure and input data of the ETOM are continually updated to: provide a more complete and accurate representation of the world energy system; generate new outputs relevant to our stakeholders; and, to reflect recent changes in the energy sector. The most significant changes to the ETOM since our 2017 Outlook include new modules to represent power grids and LNG terminals; improved modelling of the demand for manufactured products; detailed representation of end uses in the buildings sector; and new energy carriers in the form of hydrogen and off-grid PV.

FIGURE 3.2

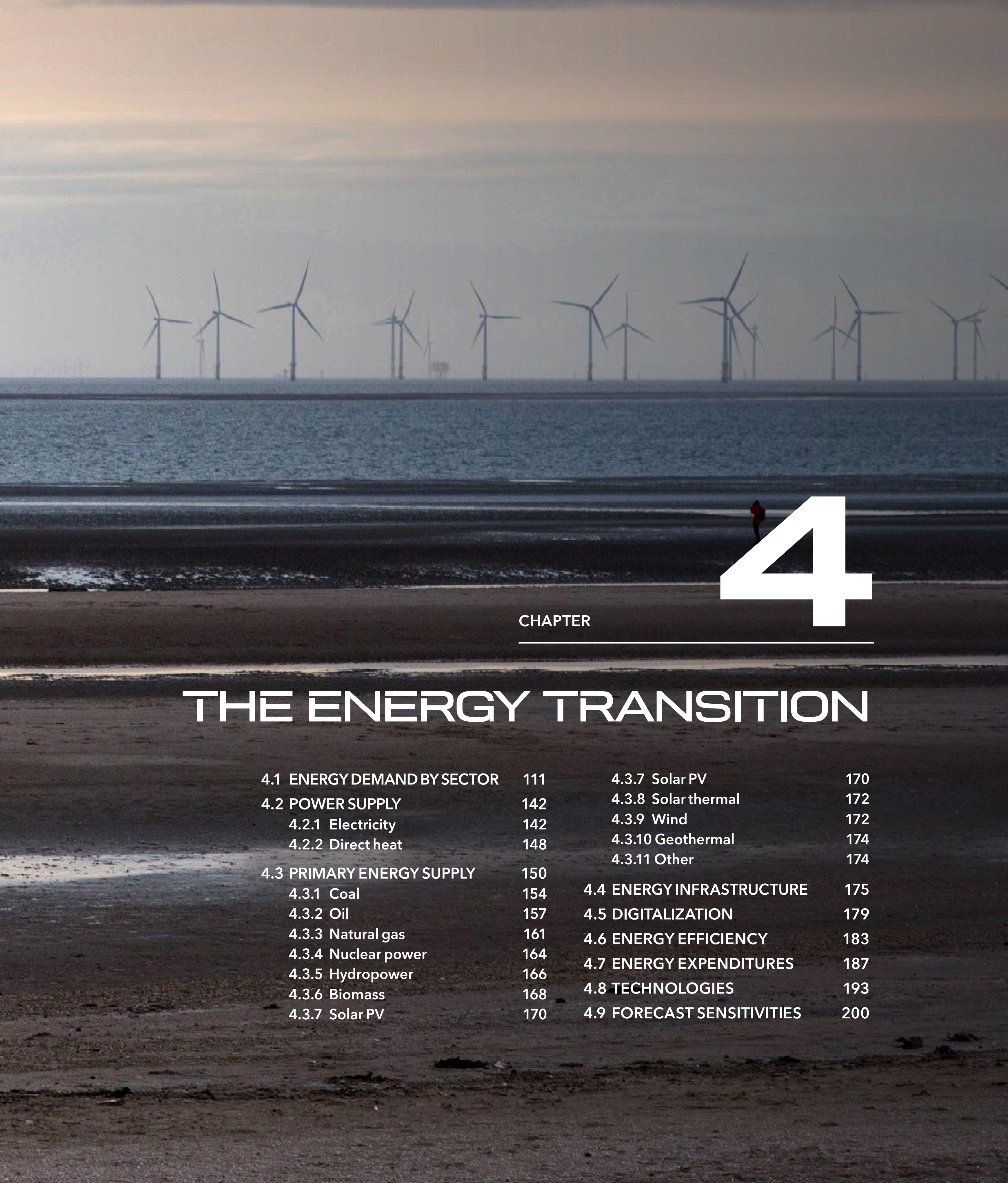
Global flows of energy carriers from primary energy supply to final energy demand, in 2016 and 2050



>> The three main drivers of the energy transition - electrification, decarbonization, and energy efficiency - are evident in this comparison of energy flows for 2016 and 2050. In 2050, less fossil fuels go directly into final demand sectors and much more primary energy is devoted to the generation of electricity - where there is an overwhelming share of non-fossil sources. This creates a more efficient energy system with less energy lost as heat in power generation and in final demand sectors. With ongoing efficiency gains in end use application (linked mainly to digitalization) the result is less energy used overall.



Flows smaller than 500 PJ are not shown.



CHAPTER 4

THE ENERGY TRANSITION

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4. THE ENERGY TRANSITION

The most pronounced characteristic of the energy transition today is decarbonization. Electrification is also a megatrend and is part of the same decarbonization shift.

In addition to these major shifts, there are several other less pronounced changes taking place, such as the shale revolution in hydrocarbon extraction.

In the sections that follow, we present the results from our forecast, highlighting both the absolute figures of future energy demand, supply, and production, and also focusing on the transition itself. Towards the end of the chapter, we discuss uncertainties and sensitivities in our forecast and quantify the impacts of key changes in our assumptions.

MEASURING ENERGY; JOULES, WATTS AND TOES

EJ, TWh or Mtoe? The oil and gas industry normally presents its energy figures in tonnes of oil equivalents (toe), while the power industry uses kilowatt hours (kWh). The SI system's main unit for energy, however, is joules, or rather exajoules (EJ) when it comes to the very large quantities associated with national or global production. EJ is the primary unit we use in this Outlook.

So, what is a joule? Practically one could think of a joule as the energy needed to lift a 100 g smart-phone 1 meter up; or the amount of electricity needed to power a 1-watt LED-bulb for 1 second (1 Ws). In other words, a joule is a very small energy unit, and, when talking about global energy, we use EJ, being 10^{18} J, or a billion billion joules.

Another way of understanding energy quantities is to estimate the energy needed per person. The present amount of primary energy used per person annually averages 78 gigajoules (GJ, i.e. billion J). Shell (2016) expects that 100 GJ of primary energy per person is what is needed to support a decent quality of life. In the much more efficient energy system of the future, we think 100 GJ is not needed; as an example, we forecast Europe's average primary energy use to be 83 GJ per person in 2050.

In this Outlook, we use J or EJ as the main unit of energy, but in a few places, we use Wh, or Mtoe. The conversion factors we use in this document are:

$$1 \text{ EJ} = 277.8 \text{ TWh}$$

$$1 \text{ EJ} = 23.88 \text{ Mtoe}$$

4.1 ENERGY DEMAND BY SECTOR

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

In 2016, total final energy demand was estimated at 403 exajoules (EJ); we forecast an increase to 468 EJ by 2035, thereafter slowly reducing to 451 EJ in 2050.

As indicated in Figure 4.1.1, the world's energy demand rose by 35% over the last 15 years. However, in the coming 15 years we forecast energy demand to increase by just 15%, and thereafter level off and start to decline. This profound demand down-shift is linked to a deceleration in population and productivity growth, and to an accelerating decline in energy intensity. Section 4.6 gives more details on energy efficiency.

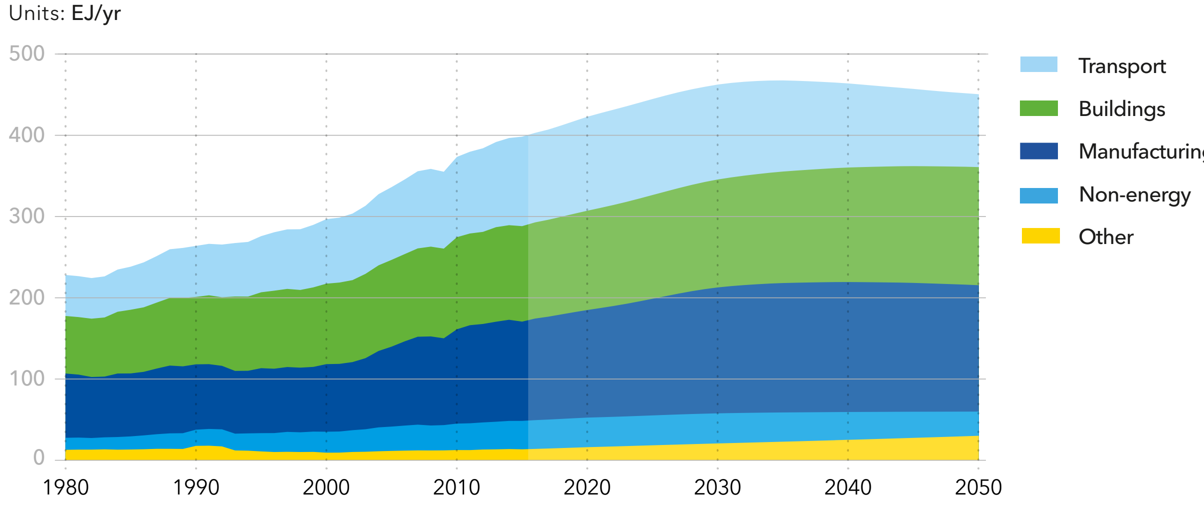
Figure 4.1.1 further illustrates how the world's energy use is currently split in roughly equal shares between three dominant sectors: transport (27%), buildings (29%), and industry/manufacturing (31%). In the decades to come, manufacturing and buildings will grow both in absolute and relative terms, to 34% and 32% shares in 2050, respectively. The energy demand of the transport sector peaks already in 2026 and will then start to decline as electrification of the road transport sector materializes, bringing the sector's share of energy use down to 20% in 2050. The non-energy use sector, which includes feedstock for lubricants and plastics, asphalt and petrochemicals, currently consumes 8.8% of the energy, and its share will slowly decline over the forecast period to 6.5% in 2050.

These four categories are described in detail in the coming sections. The final category, labelled "other", is split between agriculture, forestry, military, and, together with some other smaller categories, is not further discussed in this Outlook.

FIGURE 4.1.1

World final energy demand by sector

Units: EJ/yr



4.1.1 TRANSPORT

Transport energy demand today is dominated by road transport, followed by aviation and shipping, and this picture does not change significantly over the forecast period. The total transport demand is growing from 110 EJ today, peaking at 118 EJ in 2026 and then declining to 90 EJ in 2050, as illustrated in Figure 4.1.2.

ROAD TRANSPORT

In this section, we set forth our thinking behind our estimates of the future size of the global light- and heavy-vehicle fleet, our understanding of the impact of policies and technology on new patterns of ownership and use, and the impetus behind the rapid electrification of road transport worldwide.

Historically, the global demand for vehicles has correlated well with GDP, albeit with regional differences: As GDP increased, so did vehicle density. Yet we forecast that future mobility, including the use of private cars, will change – but the pace and nature of that change is a key question. We see the future growth as being dampened by a multitude of factors. These factors include acceleration in the following areas:

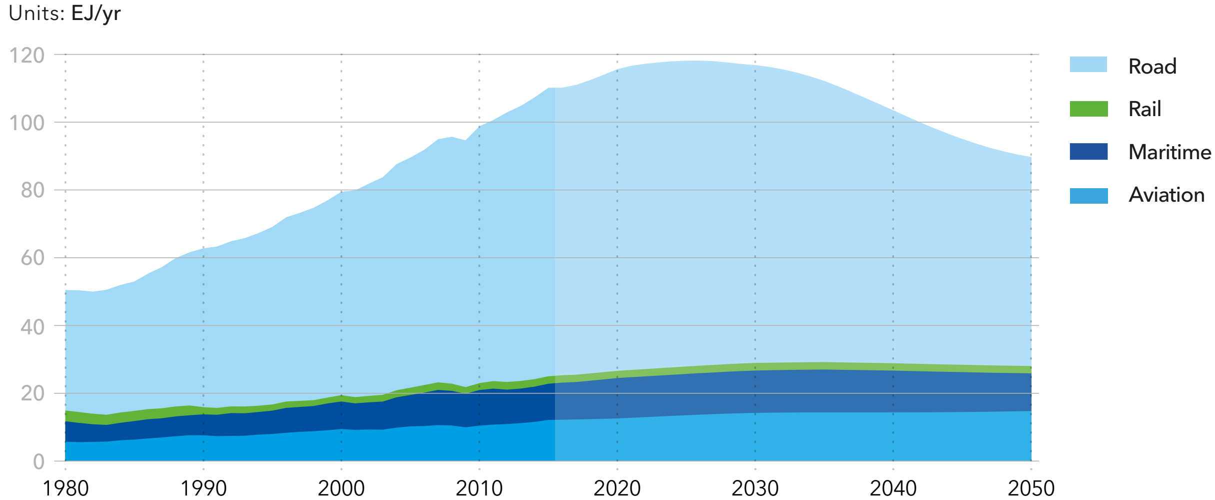
- Measures to curb pollution and congestion in large cities
- A focus (across all sectors – government, business and civil society) on sustainability
- Urbanization effects with less transport needs
- Digitalization that enables both less commuting, as well as automation and increased communal use of light vehicles through access and sharing models.

These factors, especially the battle against air pollution, are likely to make future car use and ownership less attractive, stifling individual ownership growth in emerging economies.

FIGURE 4.1.2

World transport sector energy demand by sub-sector

Units: EJ/yr



Ownership diffusion will not track rising living standards as closely as seen in OECD countries in previous decades.

For road transport, we differentiate between light and heavy vehicles, but combine passenger and cargo transport within each of the two forms. There are currently one billion light vehicles. Extending historical growth trends, incorporating regional differences, and adjusting for the limiting factors above, indicates that there will be some 1.6 billion light vehicles by mid-century, 900 million less than would have been the case without the dampening factors.

For heavy vehicles, we do not expect the same limiting factors to apply, and our forecast shows an increase from 270 million heavy vehicles in 2016 to 530 million in 2050.

We forecast an acceleration of communal driving schemes, with taxis and ride-sharing augmented by autonomous cars from 2025, once the technological and legislative challenges are overcome. With taxis and ride sharing, cars are typically used many hours per day and drive five times longer than the standard, non-communal cars – i.e., our reference vehicle. Autonomous cars are expected to be used 50% more than the reference, both for communal and non-communal cars. The reference vehicles have differing annual mileage across the regions, but typically are in the 10,000 to 25,000 km/year range.

Communal vehicles are likely to have the fastest uptake in urban areas, while the rural districts are more challenging. The fraction of communal vehicles is forecast to grow to 23% in OECD countries, but reach a full 30% in emerging and developing economies, already by 2040. But since, on average, they drive five times longer than private cars, their main impact on energy use will be the fact that they contribute to faster vehicle rejuvenation and energy efficiency through more speedy fleet turn-around.

Zero-emission vehicles (ZEVs), already preferred, will continue to be promoted heavily, particularly in cities, and aided by public procurement policies. Big players, such as India and Europe, are aiming for total transition of their fleets to ZEVs within decades. Several countries anticipate ZEVs capturing 100% of the new-sales market by 2030. China's current five-year plan subsidises ZEV uptake.

Supported by a multitude of sources (e.g. BNEF 2016, McKinsey 2017, IRENA 2017), we expect EVs to reach cost parity with conventional light vehicles (based on full lifecycle costs, including fuel and maintenance) in 2024. Key questions at present concern the extent to which charging infrastructure can keep up, whether range restrictions of EVs influence buyer preferences as the average range improves, and what local and national policies will be applied to increase uptake in the short term.

These initial factors will, however, rapidly pale into insignificance once EVs break through the cost parity level. The effect of cost reduction will be felt evenly across the world, but charging infrastructure will be rolled out at varying speeds across world regions.

In line with new product diffusion theory (Rogers 1976), we expect uptake of EVs to follow an S-shaped curve, reflecting the adoption of new products and technology. We have used a version mathematically described by the Bass Diffusion Model (Bass 2004). Digital cameras, and mobile phones are but two recent examples of S-shaped market growth. Our forecast is that the 50% point where half of all new cars sold are EVs will be reached in 2027 for Europe, 2032 for North America, OECD Pacific, Greater China and the Indian Subcontinent, and 2037 for the rest of the world, as illustrated in Figure 4.1.3. The main reason for the lag is associated with the challenge of infrastructure keeping pace with developments, but countries such as India, which have declared ambitious policies, will, at least partly, succeed in their high ambitions. In sum, the year when EVs are 50% of global new car sales is, in our estimation, 2033.

With an average vehicle life time of 10 to 18 years, depending on region, it will take two or more decades to phase out combustion vehicles entirely. In 2040, half of the light vehicle fleet will be electric, and by 2050, only 21% of the energy for light vehicles will come from oil, with 2.0% and 2.5% coming from gas and biofuels respectively, and 75% from electricity. With a similar, but slightly slower transition to electric drive-trains for heavy vehicles, this is the main driver behind declining global oil demand – a downward trajectory starting in less than ten years from now.

For heavy vehicles, the transition will take longer as the fleet is more diverse, and saturate at 80% of the fleet, as certain vehicles have high requirements for power and range. Buses and heavy vehicles in urban areas do not have the same challenges, and the uptake of EVs for this sub-sector will start earlier. Municipal buses will be at the forefront of electrification, as electric urban transport benefits doubly from zero road emissions and ample grid capacity (BNEF 2018). Heavy trucks have less to gain from electrification. We lag the half of maximum uptake (i.e. 40%) year for heavy vehicles by 3 years from the light vehicles, except for Greater China where we foresee simultaneous light and heavy vehicle uptake in their aggressive transition policies. Owing to the different characteristics affecting uptake, the resulting S-shaped growth is less steep than for light vehicles, as illustrated in Figure 4.1.4.

Half the sales of heavy vehicles will be EVs in 2037, and by 2045, half the heavy vehicles will be EVs. The overall number of vehicles in our forecast is illustrated in Figure 4.1.5.

FIGURE 4.1.3

Market share of non-combustion light vehicles by region

Units: Percentages

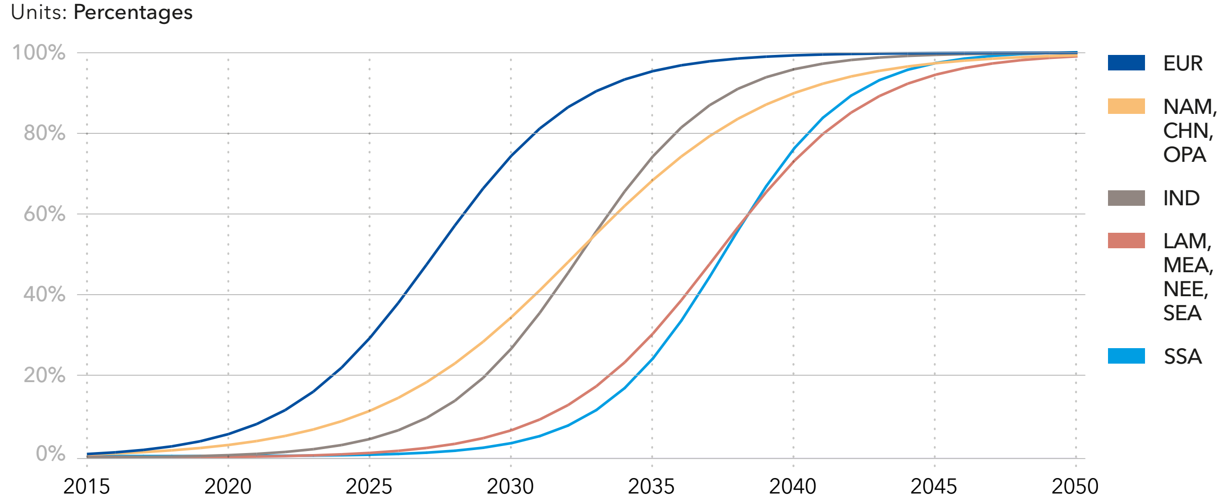


FIGURE 4.1.4

Market share of non-combustion heavy vehicles by region

Units: Percentages

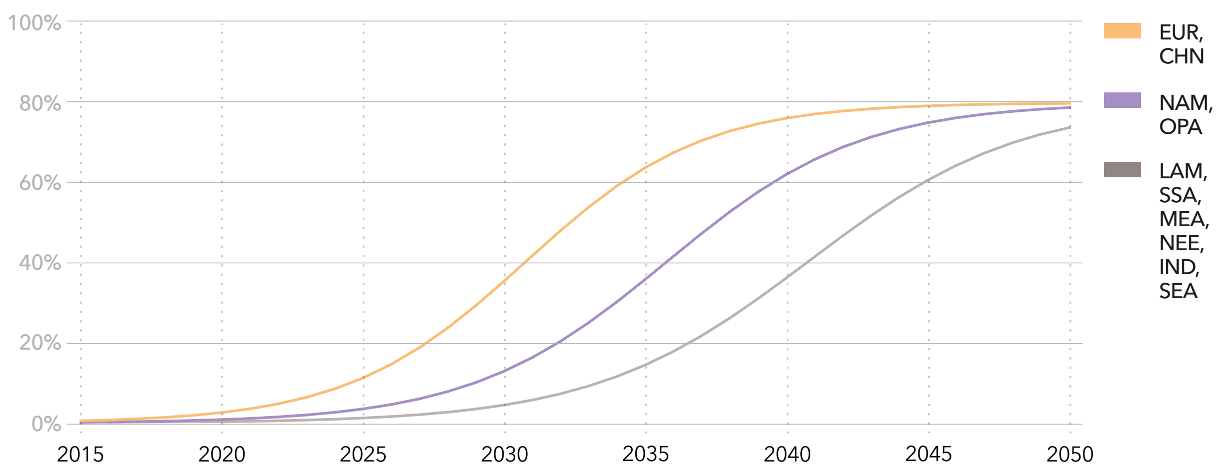
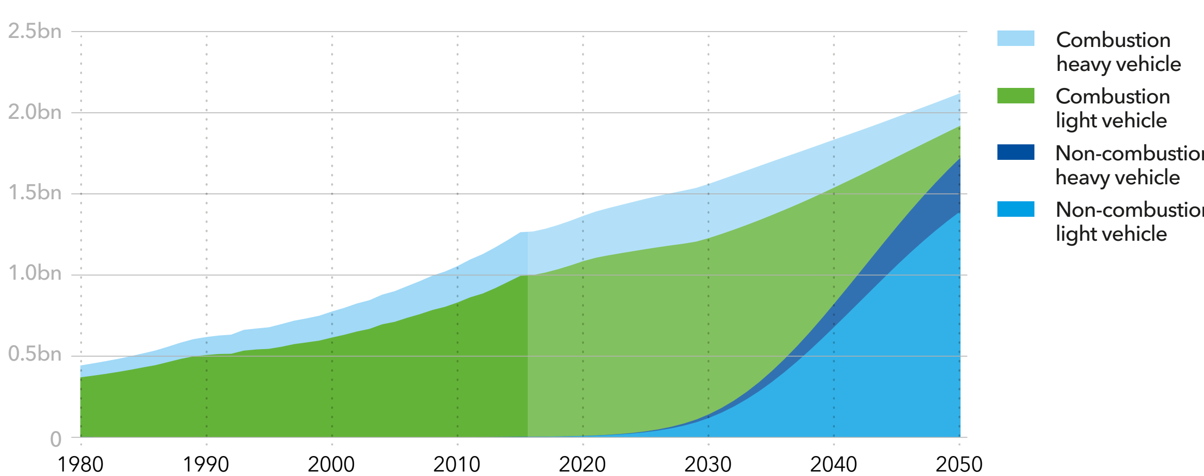


FIGURE 4.1.5

Number of vehicles worldwide



Fuel consumption is dominated by long-distance trucks, by 2050, 49% of heavy vehicles fuel will still be oil, 4.4% will be gas, and 6.4% biofuel, while the 36% share of electricity and 4.3% hydrogen in the fuel mix will be increasing rapidly. That 36% will punch above its weight and will power 63% of heavy vehicles – an illustration of the superior energy efficiency of electric vehicles.

Light hydrogen-fuel-cell electric vehicles (FCEVs) are already being built, and while they have superior fuel economy compared with combustion engines, we foresee them as maintaining a substantial fuel economy handicap compared to battery electric vehicles (BEVs), inhibiting mass adoption. Yet, hydrogen as an energy carrier has far higher energy density than batteries, and so, for a sizable fraction of the fleet and in regions where we foresee a heat-driven hydrogen distribution network in use (Europe, North America, OECD Pacific and Greater China), we forecast a FCEV uptake of 5-13% of all heavy vehicles in 2050.

RAIL TRANSPORT

Many of the world's railways, particularly commuter networks and high-speed links in Europe, Japan, and elsewhere, are already electrified. However, many long-haul transcontinental lines rely on diesel-hauled trains. We predict that electrification will only increase gradually in rail transport, driven partly by governments, but mainly by economics.

Rail transport, used for both passenger and cargo transport, is the little brother of the transport forms. We have used a relatively simple correlation between GDP and passenger transport for each region, and continued this trend using our GDP estimates. The same is done for freight transport. Under these assumptions, total passenger transport will increase from 3.5 trillion passenger-km/year in 2016 to 10 trillion passenger-km/year in 2050, and tonnes transported increase from 11 trillion tonne-km in 2016 to 24 trillion tonne-km in 2050. The Indian Subcontinent is the leading region for passenger transport and Greater China for freight, and both will remain so throughout the forecast period.

Energy intensity is calculated using a continuation of historical trends of energy used per passenger and per transported tonne, on a regional basis. This includes considerations of changes in average distance travelled, as well as the 2.6% annual average energy efficiency improvement of the trains to 2050. The total energy use of rail will remain stable from 2015 to 2050, at around 2.0 EJ/year, despite both passenger and freight transport more than doubling.

The energy mix for the rail transport sector is currently 39% electricity, 57% oil, and 4% coal. Most new railways built, including high-speed lines, are electric, while some existing railways are undergoing electrification. Electricity will increase throughout the forecast period, as will biofuel use, which will replace 10% of oil used by 2050. The 2050 energy mix for rail transport will be 55% electricity, 40% oil and 4% biofuel, and coal declines to zero. Natural gas will continue to play a marginal role, though important in niche applications.

AVIATION

Aviation demand, measured in number of passenger trips, has been increasing steadily and will continue to do so throughout the forecast period. Aviation demand correlates well with GDP on a regional basis, a dynamic we see holding into the future. Growth is faster in developing than in mature economies, but North America will remain the region with most aviation in 2050. Globally, the total number of air passengers will increase from 3.6 billion passenger-trips in 2016 to 8.8 billion passenger-trips in 2050. These numbers obscure contrary trends – connectivity and virtual meetings will reduce travel even as more people have the ability and means to travel. Freight planes are modelled as a constant multiplier on passenger trips.

The energy efficiency of aviation will continue to improve steadily; the higher efficiency of new aircrafts is the most important factor. In our forecast, energy efficiency is trend extrapolated from the fraction of aviation sector's energy use to the per passenger trip on a regional basis. This includes consideration of changes in average distance travelled; longer routes may outweigh the improvements of reduced consumption per kilometre. The total energy use of aviation will increase from 12 EJ in 2015 to 15 EJ in 2050.

Aviation currently has few alternatives to oil. The emerging blending of biofuels will grow stronger, as local requirements to shift to biofuel will spread. In the coming decades, we expect few realistic large-scale alternatives to oil or biofuel. Since there are few other low-carbon alternatives, aviation and maritime sub-sectors are likely to be prioritized sectors for biofuel, and we forecast a scale-up of the biofuel share of aviation fuel mix to 15% in 2040 and 41% in 2050, which amount to 47 and 136 million tonnes per year, respectively. As explained in Section 2.7, the growing biofuel demand of the transport sector can be met without risking food shortages, thanks to new generations of biofuels with higher yields and international trade.

Electric aeroplanes with batteries are currently in their infancy. We expect that, by 2050, they will be used at scale on the shortest routes, representing 3% of the fuel use in 2050, as the shortest routes do not contribute much to overall consumption (but will propel more than twice that share of passenger-kilometres due to higher energy efficiency of electric engines – even accounting for higher weight and less payload).

MARITIME TRANSPORT

In maritime transport, GHG regulations have been more challenging to put in place than regulations limiting the health-damaging emission of sulphur dioxide and nitrogen oxide gases. The International Maritime Organization (IMO) seeks to lead the global approach through a comprehensive strategy for reducing GHG emissions from ships, and has recently (April 2018) adopted a new GHG-reduction strategy to reduce total GHG emissions from shipping at least by 50% in 2050. Further, we believe that regional policies will be important for restricting heavy fuels and promoting alternative fuels and power. Local pollution reduction policies and subsidies in decades to come will support and drive initiatives for harbours and land-based infrastructure to offer shore-based power supply.

Most of the world's transport by volume and weight is seaborne, as in terms of costs and emissions per tonne-mile, shipping is by far the most efficient. Outside of a limited number of trunk oil and gas pipelines, the world's fossil fuels are typically totally dependent on marine vessels for their transportation. In our analysis, fossil fuel shipping demand is derived from the difference between regions' demand and supply of oil, gas and coal.

Furthermore, we forecast the demand for bulk transport (except coal) using manufacturing of base materials, and container demand results from the amount of manufactured goods. Looking at average transport distances, only small variations are expected over the forecast period.

As world trade volumes increase over the next two decades, so will tonne-miles needed to ship the cargo; trade volume changes are far more dynamic than average distances as shown in Figure 4.1.6 and 4.1.7 below. In the Maritime industry implications report (DNV GL 2018c), more details of each ship type and changes in trade are given.

Shipping consumes a significant share of the world's oil, currently about 6.7%. As a sector, maritime is hard to electrify, but a drive to make the industry more environmentally friendly will lead, in our estimate, to 1.4% hydrogen (typically for cruise liners, and coming with 'clean energy' certification), 5.2% electricity (much of it used while ships are in ports, and for very short routes), 25% gas, and 37% biofuel in the shipping fuel mix by 2050 (slightly smaller than the share of biofuels in aviation), with variations for different ship types. The remaining 32% will come from oil.

Shipping will also become more effective, with improved planning, hull, engine, and fuel management projected to produce an average of 20% reduction in fuel consumption per tonne-mile over the period.

Total energy demand for shipping is forecast to grow slowly from 12 EJ currently to a peak of 13 EJ in the mid-thirties back to 12 EJ by mid-century. The recently agreed-upon IMO mandate to reduce GHG emissions from 2008 to 2050 by 50% will be fully met, as we show in the companion maritime forecast (DNV GL 2018c).

Looking at transport as a whole, the energy mix changes are huge, as illustrated in Figure 4.1.8. The 2050 transport energy mix is 41% electricity, 38% oil, 15% biomass, 5% natural gas and 1.6% hydrogen.

FIGURE 4.1.6

World seaborne trade by segment

Units: Mt/yr

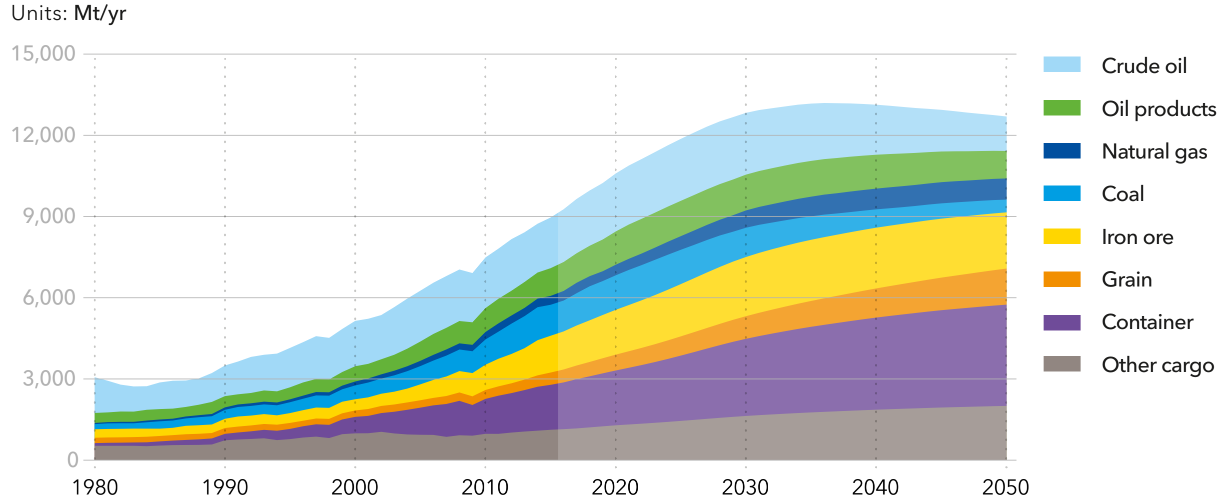


FIGURE 4.1.7

World seaborne trade in tonne-miles by vessel type

Units: Gt-nm/yr

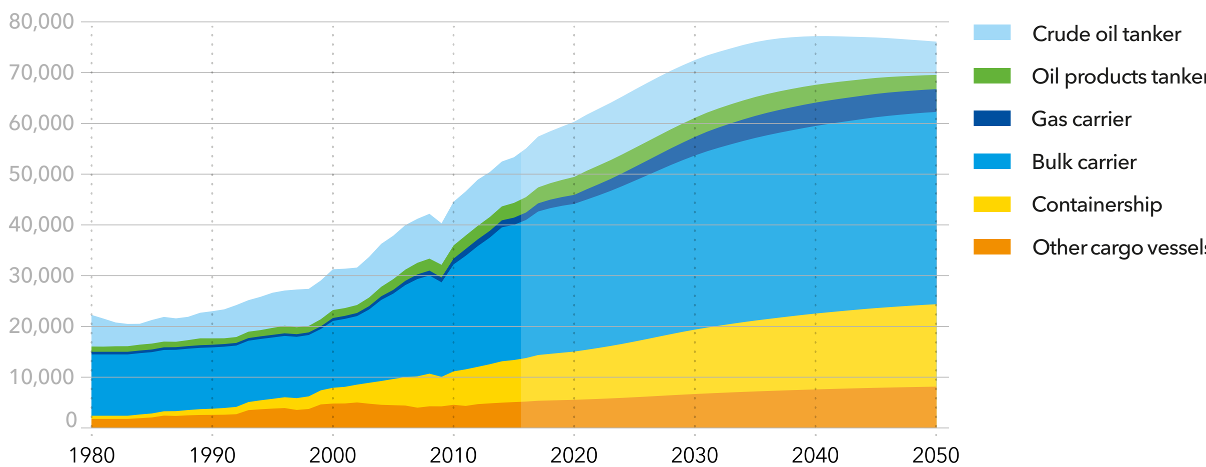
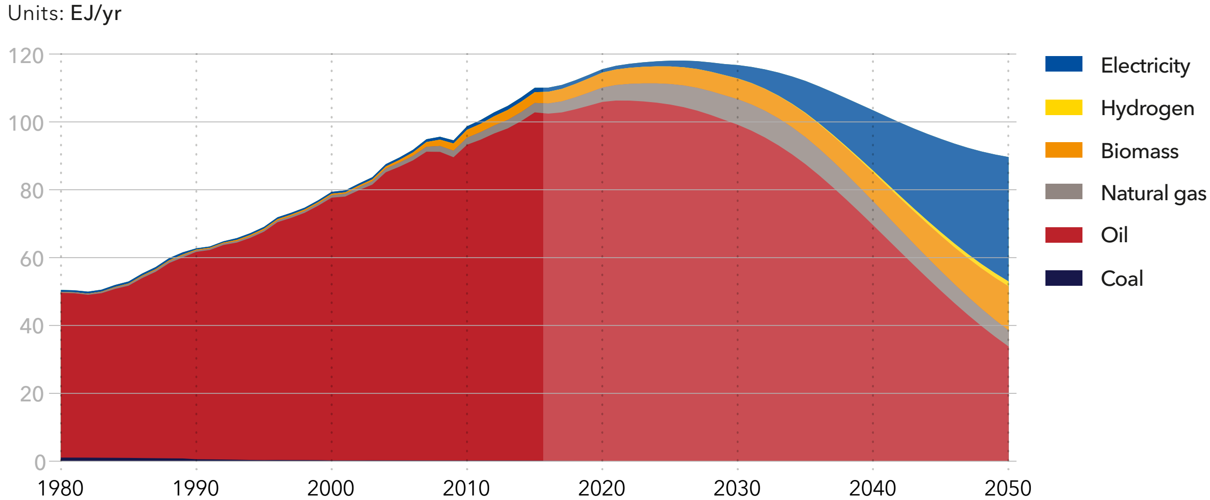


FIGURE 4.1.8

World transport sector energy demand by carrier

Units: EJ/yr



4.1.2 BUILDINGS

Buildings consumed about 29%, 118 EJ, of the world's energy in 2016 (Figure 4.1.9). The energy was used for cooking, heating, cooling, lighting, and household appliances. About three-quarters of this energy is consumed in residential buildings. In the future, a larger share of energy demand growth will come from commercial buildings, due to the developments described below.

For residential buildings, we estimate final energy demand for five end uses: appliances and lighting, cooking, space cooling, space heating, and water heating (Figure 4.1.10). We allocate all cooking-related energy use to residential buildings, assigning none to commercial buildings. As direct historical data are not available for end uses, the relevant figures presented in this report are own estimates based on four IEA reports: Energy Balances (2018), Energy Technology Perspectives (2016, 2017), and Energy Access Outlook (2017).

Figure 4.1.11 describes drivers of the energy demand for five end uses in residential buildings and four in commercial buildings, as modelled in the ETOM. From historical data, we estimate final energy demand by first establishing relationships between external drivers and end-use demands. We then use our efficiency-improvement projections to predict levels of final energy use.

Floor area is one of the most important drivers for buildings energy demand. Table 4.1.1 presents residential and commercial floor area in 10 regions. While Greater China remains the region with largest floor area to mid-century, Sub-Saharan Africa shows the largest percentage increase in both categories.

FIGURE 4.1.9

Change in world buildings sector energy demand by building type

Units: EJ/yr

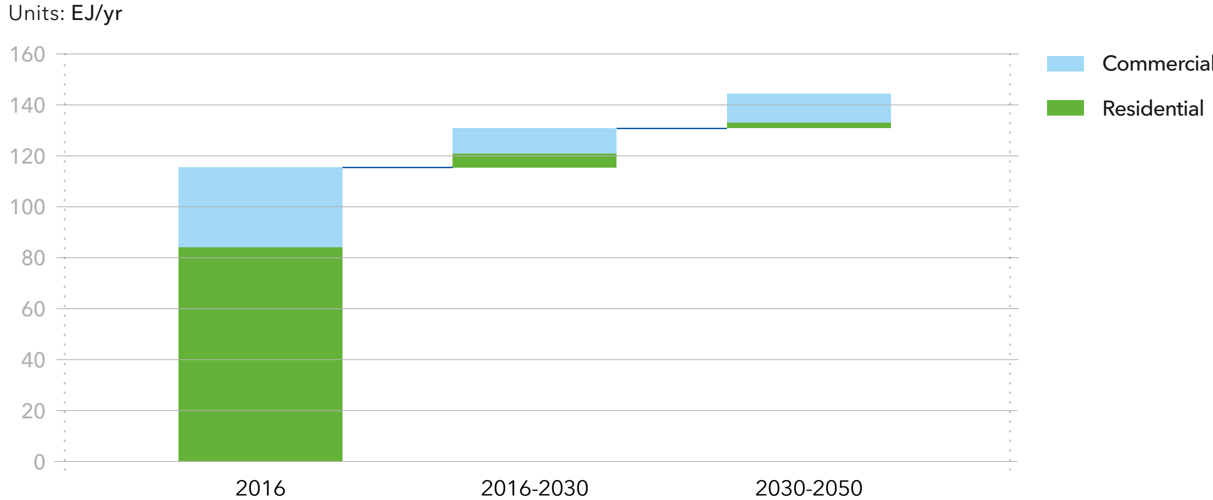


TABLE 4.1.1

Floor area of buildings by region

Residential (1000 km²)	NAM	LAM	EUR	SSA	MEA	NEE	CHN	IND	SEA	OPA	TOTAL
2016	22.5	14.1	20.3	10.8	12.7	6.8	41.8	18.0	12.1	7.4	166.4
2030	25.6	17.6	22.7	16.5	18.8	7.7	57.5	25.6	18.1	9.1	219.2
2050	29.3	25.2	26.1	30.9	30.6	10.1	61.7	34.4	25.3	10	283.6

Commercial (1000 km²)	NAM	LAM	EUR	SSA	MEA	NEE	CHN	IND	SEA	OPA	TOTAL
2016	8.2	1.2	6.6	0.3	1.9	1.2	9.0	0.8	1.3	3.5	34.2
2030	11.6	1.6	8.3	0.6	3.1	1.1	20.8	1.8	3.0	4.7	56.6
2050	15.5	3.2	11.6	1.7	6.8	1 .2	31.0	4.4	7.2	5.8	88.5

FIGURE 4.1.10

World buildings sector energy demand by end use

Units: EJ/yr

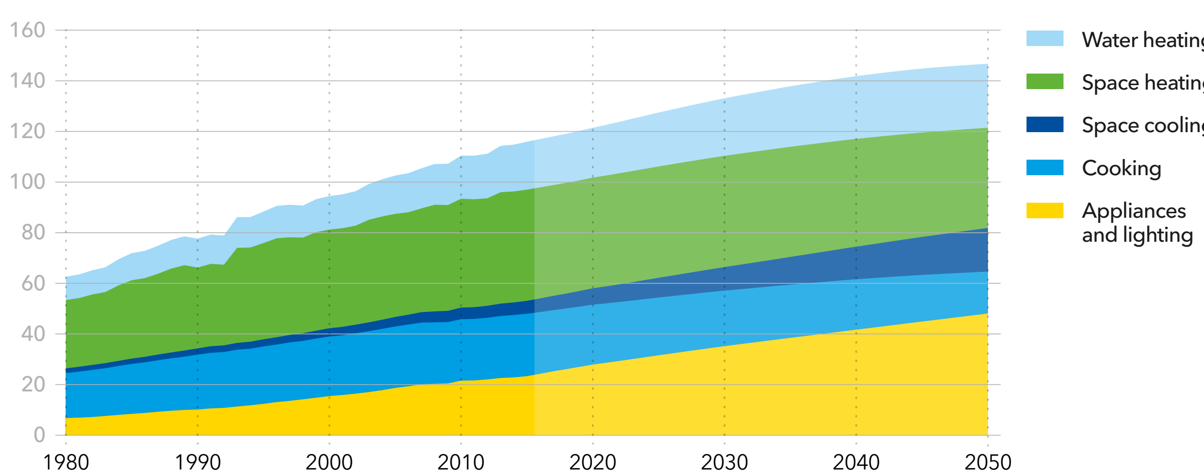
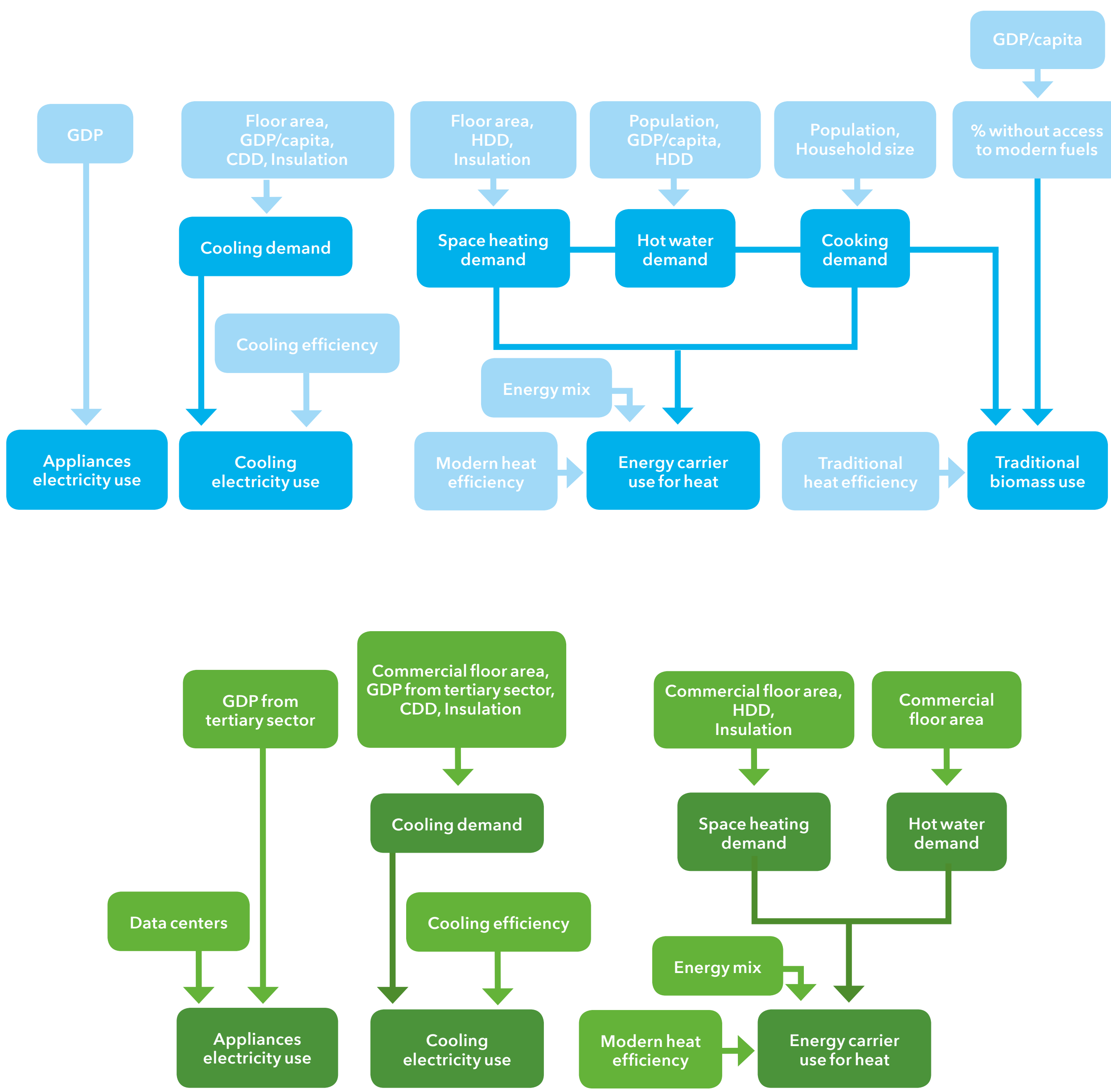


FIGURE 4.1.11

Drivers of the energy demand for residential (top) and commercial (bottom) buildings



CDD - Cooling Degree Days , HDD - Heating Degree Days

APPLIANCES AND LIGHTING

Residential appliances and lighting encompass everything from reading lights, phone chargers, and computers, to refrigerators, washing machines and dryers. Appliances and the services they provide evolve; but instead of separately modelling the evolution of equipment and its efficiency, we directly estimate the electricity it uses, a requirement dominated by appliances.

Despite improvements in the energy efficiency of appliances and lighting, historical evidence suggests that, as GDP per capita increases, the electricity per person used for appliances and lighting increases. For people on lower incomes, this shift may happen when disposable income rises enough to afford, say, a washing machine instead of washing clothes by hand, or a television. At the other end of the scale, increased income may manifest itself through buying a home entertainment system or keeping porch lights on all night.

We therefore estimate residential appliances' energy demand as a function of regional GDP, adjusted for a 0.6%/year efficiency improvement.

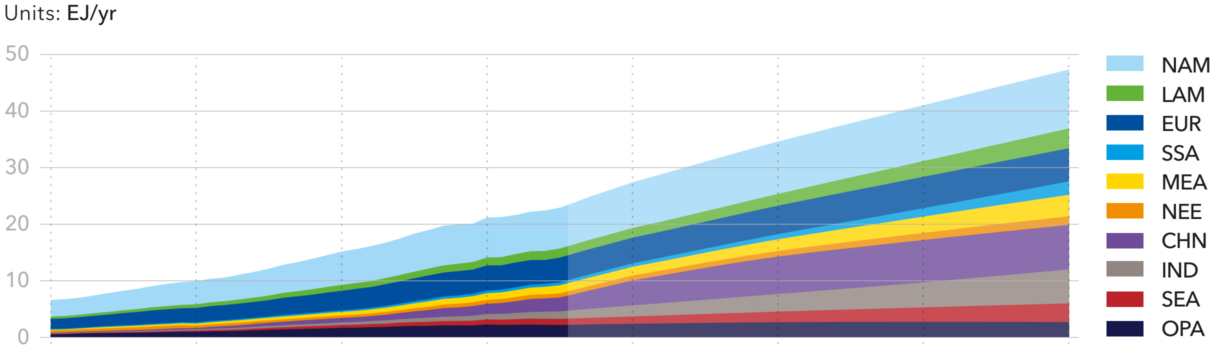
Due to lifestyle differences, the income elasticity of such demand is by far the strongest in North America, which leads us to use a higher 'appliances electricity demand per unit GDP' multiplier for this region.

Commercial buildings' appliances and lighting energy demand is a function of a region's GDP contribution from the tertiary sector, services. As income per capita increases, the tertiary sector's share in GDP tends to rise. Consequently, the appliances energy demand of commercial buildings increases in all regions, at varying rates. We also expect the electricity consumption of data centres and computers, which together constitute about 4% of commercial buildings' electricity demand (IEA 2017b), to increase by 4% annually (Sverdlik 2016), reaching 3 EJ/year, or 6% of commercial buildings' energy demand in 2050. We forecast that the combined appliances and lighting energy demand for residential and commercial buildings will double between 2016 and 2050 (Figure 4.1.12). Three regions, Greater China, the Indian Subcontinent and North America, will account for half the growth.

FIGURE 4.1.12

Appliances and lighting energy demand by region

Units: EJ/yr



SPACE COOLING

We estimate space cooling to account for only 4.6% of buildings' energy demand in 2016. We forecast that its share will increase to 12% by 2050 (Figure 4.1.10), split roughly equally between residential and commercial. Demand for space-cooling energy is shaped by:

- increasing air-conditioner market penetration driven by rising standards of living and an increase in cooling degree days;
- increasing air-conditioner usage per unit of floor area, as more people need and can afford to air condition more space in their homes, and for longer;
- improvements in building envelope insulation that reduce the loss of cool air inside buildings;
- and, by increased efficiency of air conditioners.

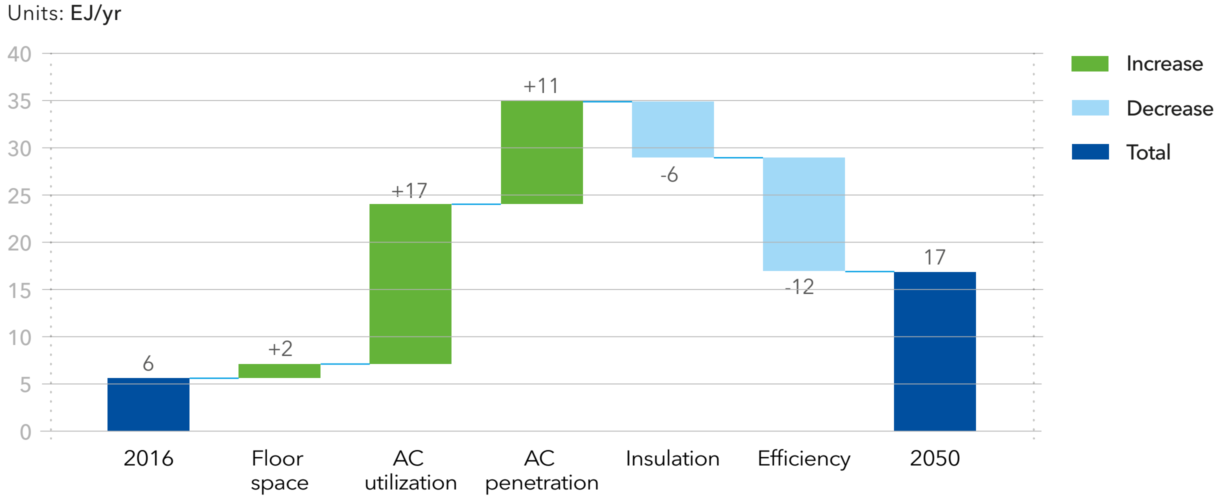
The increase in final energy demand for space cooling – due to increased floor space and greater air conditioning use, with market penetration averaging more than 85% globally – will exceed savings from insulation and improved equipment efficiency. The result will be a net increase of 11 EJ/year (Figure 4.1.13). This is despite an average efficiency improvement of 71% and an 17% reduction in energy losses over the period 2016–2050 due to insulation.

These trends will affect the geographical distribution of cooling demand. North America accounts for about 40% of global electricity demand for cooling now. In 2050, about 30% of cooling demand will come from Greater China, and another 46% from regions dominated by countries that are currently non-OECD.

FIGURE 4.1.13

Change in world final energy for space cooling

Units: EJ/yr



SPACE HEATING

Space heating is a more mature market than space cooling in terms of market penetration and potential efficiency gains. To understand the dynamics of energy demand for space heating, we need to make a distinction between final energy and useful energy. Final energy is the energy content of the fuel used for heating. It is the amount of energy reported to be used for buildings or any other demand sector. Useful energy is the amount of heat received after accounting for losses in conversion and distribution in the building. Think of an apartment building using a gas boiler for space heating. Final energy is the energy content of the natural gas purchased from the local distribution company; useful energy is the heat that the apartment receives from its radiators after some is lost in the boiler and piping.

With increasing population and floor area, useful heat demand for space heating continues to grow towards 2050 (Figure 4.1.14). Two other drivers of this trend are increased insulation and decreased heating degree days due to climate change, without which useful heat demand would be 13% and 6% higher respectively.

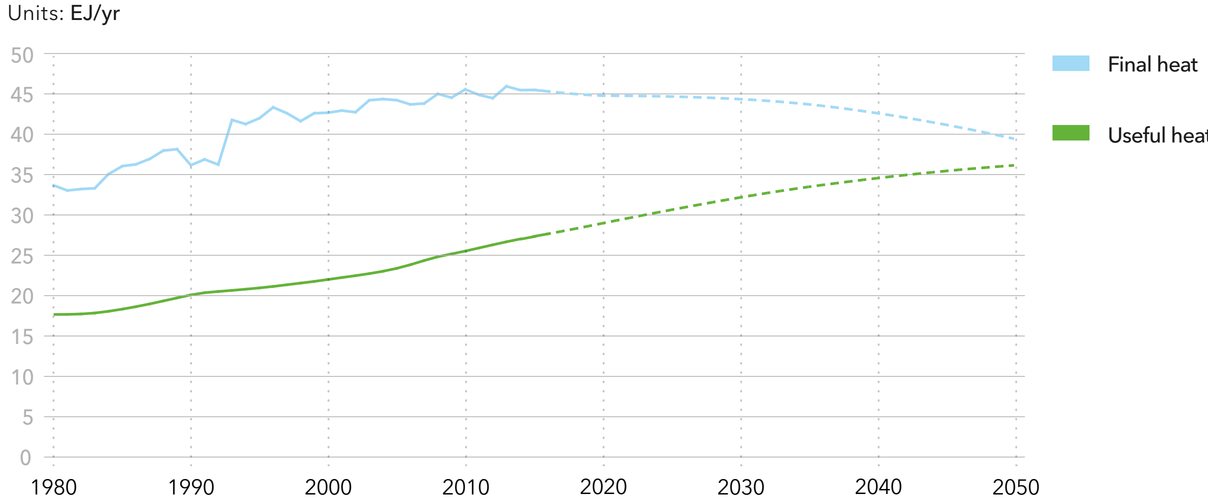
The ratio of useful to final energy demand shows the average efficiency of installed heating equipment. This efficiency varies widely between technologies, from less than 10% for traditional, open wood-burning to more than 300% for heat pumps.

With continued improvements in individual technologies, and a shift to more efficient and cost-effective technologies, the average efficiency of space heating will increase from about 61% in 2016 to more than 90% in 2050. Consequently, the final energy demand for space heating will decline after 2030, reducing from 45 EJ/year to 40 EJ/year in 2050. As market penetration and income are not as significant in space heating as in cooling, the regional split of demand will remain stable, with North America, Europe, North East Eurasia and Greater China constituting around 70% of the final energy demand.

FIGURE 4.1.14

World final and useful heat demand for space heating

Units: EJ/yr



WATER HEATING

Hot-water usage per person varies greatly worldwide. In developed regions, hot-water tanks are frequently used continuously to serve multiple needs, from daily showers to washing machines and dishwashers. In some less developed countries, water is heated on demand by inefficient methods and only for basic needs. For residential buildings, GDP per capita is the single biggest driver of hot-water demand per person; colder climates also drive usage. The water heating demand of commercial buildings – about 10% of global final energy used for water heating – is driven primarily by floor area.

Globally, we forecast that useful energy demand for water heating will grow from 8.9 EJ/year in 2016 to 13 EJ/year in 2030 and 19 EJ/year in 2050. The average efficiency of water heating will increase from 46% in 2016 to 59% in 2030 and 77% in 2050. Figure 4.1.15 shows the resulting final energy demand for water heating and its regional breakdown.

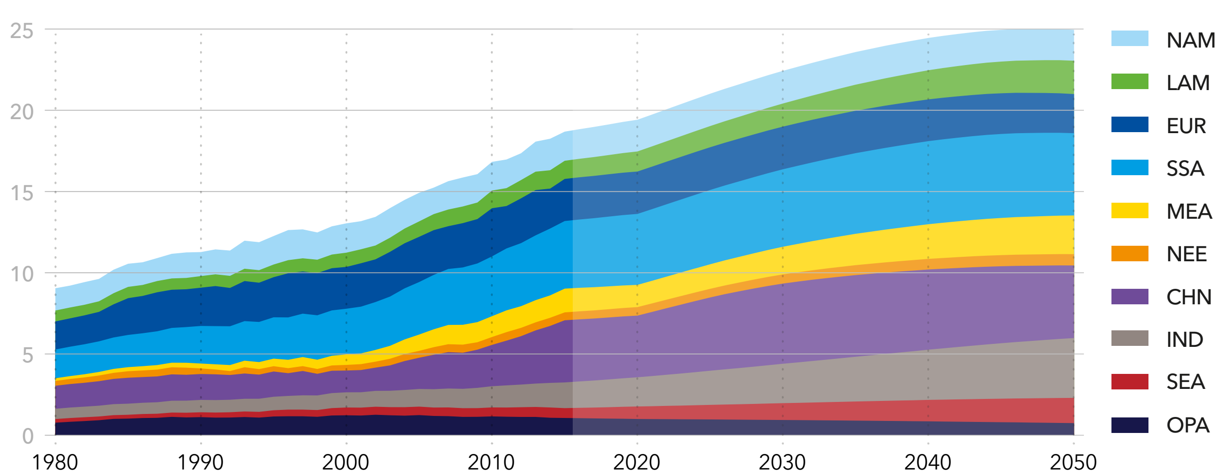
COOKING

Energy demand for cooking is driven mainly by the number of households, but the average number of people in households also plays a part. The global average household size is currently about 3.5 people. We estimate that a typical household of 3.5 people needs 2.1 GJ/year of useful heat for cooking, using 2014 estimates for final energy use for cooking (IEA 2017d) and an average global energy efficiency of 15%. We then adjust this number for household size, where one additional person creates an additional 300 MJ/year of useful heat demand. By 2050, the average household size is expected to decline to 2.4 (Urge-Vorsatz et al. 2015), which will reduce per household useful-energy demand for cooking to 1.8 GJ/year. Taking all these factors into account, global total useful energy demand for cooking will rise from 4.4 EJ/year to 6.9 EJ/year between 2016–2050.

FIGURE 4.1.15

World final energy demand for water heating by region

Units: EJ/yr



While cooking made up 29% of the global final energy demand of residential buildings in 2016, its share is expected to reduce to below 18% by 2050 because of large efficiency improvements. Globally, 31% of the population use traditional cooking methods, burning biomass (animal waste, charcoal, wood) with efficiencies of around 5-10%. This involves about 2.3 billion people, with the majority in Sub-Saharan Africa and the Indian Subcontinent. By 2050, this number will decline 34%, bringing large efficiency improvements that will be further boosted by switching from coal to gas or gas to electricity everywhere.

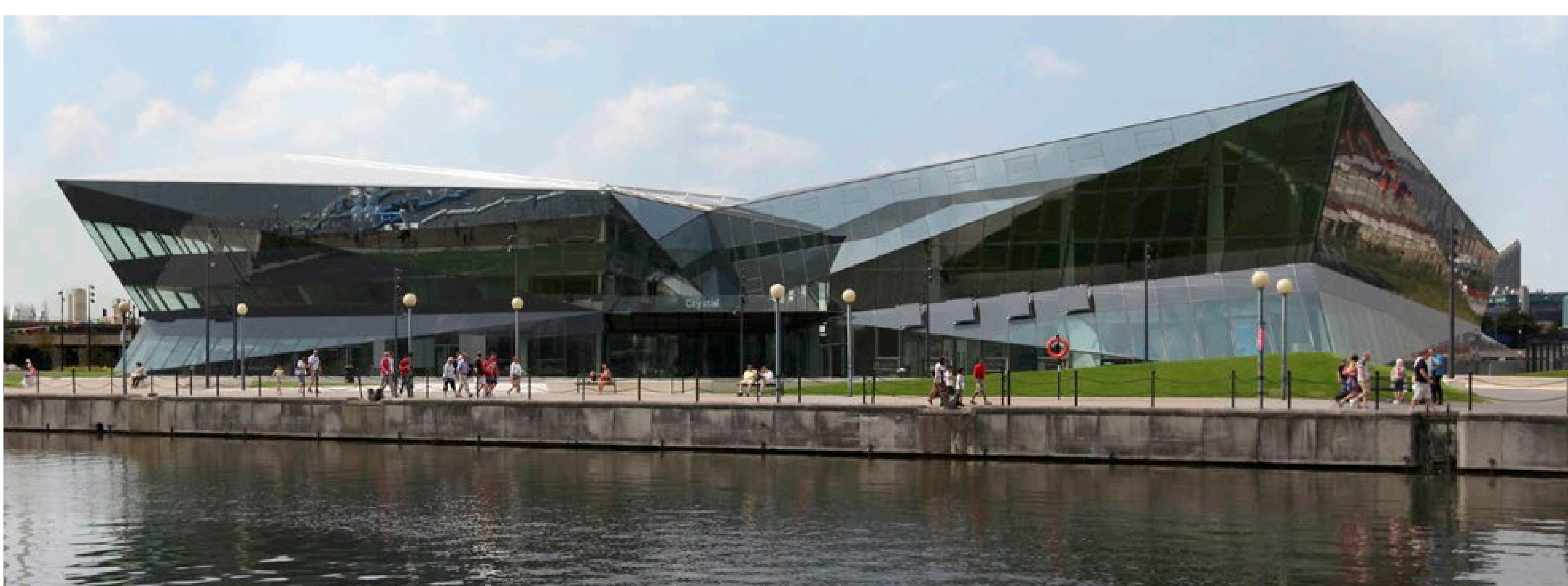
POLICY ISSUES

For buildings, energy-efficiency improvements typically have a short payback time, but developers and retrofitters frequently fail to implement them. Smarter energy policies will continue to target this short-sightedness; the potential gains to society are too positive to ignore. Developing countries will seek to reduce the burning of solid biomass for cooking, and the local use of kerosene, a major health hazard responsible for more deaths than any disease. Co-evolution of rising living standards, electrification, and improved bioenergy use is at the heart of the energy transition. It is the raison d'être of the USD 100bn Paris Agreement Green Climate Fund targeting developing countries. This Fund, and similar knowledge- and financial-transfer mechanisms, will contribute significantly to the transition to more environmentally- and climate-wise cleaner fuels.

ENERGY MIX

We analyse the energy mix of buildings by two broad groups of end uses: space cooling together with appliances and lighting, which use electricity; and, heat-related end uses (space heating, water heating and cooking) with a mix of energy carriers.

For many of world's regions, the energy source for space cooling and appliances and lighting is simply electricity from grid-connected sources.



Except for in Sub-Saharan Africa and the Indian Subcontinent, more than 90% of people can already access such power. For the other two regions, where the electricity load is low and the cost of grid connection is high due to large distances, off-grid solar PV systems will be an economically feasible alternative for a fraction of the population. This applies mostly for appliances and lighting rather than space cooling.

Nonetheless, global off-grid solar PV demand will reach only 1.1 EJ/year in 2050, meeting 27% of Sub-Saharan Africa's space cooling, appliances, and lighting energy demand, and 5% of the Indian Subcontinent's. More information about electricity access is presented in the Energy Access factbox and in the regional sections of this report.

Electrification and less biomass use are the two large-scale transitions evident for other end uses. As alternative fuels become available and affordable, there will be switching from traditional cooking and water-heating methods. By 2050, people lacking access to modern cooking and water heating will constitute only 13-14% of the world population.

The decline of biomass in space heating, water heating, and cooking is mostly matched by increases in electricity and direct solar thermal, i.e. solar water heaters (Figure 4.1.16). This does not mean that all people that abandon biomass will immediately move to electricity, many of them will move to natural gas, making it the largest single source of energy for these three heat-related end uses.

Energy supplied from solar water heaters will roughly double between now and 2050, due mostly to developments in Greater China, North America, Europe, Indian Subcontinent, the Middle East and North Africa (Figure 4.1.17).

Hydrogen will also appear as a new energy source for heat-related end uses of buildings in four regions where available gas distribution networks make it a viable alternative (Figure 4.1.18). This is further described in the infographic on hydrogen.

FIGURE 4.1.16

World final energy demand for space heating, water heating and cooking, by energy carrier

Units: EJ/yr

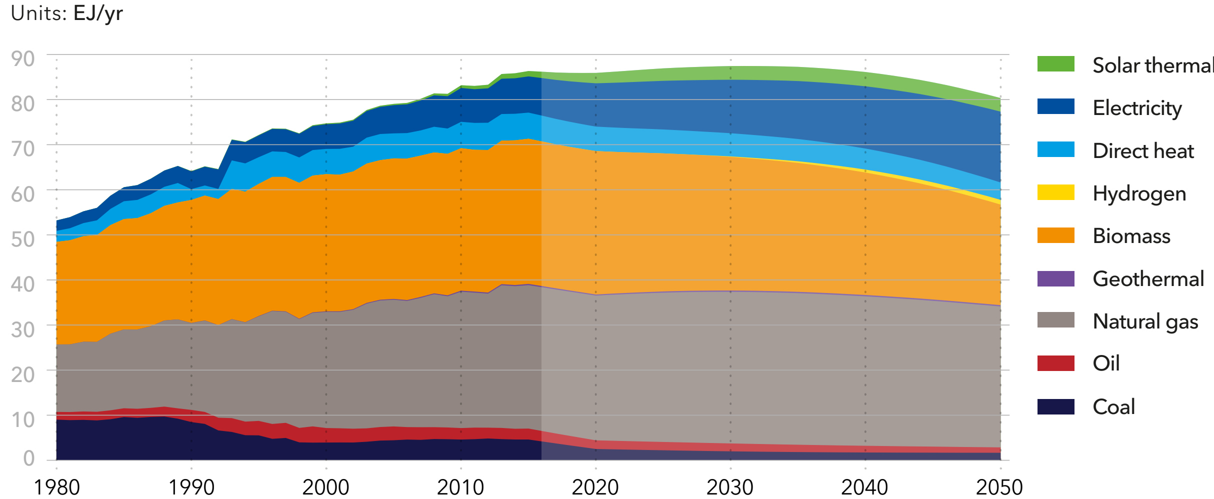


FIGURE 4.1.17

World solar thermal energy demand in the buildings sector

Units: EJ/yr

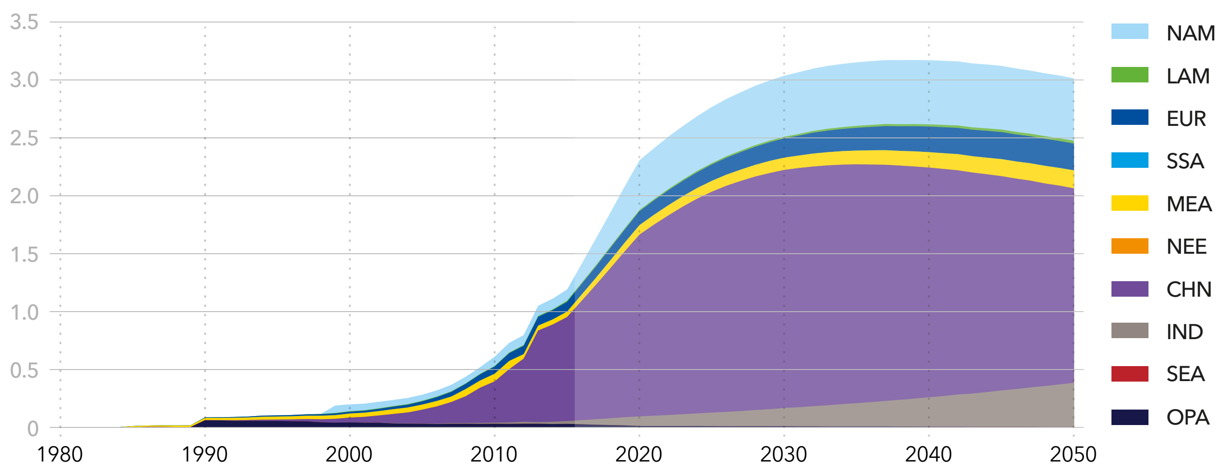


FIGURE 4.1.18

World hydrogen demand in the buildings sector

Units: EJ/yr

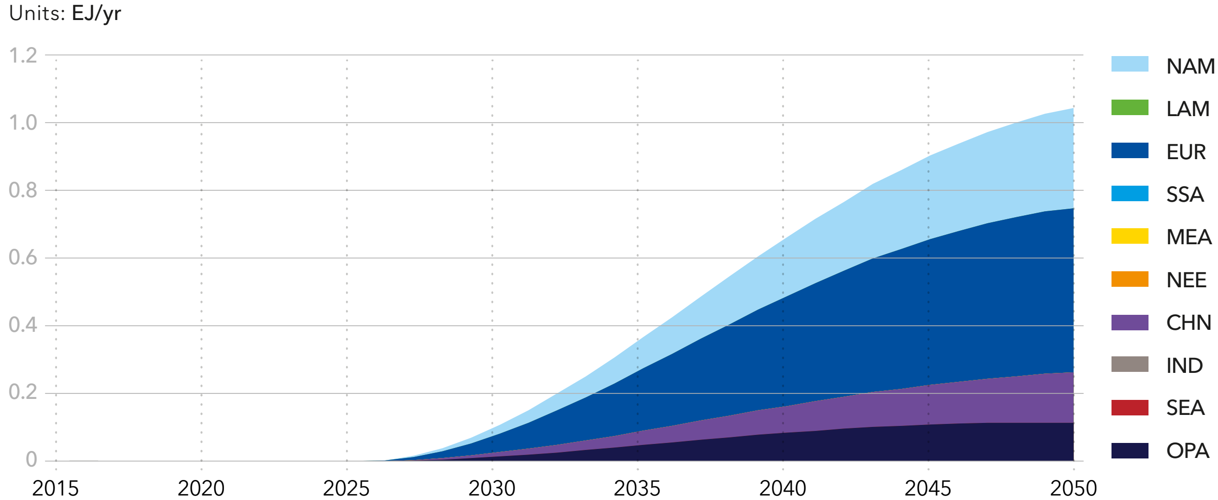


Image courtesy - Patrick Bentley/SolarAid

ENERGY ACCESS

UN Sustainable Development Goal #7 is to 'ensure access to affordable, reliable, sustainable and modern energy for all'. As these four dimensions indicate, energy access has multiple facets, each of which lies on a continuum. For example, reliability of access could range from having intermittent power for a few hours per day, and with unpredictable blackouts and brownouts, to having essentially 100% electricity supply year-round. So, it is not easy to measure energy access, yet alone try to classify populations as being 'with' or 'without' it.

The IEA defines energy access as 'a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average'.

The IEA's Energy Access Outlook (2017) report considers a basic bundle of energy services to mean at least several lightbulbs, 'task lighting' such as a flashlight, phone charging, and a radio. It defines access to clean cooking facilities as access to, and primary use of, modern fuels and technologies, including natural gas, liquefied petroleum gas, electricity, and biogas, or improved biomass cook stoves, as opposed to the basic biomass cook stoves and three-stone fires used in developing countries.

In terms of electricity access, two regions with low access to electricity will benefit from leapfrogging opportunities of off-grid PV systems. In Sub-Saharan Africa, the share of population using off-grid PV as the electricity source will exceed 50% by 2050. In the Indian Subcontinent, due to lower cost of grid access and higher penetration levels of grid-connected electricity already available, the share of off-grid PV will reach around 30%. Off-grid PV is described in more detail under PV in the energy supply section of this chapter, and in the Sub-Saharan Africa regional description (Section 5.4).

When it comes to accessing both modern cooking and water heating, the world will not achieve universal access to modern fuels (we also include some non-clean fuels such as coal and oil in the modern fuels definition). In 2050, 300–400 million people in Sub-Saharan Africa will still be relying on traditional biomass for their cooking and water heating needs. In the Indian Subcontinent, the share of population without access to modern water heating will shrink markedly from 29% to 8%; but progress in access to modern fuels for cooking will be slower.

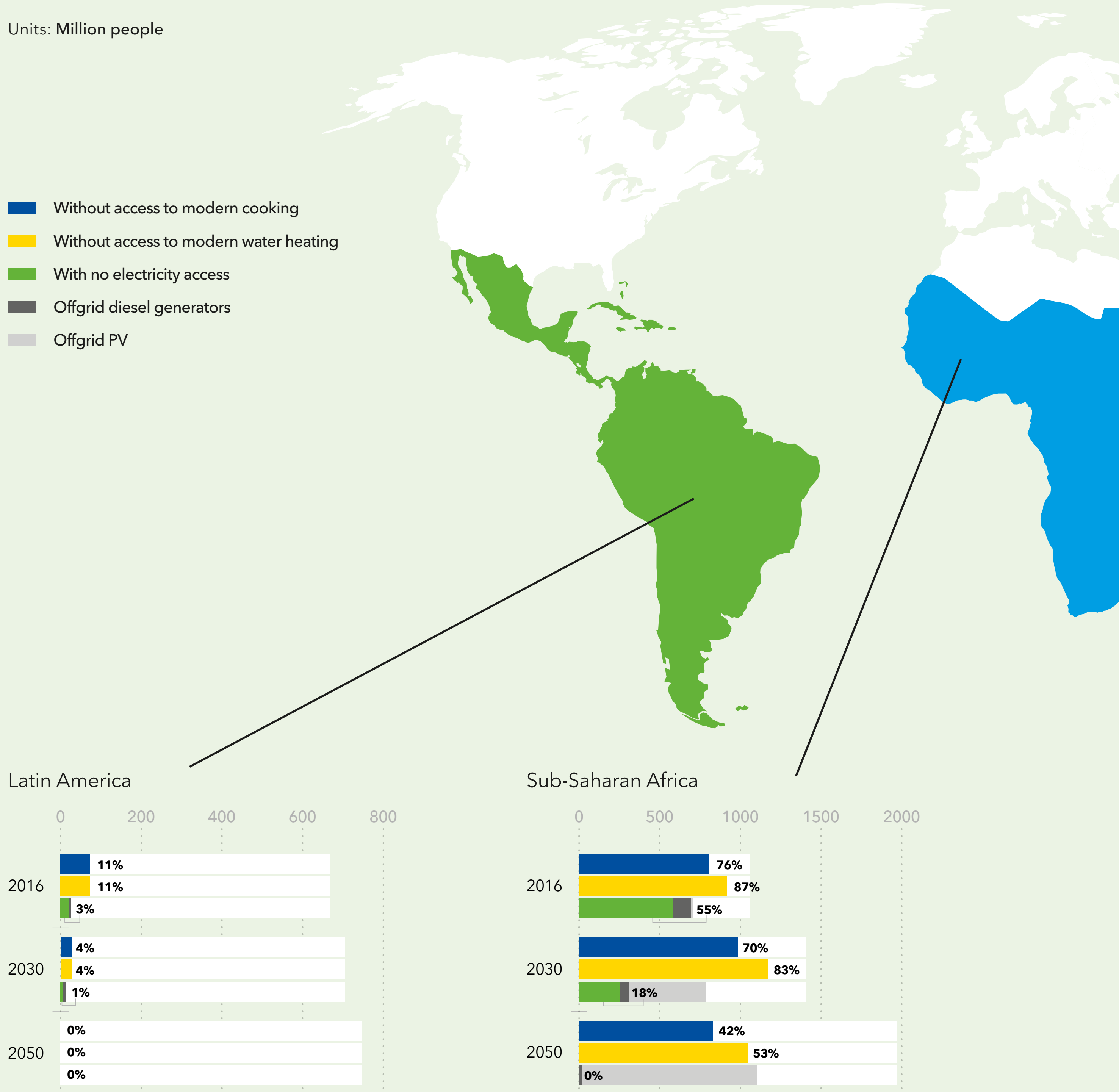
> “Off-grid PV presents Sub-Saharan Africa and the Indian Subcontinent with 'leapfrogging' opportunities.

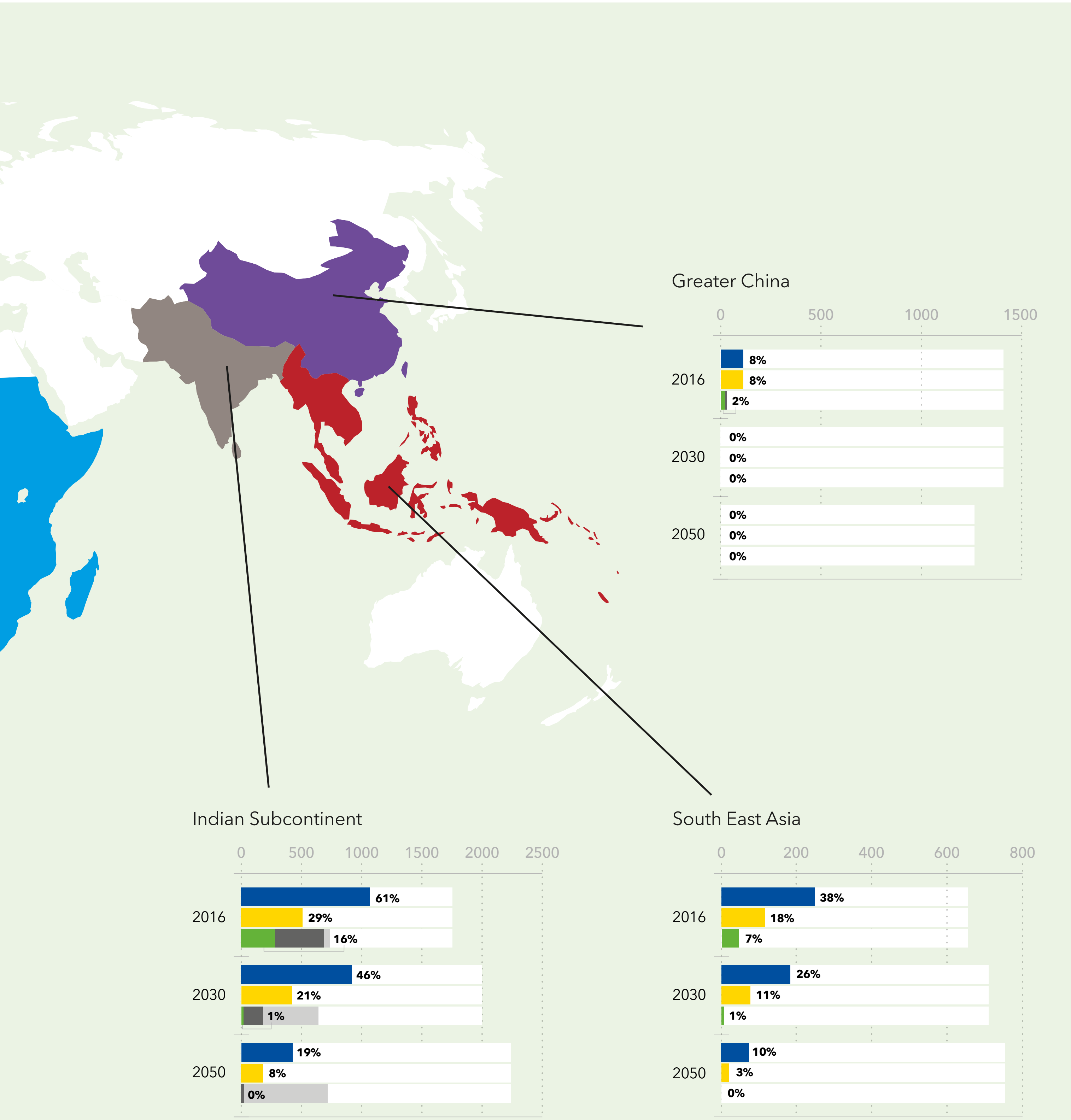
Looking at the more specific and 2030-focused SDG target 7.1: “By 2030, ensure universal access to affordable, reliable and modern energy services”, this will largely be met for all regions except Sub-Saharan Africa for access to electricity, while it will not be met for either Sub-Saharan Africa, Indian Subcontinent or South East Asia for access to modern cooking and modern water heating.

FIGURE 4.1.19

Energy access: progress across five regions

Units: Million people




Greater China
0
500
1000
1500
2016
8%
8%
2%
2030
0%
0%
0%
2050
0%
0%
0%
Indian Subcontinent
0
500
1000
1500
2000
2500
2016
61%
29%
16%
2030
46%
21%
1%
2050
19%
8%
0%
South East Asia
0
200
400
600
800
2016
38%
18%
7%
2030
26%
11%
1%
2050
10%
3%
0%

4.1.3 MANUFACTURING

In this Outlook, the manufacturing sector is an aggregation of all related activities in the extraction of raw materials – excluding coal, gas, and oil – and their conversion into finished goods. We analyse the sector as two categories:

- **Base materials** such as chemicals and petrochemicals; iron and steel; non-ferrous materials, including aluminium; non-metallic minerals, including their conversion to cement; paper, pulp, and print; and, wood and its products.
- **Manufactured goods** including construction equipment; food and tobacco; electronics, appliances and machinery; general consumer goods; textiles and leather; and vehicles and other transport equipment.

FUTURE OF MANUFACTURING SUPPLY AND DEMAND

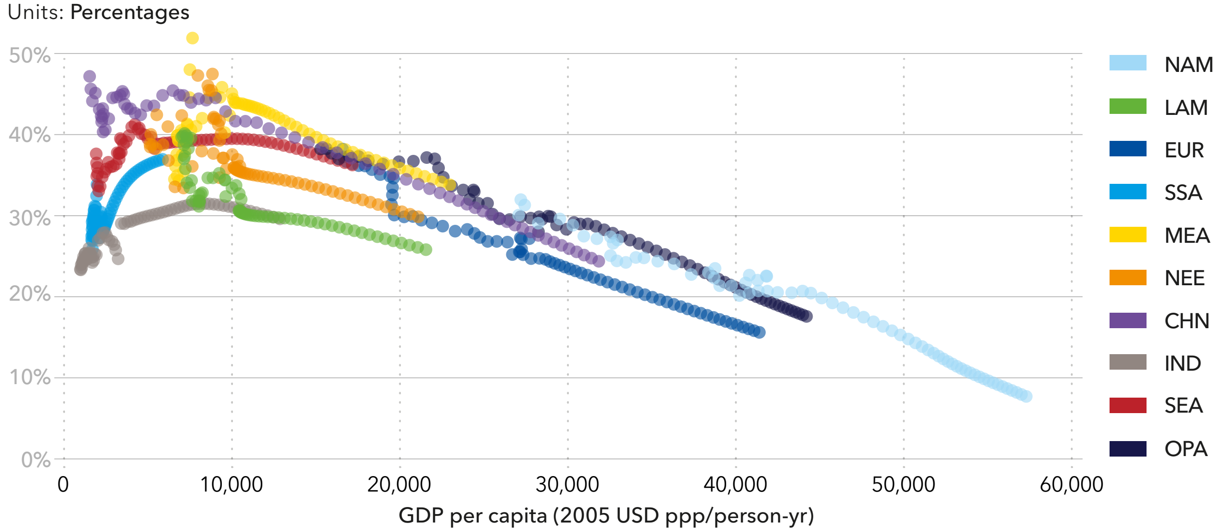
There is historical evidence that the industrial (secondary) sector of a region evolves as the standard of living, as measured by GDP per capita increases. As this gauge of income per person increases, a region transitions from an agrarian economy to an industrial one, and then becomes based on services (tertiary).

Whereas the Indian Subcontinent, South East Asia, and Sub-Saharan Africa display growing secondary sector shares in GDP, the trend is much more marked in the remaining regions – notably so in Greater China – whose economies are transitioning to domination by service sectors (Figure 4.1.20). The consequence is that the monetary value of global manufacturing output will grow more slowly than GDP.

FIGURE 4.1.20

Share of secondary sector in GDP as a function of GDP per capita

Units: Percentages



Each point represents a year. Source: Historical data 1980-2015: Gapminder, 2016-2050: DNV GL

Figure 4.1.21 shows how manufacturing-sector GDP translates to physical output. Historically, there has been a steady increase in the ratio between the weight of manufactured goods and the unit of manufacturing revenue. The main driver of this has been the shift of manufacturing to low-cost regions, such as Greater China, which deliver more output per dollar. As standards of living rise in less-wealthy regions, this trend will level off.

Continually improving efficiency in the use of materials in manufacturing is already well-established, and charts as a steady decline in the amount of base materials needed for each kilogramme of manufactured goods. We predict that this trend will continue uninterrupted, reducing the requirement for base materials, partly because of circular economic processes and partly based on continual changes in types of manufactured goods that are produced.

Thus, during the 2016–2050 period, while the output by weight of manufactured goods rises 130% from 13 to 30 billion tonnes, the global production of base materials will increase just 68%, from 31 to 51 billion tonnes (Figure 4.1.22).

The regional demand for manufactured goods is assumed to be proportional to each region's GDP. Consequently, Greater China, Europe, Indian Subcontinent, and North America will be the largest consumers of manufactured goods. Regions producing larger proportions of world manufacturing are also those that show larger shares in demand for base materials.

The share in global manufacturing production for each region is directly related to the GDP of the secondary sector (forecast as shown in Figure 4.1.20) and the weight of manufacturing output per sales dollar from manufacturing.

FIGURE 4.1.21

Trends of the unit value of manufacturing, and the ratio of manufactured goods to base materials

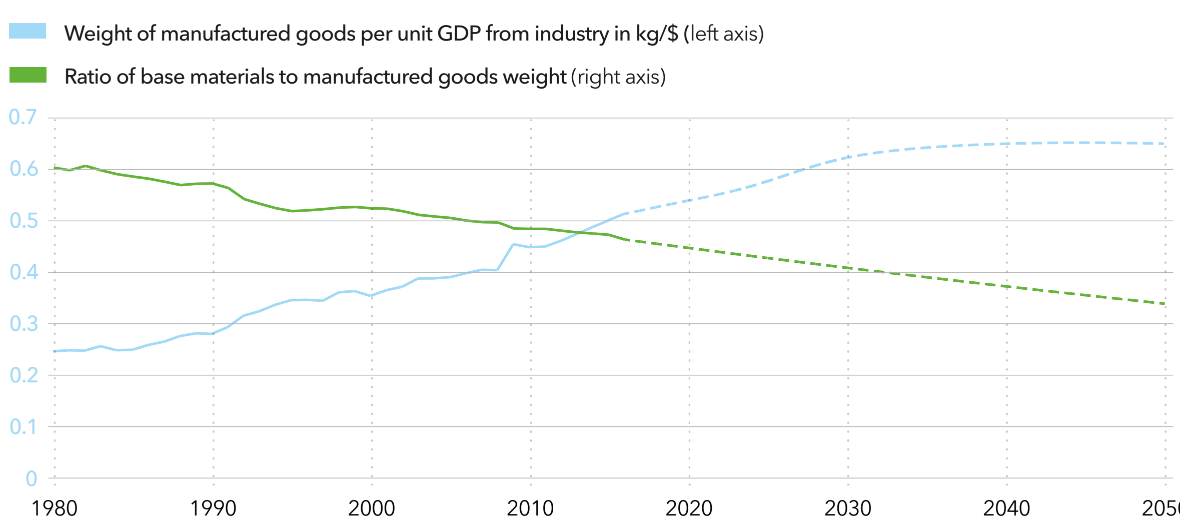


FIGURE 4.1.22

World manufacturing output by sector

Units: Gt/yr

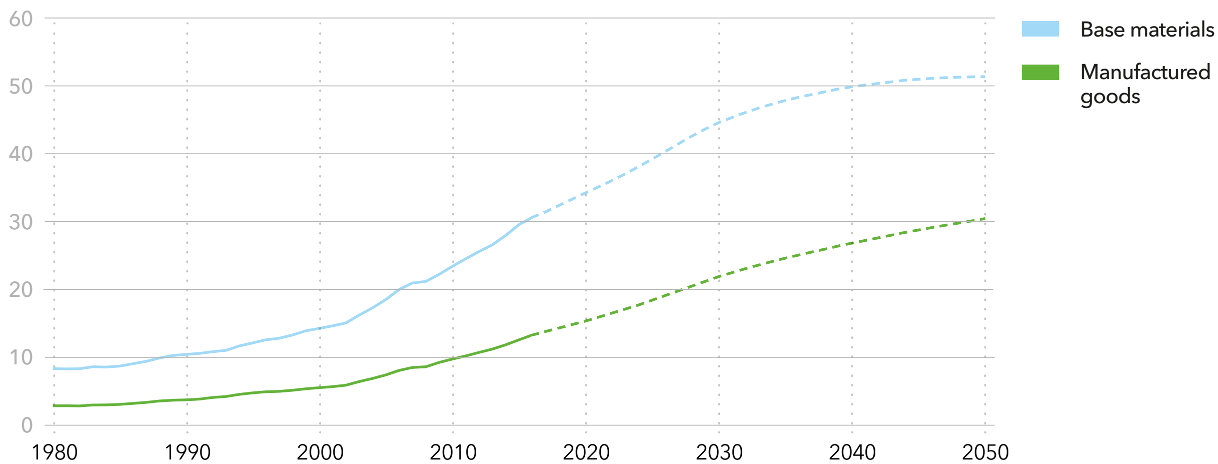


FIGURE 4.1.23

Total manufacturing production and resulting trade deficit of regions

Units: Gt/yr

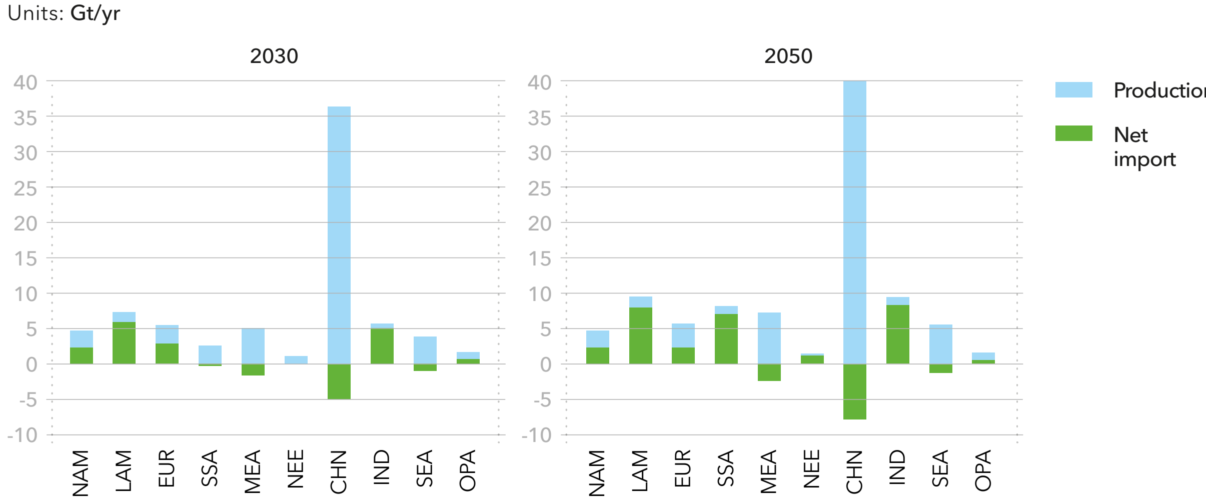


Figure 4.1.23 shows our forecast for the total manufacturing production of regions, and the net imports required to meet demand; or, net exports (indicated by a negative value) if there is more than enough regional production to meet regional demand.

We see Greater China remaining the largest manufacturer and net exporter. Regions such as the Indian Subcontinent, Latin America, Middle East and North Africa and Sub-Saharan Africa also increase manufacturing output between 2030–2050, but with the exception of MEA, these regions are net importers by 2050. The recent trend of production moving to ever cheaper countries, is being partly countered by automation and robotization making manufacturing less dependent on labour cost. This will influence the future location of manufacturing. Large global initiatives, such as China's "One Belt, One Road", will also play a role.

ENERGY DEMAND FROM THE MANUFACTURING SECTOR

The manufacturing sector is the largest consumer of energy. In 2016, 125 EJ of final energy was consumed by the sector, representing 31% of global final energy demand. We forecast the manufacturing sector's energy demand will rise by about 28% until the early 2030s, then flatten at around 160 EJ/year towards 2050. This slowdown happens despite continued increases in manufacturing output (Figure 4.1.24) and is due to continual improvements in energy efficiency.

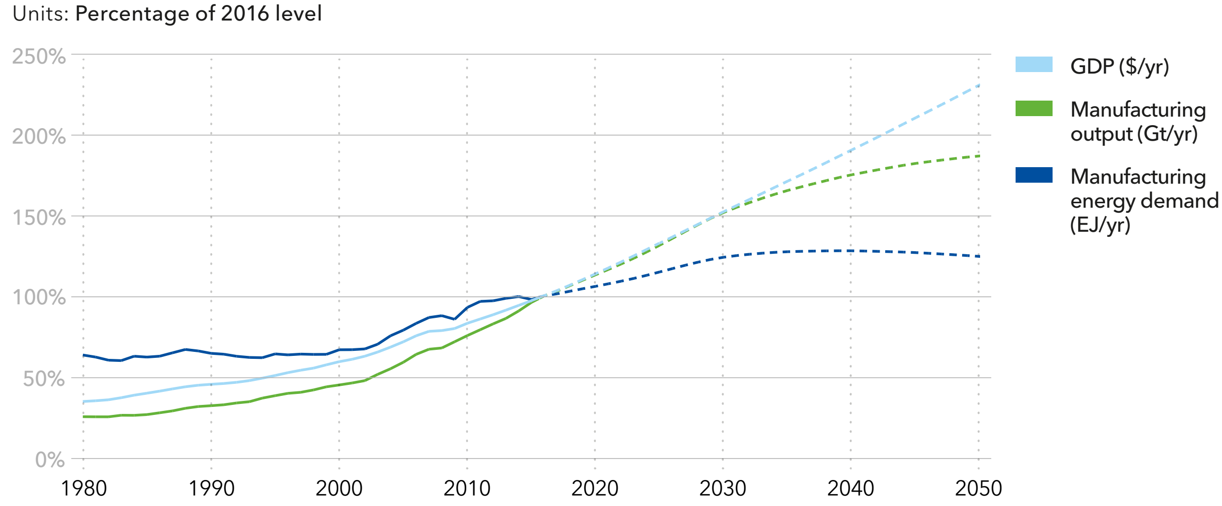
Based on internal and external expert judgement, we forecast a range of energy-efficiency improvement rates, varying between regions to reflect policy and technology differences between them. Energy-efficiency improvements of 35–50% are forecast over the period 2016–2050, giving average annual improvements of 0.9–1.2%. These figures also include effects of increased recycling, which will translate to a global average of 0.2–0.3% energy-efficiency improvement per year for base materials production.

Manufacturing will change further as we enter the so-called fourth industrial revolution, involving increased automation. Customization and efficiency will likely improve as part of this, both for production of base materials and for manufactured goods. This is included in the efficiency factors used in the model.

FIGURE 4.1.24

The decoupling of manufacturing energy demand from manufacturing output and GDP

Units: Percentage of 2016 level



The evolution of the energy mix in the manufacturing sector is dependent on technology innovation, resource availability, and policy and economic incentives. We estimate this mix through an adjusted continuation of linear trends for the various energy sources, separated for base materials and manufactured goods in each region.

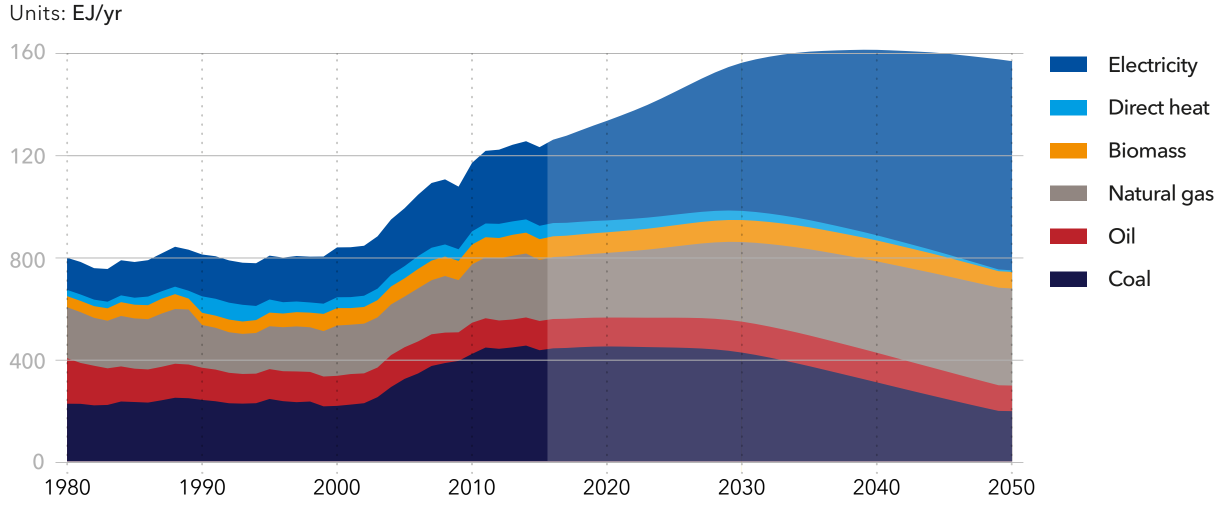
In manufacturing, decarbonization is, and will remain, high on the agenda in OECD countries. R&D and investment support for cleaner production processes will continue. Chinese and Indian policy efforts will help to shift energy use towards electrification and boosting energy efficiency. Policies in OECD nations will later spread to emerging economies to boost decarbonization. Current UN schemes to promote such transfers will intensify.

Overall, the share of electricity will increase from 26% in 2016 to 52% in 2050. For manufactured goods, the share of electricity rate will rise from 33% to 55%, while growing from 22% to 50% for base materials. New technologies such as electric arc furnaces also contribute to energy efficiency improvements discussed above. The changes in energy mix over the Outlook period are shown in Figure 4.1.25.

FIGURE 4.1.25

World manufacturing sector energy demand by carrier

Units: EJ/yr



4.1.4 NON-ENERGY USE (FEEDSTOCKS)

In 2016, 7.5% of global primary fossil fuel supply was used as feedstock, mainly in the petrochemical sector. Some 30% of total feedstock is used to produce plastics; the rest goes to making cosmetics, fertilizers, paints, and other chemicals. Note that coal used in steel production is not included under feedstock use, but under manufacturing energy use. As petrochemical production is included under base-material production, we calculate the demand for feedstock in each region based on the feedstock intensity per thousand tonnes of base material produced. The feedstock intensity is based on historical data and is adjusted towards the future to account for increased plastic recycling. We estimate the global recycling rate to improve modestly, from around 11% in 2016 to 16% in 2050. Although recycling rates in regions like Europe and the OECD Pacific are increasing considerably, the global growth rate is relatively modest as plastic production will see the largest growth in regions where recycling rates are lower. Chemical recycling initiatives may change this dynamic considerably, and we point to early developments in this field as one of the trends to watch in the next five years (see Chapter 6).

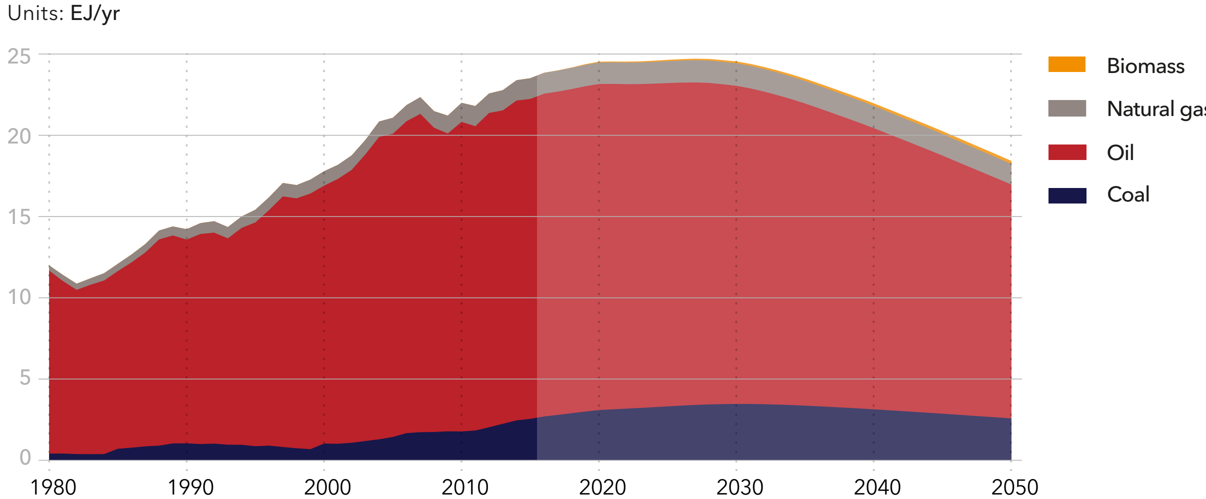
The resulting feedstock use is almost flat until the early 2030s, then declines by 20% by mid-century (Figure 4.1.26). Bio-based feedstocks have the potential to reduce fossil fuel demands in the long term, although they will need strong policy support to take off and grow.

The share of natural gas as a feedstock is forecast to grow in North America, Europe, and the Middle East and North Africa, while oil will continue to provide the major share of feedstocks globally. Coal will remain an important feedstock in Greater China, with coal-gasification capacity growing.

FIGURE 4.1.26

World non-energy use of energy carriers in manufacturing

Units: EJ/yr



4.1.5 FINAL ENERGY DEMAND FROM ALL SECTORS

By combining the various energy-demand and energy-mix values of each of the energy sectors, we forecast the world's final energy demand by energy carrier, as illustrated in Figure 4.1.27. 'Final' energy here means energy delivered to end-use sectors, excluding losses and energy used by the energy sectors themselves.

The ongoing transition is dramatic in relation to the growing dominance of electricity in the mix. In 2016, electricity represented 19% of the world's final energy use, but in 2050 it will represent 45% of final energy use, growing from 75 EJ/year to 205 EJ/year. The annual average growth in electrification in our forecast is 3.0% per year, which is the same rate of growth that we have experienced since 1990.

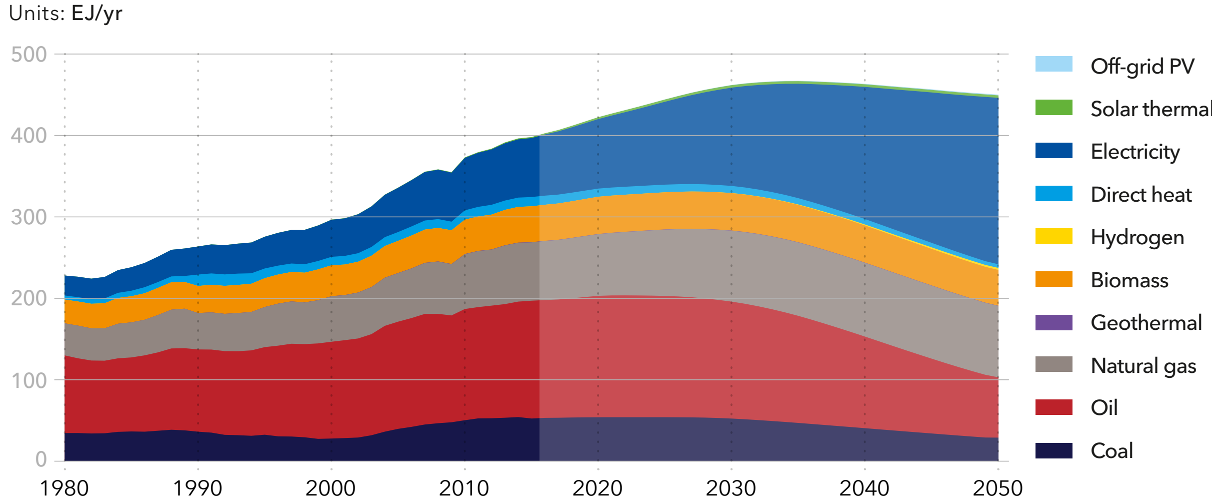
The reason for a robust continuation of electrification is that electric systems have small losses compared to fossil and biomass-fuelled systems, and when technological progress makes electricity available in ever new applications, more and more users will make the switch. Furthermore, there are new applications requiring energy – e.g. modern communication appliances and air conditioning – where there are few or no alternatives to electricity. And finally, more ambitious decarbonization policies favour electricity, especially the fraction generated by renewable low-emission energy sources.

As total demand will start to reduce, electricity will replace coal, oil, and – later – gas in the final energy demand mix. For coal, oil, gas, and biofuel, additional energy use from electricity production and direct heat will be added to the total supply figures, as described in the next chapter. The electrification trend is clear across all the regions in our Outlook, as we explain below.

FIGURE 4.1.27

World final energy demand by carrier

Units: EJ/yr



4.2 POWER SUPPLY

The world's energy mix has been predominantly fossil based for more than a century. A combination of socio-economic forces is reducing this dominance.

While, as we have shown in Section 4.1, there will be some rather dramatic shifts in forecast demand in the next three decades, the transition underway on the supply side will be even more pronounced.

The world's energy system has relatively little elasticity: overall energy supply is largely determined by overall energy demand. Our Energy Transition Outlook model (ETOM) therefore assumes that supply meets demand throughout the forecasting period, 2016–2050.

Before presenting an overview of total energy supply, we first look more closely at our forecast for the supply of electricity and direct heat.

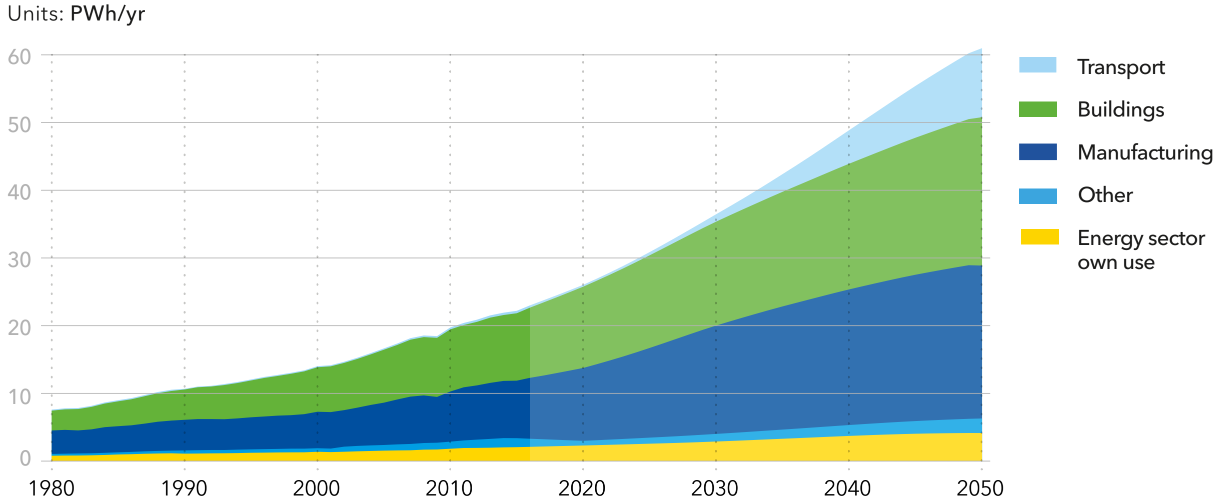
4.2.1 ELECTRICITY

On the basis of both slowly increasing energy demand and rapid electrification, as described in Section 4.1, we forecast global electricity demand to increase by 165%, from 23 petawatt hours per year (PWh/year) in 2016 to 61 PWh/year in 2050 (Figure 4.2.1). As a proportion of final energy demand, electricity increases from 19% to 45% over the period.

FIGURE 4.2.1

World electricity demand by sector

Units: PWh/yr



ELECTRICITY GENERATION

Adjusted for transmission losses (which reduce from 8% to 7% of generation in our model), global electricity generation is expected to increase from 25 PWh/year to 66 PWh/year over the forecast horizon.

We forecast how this electricity demand is met by 14 power station types: coal-fired, coal-fired CHP (combined heat and power), gas-fired, gas-fired CHP, oil-fired, nuclear, hydro, biomass-fired, biomass-fired CHP, solar PV, solar thermal (CSP), onshore wind, offshore wind, and geothermal.

Nuclear and all the renewable power sources, except for biofuel-fired power stations, produce at the stipulated capacity factor unless excess supply requires curtailment. The capacity factors of the thermal power stations are determined using a merit order algorithm that matches the probability distribution of regional electricity load with the probability distributions of variable costs of power-station types. Figure 4.2.2 shows world electricity generation by power-station type.

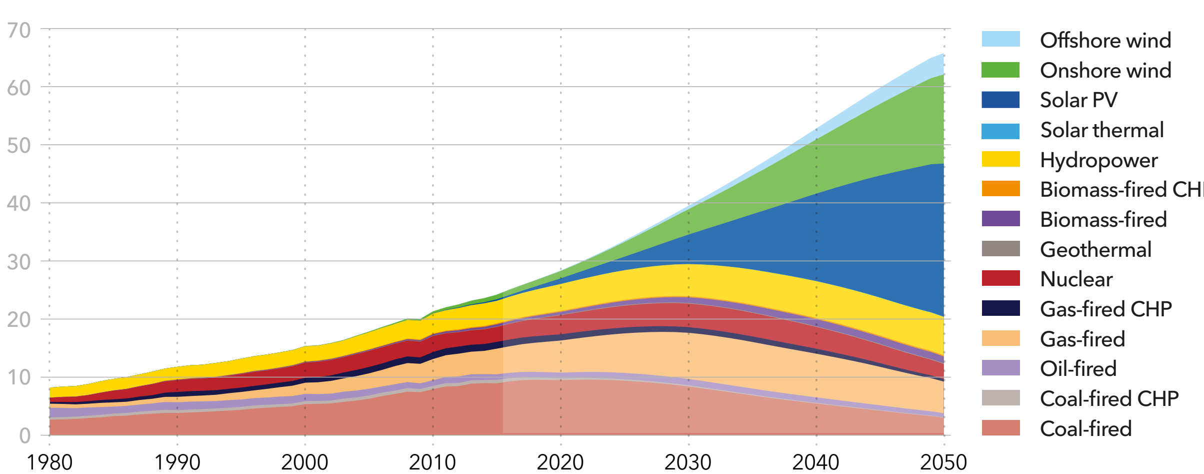
In our ETO model, we also implement a gradual shift from using variable costs to accounting for the levelized costs of electricity (LCOE) in the merit order when the share of variable renewables increases. This is to reflect future changes in the market mechanism. Finally, we include an effect from variable renewable penetration to curtailment of variable renewables. In regions with available infrastructure suitable for hydrogen, the curtailed electricity is assumed to provide energy to produce hydrogen through electrolysis.

The decrease in costs for wind and solar is steep. As the levelized costs of electricity for these sources are competitive and often lower than alternatives, they will dominate capacity additions in the years to come, particularly after 2025.

FIGURE 4.2.2

World electricity generation by power station type

Units: PWh/yr



CAPACITY ADDITIONS

Our Energy Transition Outlook model (ETOM) takes a probabilistic approach to estimating capacity additions from different power-station types. At any point in time, we first estimate the required total capacity additions based on the available annual generation and the peak electricity demand of the region (assumed to be 50% above the average load), plus a safety margin. Then, we use the average LCOE for a power-station type – and its variance due to geographical, technological and temporal variations in the cost – to determine the probability that a power-station type can provide the cheapest electricity. This determines the share of power-station type in the capacity additions.

In calculating the LCOE, we use a dynamic expected capacity factor. The levelized costs of thermal power stations reflect expected increases due to declining capacity factors, as well as the cost of any carbon price or carbon capture. We also take into account: the cost of required flexibility in terms of battery storage for variable renewables; subsidies for renewables, with varying policy effects between regions; and, learning rates in technology costs. The discount rate we use is 7% for the North America, Europe, and OECD Pacific regions, and 8% for all others.

Increased penetration of variable renewables requires increased flexibility in the power system. There are various flexibility options with different costs, response times, and scalabilities, including battery storage, demand response, flexible power stations, increased interconnection capacity, pumped hydro storage, and renewable curtailment.

In our model, we consider five of these options. First, we add additional 'backup' capacity in terms of gas-fired and oil-fired power stations to meet the peak load demand, when the share of variable renewables in the regional generation mix increases. In doing so, we assume that:

- variable renewables' capacity contributes only 5% towards peak load.
- starting from 25% variable renewable penetration, we curtail solar and wind generation, with a maximum of 24% at 100% penetration.
- 10% of battery capacity of EVs is available to provide flexibility to the power system.
- dedicated battery storage is added where flexibility from EVs is not sufficient. For example, at 50% penetration, 250 megawatts (MW) of battery-power rating is required for every gigawatt (GW) of variable renewable capacity for a discharge duration of 52 minutes.
- grid capacity is reinforced to cope with an increased share of variable renewables in the energy mix.

Existing plants are retired on reaching end of life. We assign an average lifetime of 40 years for coal power plants, 30 years for oil and gas power plants, 60 years for nuclear power plants, and 200 years for hydropower plants. In addition, a 20-year lifetime is used for wind-turbines and 25 years for solar PV panels.

Figure 4.2.3, and its accompanying Table 4.2.1, show the dynamics of installed capacity through to 2050. The majority of gas-fired and oil-fired capacity additions is the 'backup' capacity to meet the peak load.

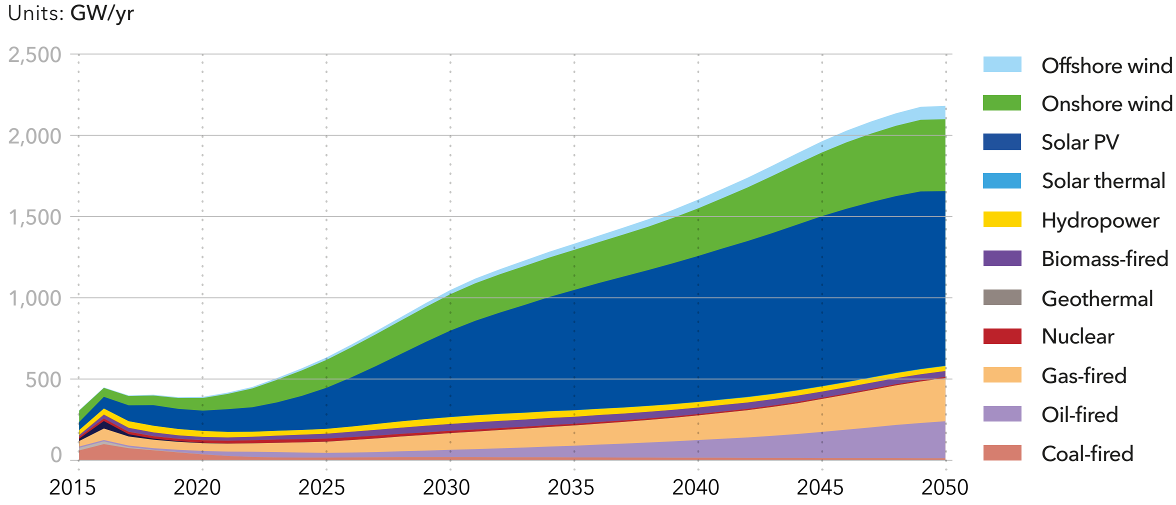
TABLE 4.2.1
World installed electricity capacity in 2016 and 2050

	Installed capacity (GW)	
	2016	**2050**
Coal-fired	1 955	1 506
Gas-fired	1 647	4 376
Oil-fired	512	2 845
Nuclear	420	502
Hydropower	1 209	2 343
Biomass- fired	377	1 061
Solar PV	290	18 895
Solar thermal	5	30
Onshore wind	452	6 146
Offshore wind	14	1 034
Geothermal	15	20

FIGURE 4.2.3

World electricity capacity additions

Units: GW/yr



TRENDS TOWARDS 2050

Coal use in power generation increased rapidly during the decade to 2014, growing from 30% to 40% of electricity generation. Coal's share will soon decrease rapidly to hit only 4.7% in 2050, as the absolute level of electricity production from coal also declines significantly. The increasing share of variable renewables and rising carbon prices makes many coal-fired power stations, and other thermal power plants, redundant. This decreases the average capacity factor (i.e. utilization) of thermal power stations in many regions.

Gas has maintained a power mix share of about 20%, and will continue to grow on a par with electricity production, maintaining its share until 2030. Towards 2040 its use will continue to grow, but at a lower rate, and will then decline to only 8.6% of the electrical power mix in 2050. Most of the gas and oil-fired capacity additions are due to increased peaking capacity demand as a result of high variable renewable (solar and wind) penetration. These peaking capacity plants are only economical for a low fraction of time.

Despite the global reduction in nuclear electricity generation after Fukushima in 2011, nuclear power will show a small and steady increase until the early 2030s, with new capacity additions, with only a few exceptions, largely in China and Indian Subcontinent. As older plants in Europe and North America are decommissioned, global electricity generation from nuclear power stations will be reduced to current levels by 2050. In relative terms, nuclear reduces its share from 11% today to 3.8% in 2050.

Hydropower includes dammed, run-of-the-river, pumped-storage, small, micro and conduit hydropower stations, as well as those exploiting tidal and wave energy. Hydropower generation has been growing quite rapidly over recent decades and we forecast that this will continue until 2030 at 2.3% per year then reduce to 0.8% per year until 2050. Growth in hydropower will be outpaced by the other generation types, reducing its share in the global electricity mix from 16% now to 14% in 2030 and 10% in 2050.

The contribution of solar PV and wind to the power mix has been increasing quickly, but from a very low base. These two renewable sources will continue to grow rapidly, making a considerable impact over the Outlook period to 2050. By then, they will dominate world electricity generation, with solar PV at 41% and wind at 30% of the mix, with one fifth of wind power being offshore.

With this high amount of variable power, the stability of the electricity system will be challenged. We do not model stability and short-term variations in our ETOM, but in the companion report Power Supply and Use (DNV GL 2018a), the feasibility of the (regional) power mix is commented upon in more detail. In Chapter 2, we also describe our investigation into the impact of resource limitations on the uptake of renewables and conclude that there is no significant obstacle.

Capacity developments of non-fossil energy sources are further discussed in the Primary Energy Supply section below.

4.2.2 DIRECT HEAT

We define direct heat as the thermal energy produced by power stations for selling to a third party, as in the case of district heating, or by industries (auto-producers) for their own use supporting their primary industrial activity. As the use of direct heat in manufacturing reduces, the direct-heat demand will decline from 11 EJ/year in 2016 to 4.5 EJ/year in 2050 (Figure 4.2.4). The historical anomalies are due to switches between fuels and sectors reported in the energy accounts, especially around the fall of the Soviet Union. Accounting for losses in distribution, global direct heat generation will correspondingly move from 13 EJ/year to 5.6 EJ/year over the same period (Figure 4.2.5).

As of 2016, coal and gas were providing 43% and 45%, respectively, of global direct heat supply. By 2030, coal will be replaced by biomass-fired technologies that mostly use municipal and industrial waste as fuel, bringing the share of coal down to 26%. In 2050, biomass will provide 35% of direct heat, while coal's share reduces to below 4%. In the meantime, the share of gas will increase to 61%.

FIGURE 4.2.4

World direct heat demand by sector

Units: EJ/yr

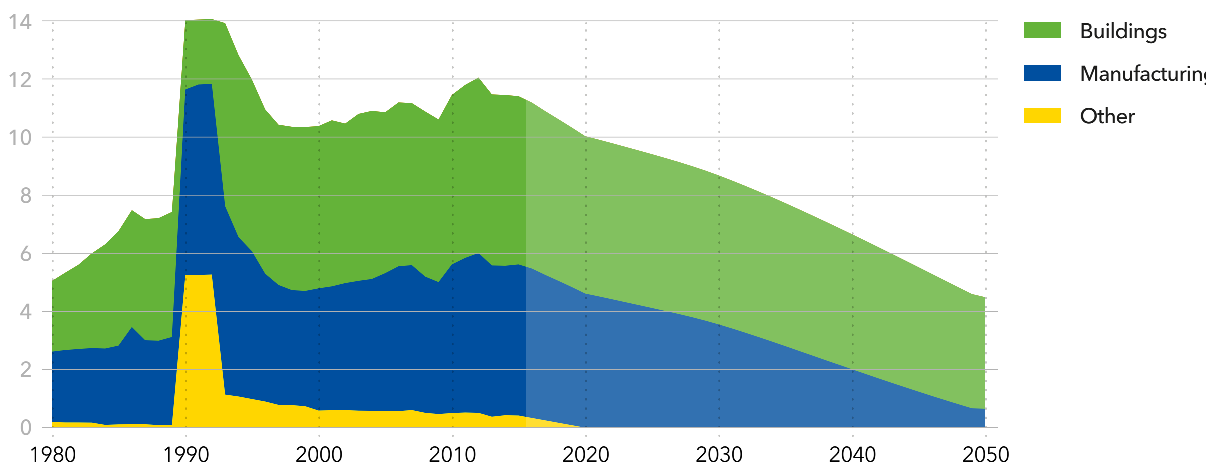
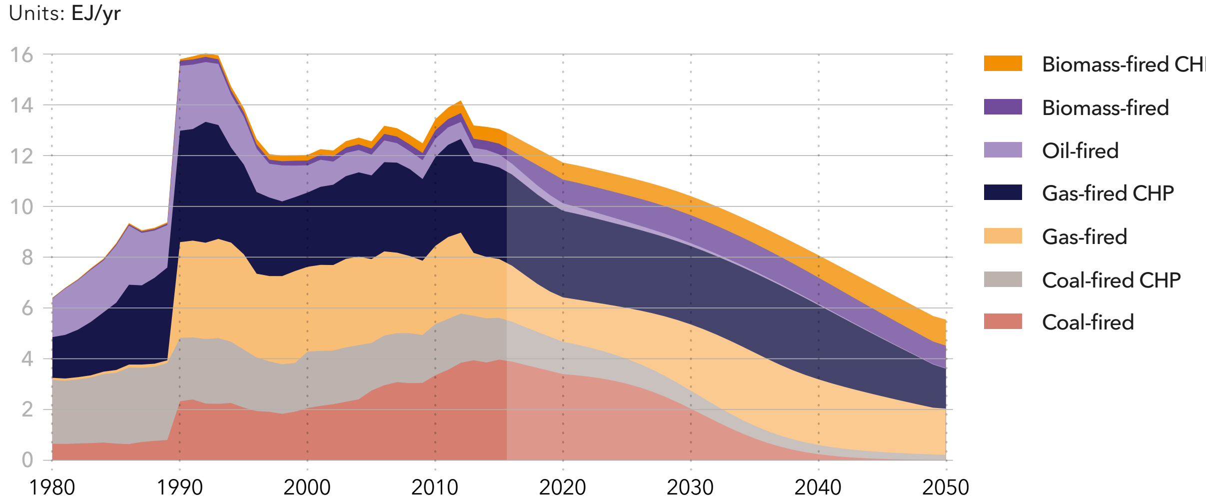


FIGURE 4.2.5

World direct heat generation by power station type

Units: EJ/yr



4.3 PRIMARY ENERGY SUPPLY

In the energy system, there are considerable losses. They occur mainly when converting one energy form to another – such as heat losses in a power plant or a combustion engine – but also when transporting energy, such as electrical power losses in grids.

There are several ways to measure energy, and in the factbox Energy counting, we explain the various methods and the Physical Energy Content Method that we use in this Outlook.

World primary energy consumption is considerably higher than final energy consumption because it also accounts for energy lost when providing electricity from burning fossil fuel, biomass, and heat. Conversion losses exceed 100 EJ per year when transforming coal, gas, oil and nuclear heat into electricity. Our forecast also includes significant grid losses between where power is produced and where it is consumed, along with other losses in the energy system. Finally, primary energy also includes the energy sectors' own use of energy.

The historical (estimated from IEA 2017) and forecast world energy supply from various primary energy sources are shown in Figure 4.3.1 and Table 4.3.1.

A key result from our study, as shown in Figure 4.3.1, is that global primary energy supply will peak within the forecast period. This will occur even though the global population and economy will still be expanding by mid-century, albeit both at a slower rate than now. The world will be producing more, but it will do so with less energy. Owing to the steady electrification of the world energy system and cumulative advances in energy efficiency, we will need less energy within a few decades.

Our forecast shows that the world's annual primary energy supply, currently 581 EJ, will grow 11% and reach a peak of 662 EJ in 2032, thereafter declining gradually to some 586 EJ in 2050, almost exactly the same as now.

In this section, we describe the outlook for the various primary energy sources, presented as both consumption and production figures. Typically, a fraction of biomass and fossil fuels are produced in one region and consumed in another and will be exported there on keel or through pipelines. While electricity is often traded within the regions we have delineated, we have assumed no inter-regional electricity exports, as it seldom crosses the regional boundaries.

Players in the energy industry have the challenging task of ensuring both short-term and long-term supplies of energy. As energy sources are depleted, and because resources and assets have limited lifetimes and then retire, capacity additions are typically necessary, even if demand for the energy source in question is in decline. Our Outlook model addresses capacity additions and retirements of all types of power generation. It also includes capacity additions and retirements for oil and gas fields, and for coal mines. Oil and gas fields have depletion factors that depend on field type, being typically 5-7% per year for oil fields and 6.5-8% per year for gas fields. The lifetimes for oil and gas wells, when new capacity must be added to continue production, are 30 years for conventional onshore, 20 years for offshore, and 10 years for unconventional onshore.

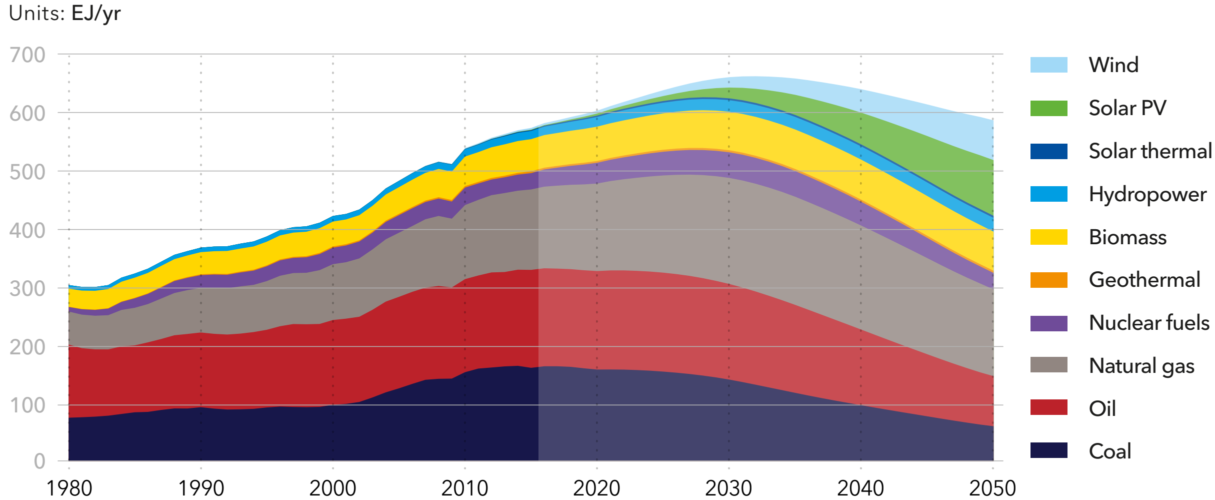
TABLE 4.3.1
World primary energy supply by source (EJ/yr)

	2016	2020	2030	2040	2050	Share in 2050
Coal	163	157	140	96	60	10%
Oil	168	169	164	130	86	15%
Natural gas	140	150	182	179	149	25%
Nuclear fuels	30	36	44	41	28	5%
Geothermal	3	3	4	4	4	1%
Biomass	56	59	66	69	67	11%
Hydropower	14	17	20	23	24	4%
Solar thermal	2	2	3	3	4	1%
Solar PV	1	3	19	55	96	16%
Wind	3	5	18	40	68	12%
Total	**581**	**603**	**660**	**639**	**586**	**100%**

FIGURE 4.3.1

World primary energy supply by source

Units: EJ/yr



ENERGY COUNTING: IS PEAK ENERGY COMING SOON? YES, BUT IT DEPENDS ON HOW YOU COUNT ENERGY

Several ways of calculating primary energy exist, each producing a different energy mix because it assigns a different efficiency to each energy source. The differences are most pronounced when measuring primary energy from non-combustibles such as renewables.

The primary energy of combustible sources such as fossil fuels and biomass is commonly defined as the heating value of combustion (or enthalpy). There is often polarized debate over calculating primary energy for non-combustible sources such as nuclear or renewables. One view is that renewables are 100% efficient because the input energy – solar, for example – is neither captured nor extracted as such and is assumed to be outside the boundary of the energy system. Other analysts assign a low conversion efficiency because, for example, solar panels convert only a small percentage of the solar energy reaching them.

These differences are apparent in the three key primary energy methods. (A fourth method called Resource Content Method also exists, assigning efficiency factors for solar and wind, but this method is not used by any of the larger forecasters).

The three key techniques:

- *The Direct Equivalent Method* distinguishes between combustion and non-combustion electricity generation. It assumes that electricity generated from all non-combustion energy sources – including nuclear, solar thermal and geothermal – is primary energy.
- *The Physical Energy Content Method* distinguishes between thermal and non-thermal sources of electricity. It assumes that the thermal energy generated from nuclear fuels, geothermal sources and solar heat, and fossil fuels, is the primary energy, while electricity from non-thermal sources – such as wind, solar PV, and hydropower – is primary.
- *The Substitution Method* computes the primary energy content of non-combustion sources by asking how much fossil fuel would be necessary to generate the same amount of electricity. This method then 'substitutes' the efficiency of an average hypothetical combustion power station for the efficiency of non-combustion sources.

We use the Physical Energy Content Method in our Outlook because this approach is in line with organizations such as Eurostat, IEA, and OECD, which allows for easy comparison with other reference forecasts. Also, the conversion of individual categories (gas, oil, solar PV, wind etc.) is directly comparable to the 'tradeable energy' metric familiar to oil and gas, and power, producers. Put simply, a tonne of crude oil is tradeable, half a day of sunshine is not, but half a day's electricity generation from a solar PV panel is tradeable. The tradeable-energy metric is both measurable and has a clear economic value as the coal, gas, oil, and power that is produced or sold.

Detailed conversion factor methods of our counting method and more details of the alternatives are provided in (DNV GL 2018e).

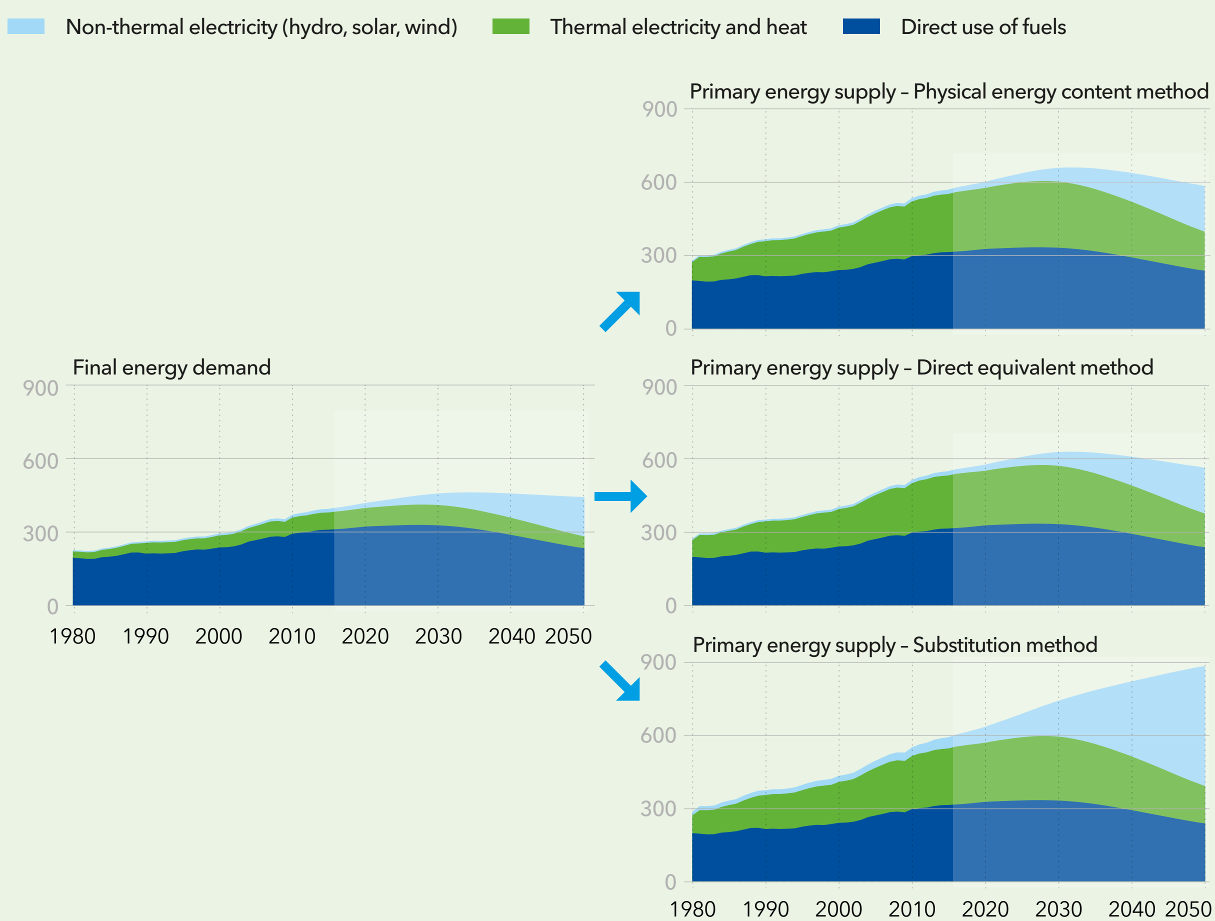
HOW WOULD OUR FORECAST DIFFER IF WE USED AN ALTERNATIVE METHOD?

Using one primary energy method over another significantly impacts energy forecasts. When the renewable share of the energy mix was low, this hardly mattered. As renewables' share is now growing rapidly, and will continue to do so, different methods produce different results, and it becomes important to understand the variations. Figure 4.3.2 illustrates how the main Outlook results for primary energy demand will change if we use another counting method.

FIGURE 4.3.2

Primary energy supply curves using three methods corresponding to the same final energy demand forecast

Units: EJ/yr



4.3.1 COAL

In some coal mining areas, policies will continue to reflect concerns for employment, potentially delaying regional decarbonization due to continued use of indigenous coal resources in domestic energy supply. As for oil and gas, these concerns will likely reduce over time.

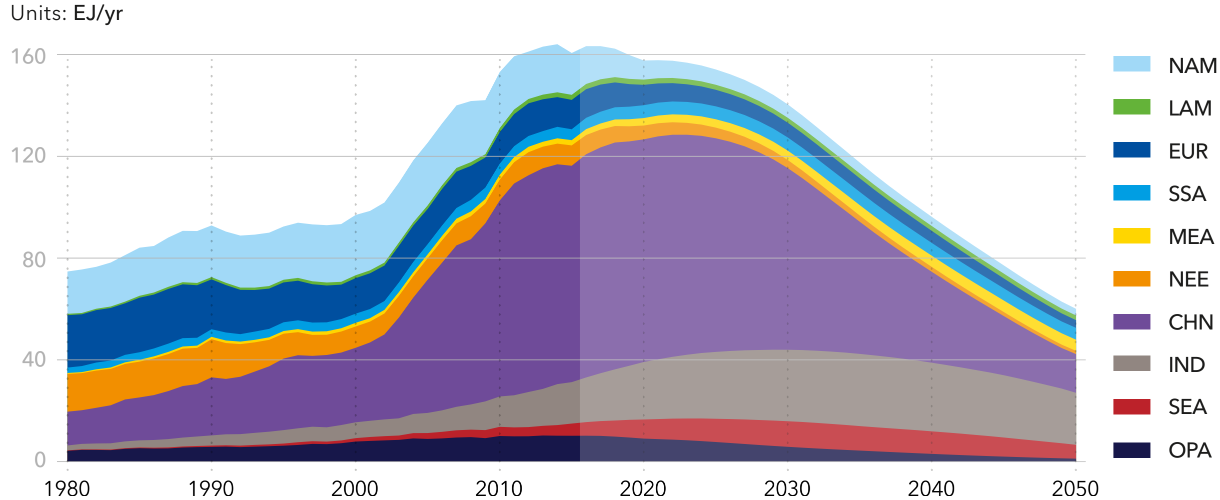
World coal consumption increased rapidly in the first decade of this century, driven mainly by strong demand growth in China. Consumption has, however, flattened and is set for continued decline in most of the world, reducing coal demand from 163 EJ in 2016 to 68 EJ in 2050, when it represents 10% of world's energy use. The decline in the first 10 years is minor, with global coal consumption hovering just below its 2014 peak year.

The predicted decline in coal consumption shows large regional variations. Consumption in OECD countries is already in fast decline, driven by a combination of climate-policy targets and regionally-dependent loss of cost competitiveness to gas-based power and renewables. This trend will continue. A surge in coal competitiveness in Europe lately is expected to be an anomaly, especially in the gas-abundant future we see unfolding. Greater China accounts for almost 60% of global coal consumption today, but Chinese consumption of this energy source has stabilized. Figure 4.3.3 indicates a rapid decline in Chinese use of coal from about year 2030; and, in the mid-2040s, it will be overtaken by the Indian Subcontinent as the largest coal consumer.

FIGURE 4.3.3

Coal demand by region

Units: EJ/yr



Many of the world's large regional coal consumers have significant domestic coal resources and source their production from their own region. The share of coal that is transported between regions is limited, and the regional coal production overview resembles the coal consumption overview.

Presently, coal is mainly used in power stations, with manufacturing the second largest sector (Figure 4.3.4). The decline in consumption by 2050 will take place in all sectors: 58% in manufacturing, and 69% in electricity generation, for example. Investors will continue to be concerned by depreciated coal-fired power station stranded assets. It remains to be seen how governments will deal with this issue and alleviate the associated economic pain.

Coal demand is distributed among two categories in our analysis, where hard coal production is four times higher than for brown coal (Figure 4.3.5). South East Asia and Europe are the main producers of the former and Greater China and Indian Subcontinent of the latter. The leading regions today will also lead in the future, except when it comes to hard coal. The tonnage of total coal produced in the Indian Subcontinent is currently less than 20% compared with the figure for Greater China. However, the Indian Subcontinent is the only region where coal output will increase every year in our Outlook: it will produce twice as much coal as Greater China by 2050.

FIGURE 4.3.4

World coal demand by sector

Units: EJ/yr

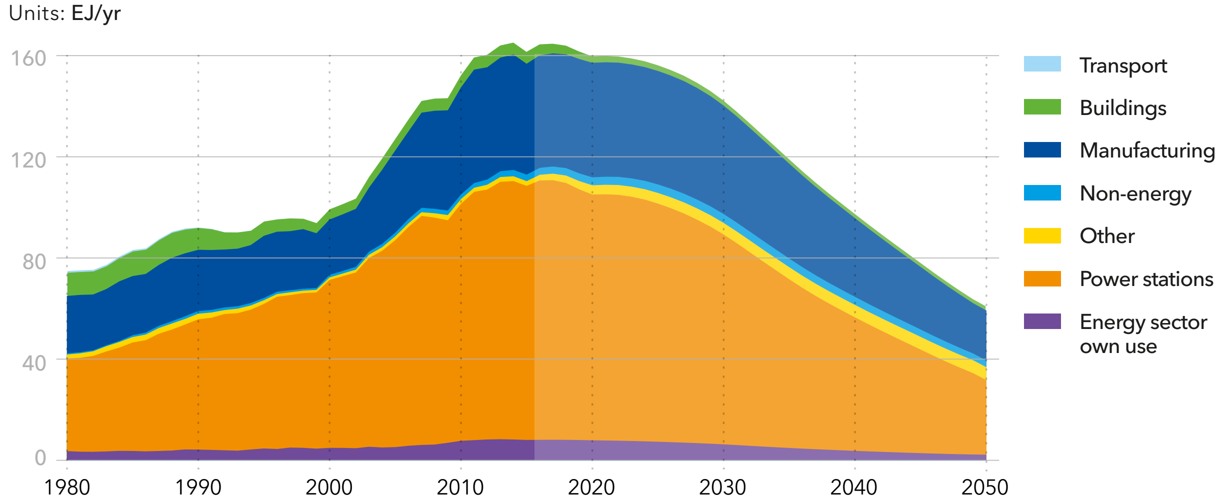
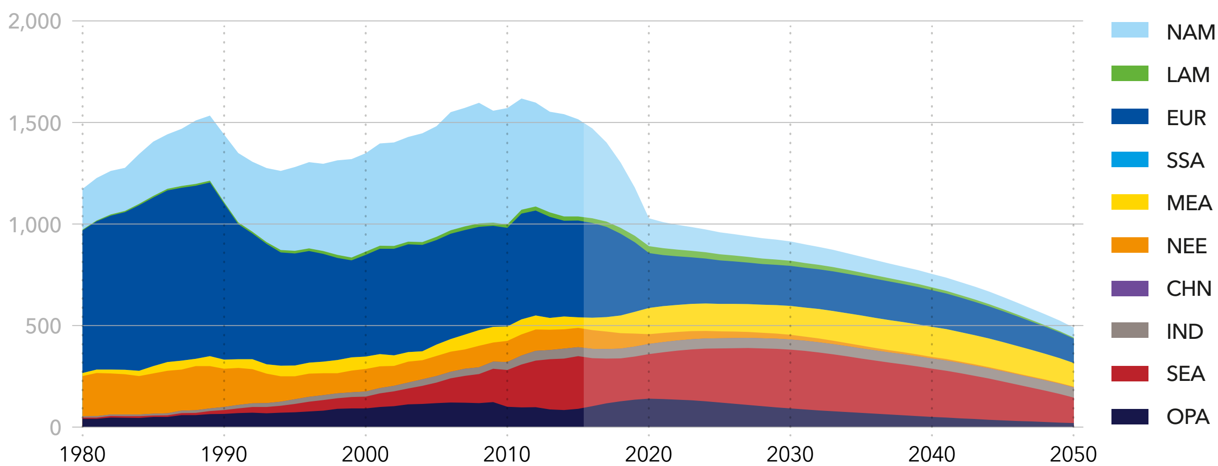


FIGURE 4.3.5

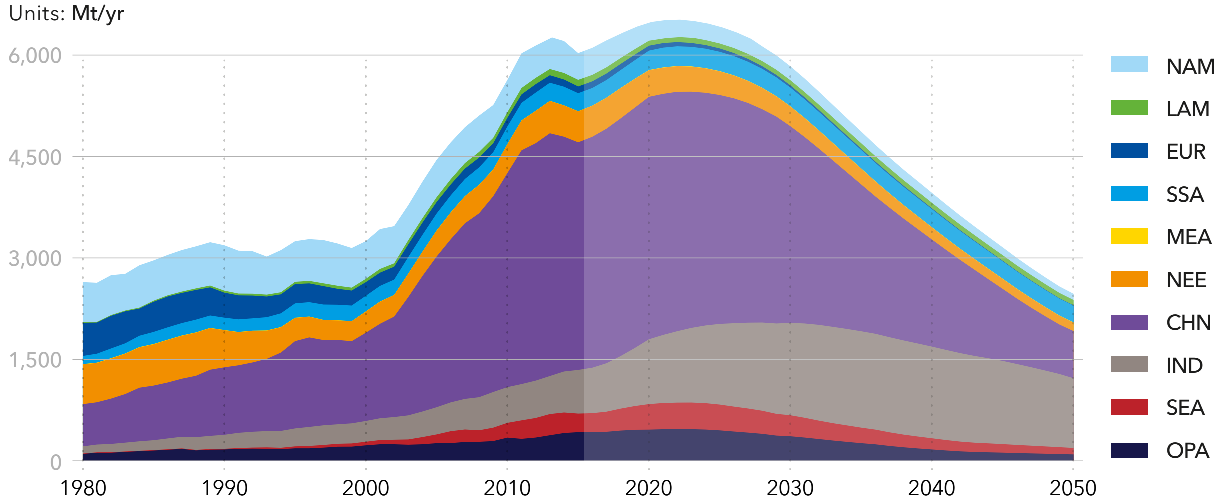
Brown coal production by region

Units: Mt/yr



Hard coal production by region

Units: Mt/yr



4.3.2 OIL

Oil and gas extraction will find it increasingly difficult to attract preferential policy treatment as governments target emissions reduction and divert attention to non-carbon energy technologies. Carbon risks and concerns about stranded assets will increasingly grab the attention of policy makers. Stranded assets are those that are losing value or becoming liabilities before the expected end of their design or economic lives due to economics, innovation, or regulation. Employment fears will extend the continuation of pro-extraction policies; but these concerns will likely reduce over time as the economy transforms with the transfer of skillsets and expertise to other industry areas.

World oil consumption has increased slowly over the last decades. However, we forecast a shift as oil consumption will inch upwards for a few years, to peak over the next decade and thereafter start a steady decline to half its peak level in 2050, as illustrated in Figure 4.3.6. Oil's share of the overall energy demand will then have reduced from the present 29% to 15% in mid-century.

North America is currently the region with the largest oil consumption. Greater China will overtake it in 2023. All regions will experience lower oil demand towards the end of the Outlook period (for Sub-Saharan Africa, the demand is essentially flat from 2040), driven mainly by EV uptake.

Transport is the main consumer of oil and will continue to be so (Figure 4.3.7). The electrification of transportation will largely be in the road segment, where a dramatic increase in EVs will significantly reduce oil consumption. Aviation and shipping will use oil for longer; in these segments, oil use will meet competition from biofuels for decarbonization rather than from electrification.

FIGURE 4.3.6

Crude oil demand by region

Units: EJ/yr

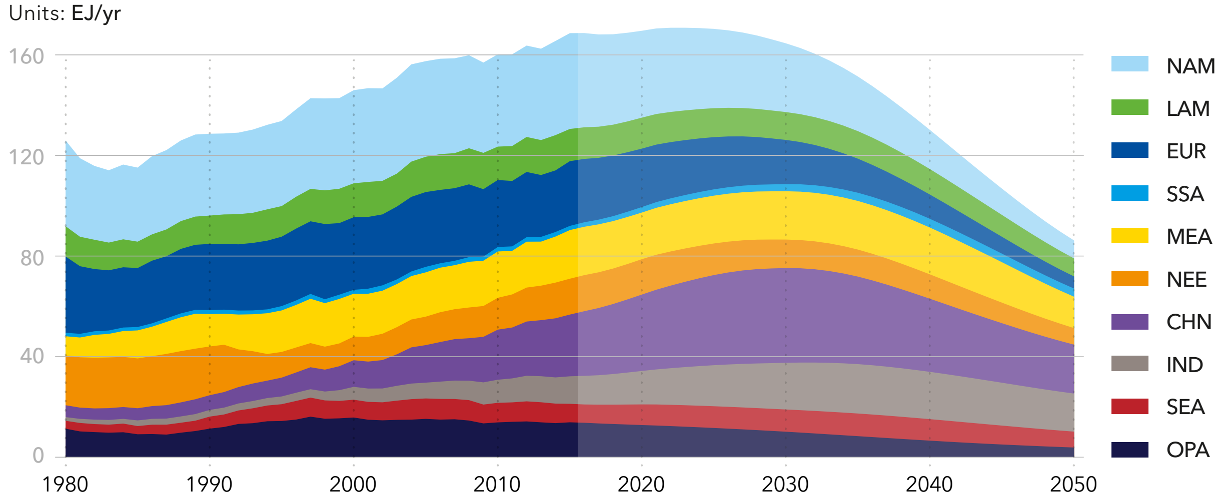


FIGURE 4.3.7

World oil demand by sector

Units: EJ/yr

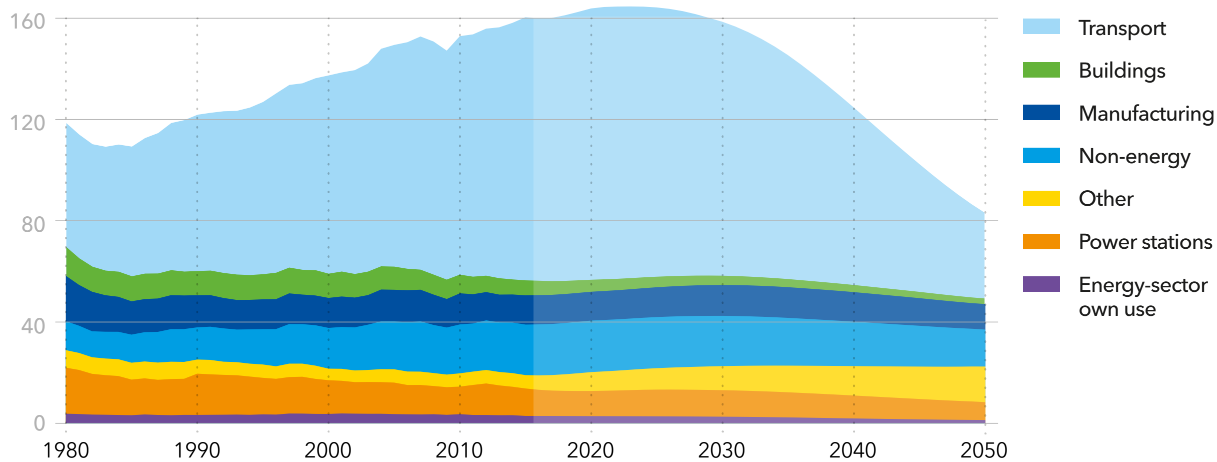
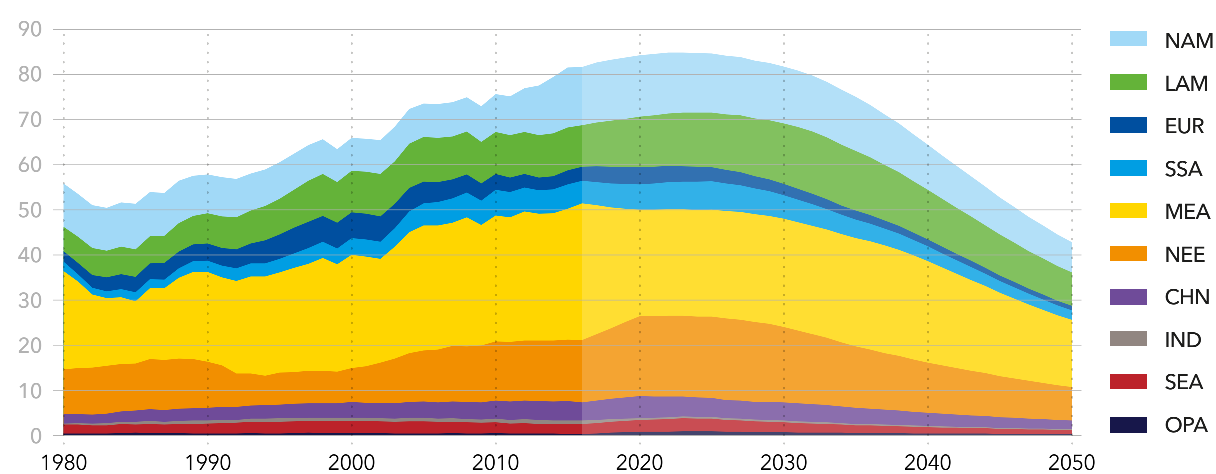


FIGURE 4.3.8

Crude oil production by region

Units: Mb/d



By 2050, oil use in transportation will be less than a third of its 2021 peak. But in some regions, other sectors' use of oil will remain constant. Consequently, the share of non-transport consumption in oil demand use will increase from about a quarter in 2016 to two-thirds in 2050.

The Middle East and North Africa region will continue to dominate the supply picture (Figure 4.3.8), as the cheapest oil resources with the easiest access are located there. North America will remain a growing producer for the next two decades, with shale oil taking a larger share in total production. The relative roles of the three dominant production regions will hold in a period of halving oil output, as Middle East and North Africa production is twice that of either North America or North East Eurasia today, and will still be so in 2050. Latin America will also increase production, helped also by a nascent shale industry. In the remaining regions, production will decline.

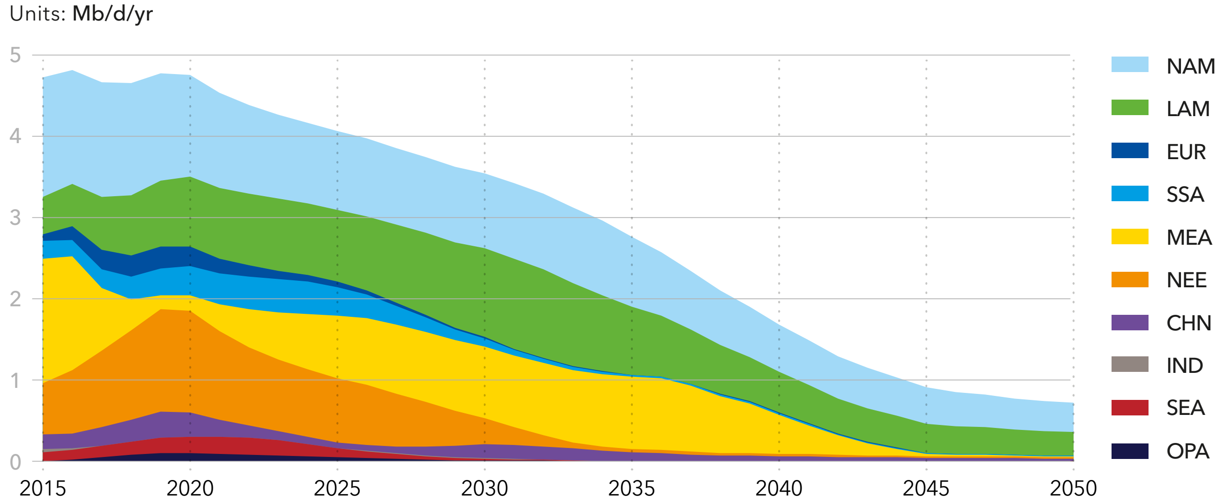
Separate forecasts for offshore oil, onshore oil, and unconventional oil are included in our supplementary publication on the implications of the energy transition for the oil and gas industry (DNV GL 2018b).

As can be seen in Figure 4.3.9 the annual rate of oil capacity additions will reduce considerably over the forecast period, but new oil fields are required until the 2040s to replace depletion of existing fields. Geopolitical concerns at sub-regional levels will increasingly play a role. Amid declining consumption in the future, we see little scope for adding capacity in high-cost areas, such as in the Arctic. After 2040 we will likely enter a period where new oil fields are not required to replace depleted fields. Whether there will be potential to optimize the world's oil resources on a global scale and stop new developments is a complex political-economic issue.

FIGURE 4.3.9

Crude oil production capacity additions by region

Units: Mb/d/yr



4.3.3 NATURAL GAS

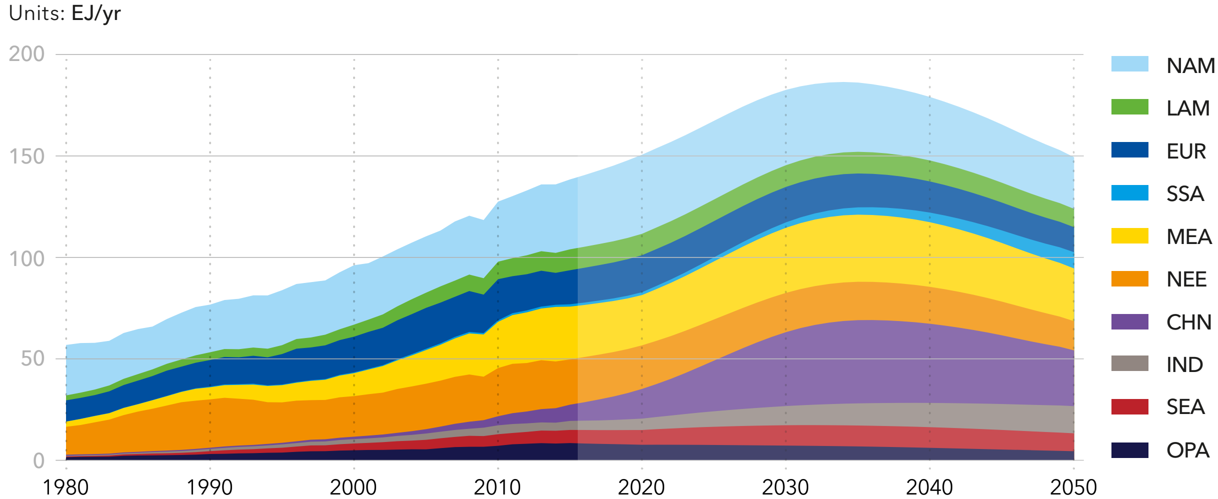
Natural gas is frequently seen as a bridge fuel. It has significant environmental advantages over oil and coal, both in terms of GHG and particulate matter emissions. Consequently, it is favoured by policy makers for urban transportation. For example, compressed natural gas is mandated for auto rickshaws in India. In the future, we see a strong and growing role for natural gas for fuelling bespoke peaking power plants, in support of renewables. In the long term, gas will encounter ever-increasing competition from renewables; so, only by capturing emissions along its value chain will it be able to maintain its role as a major energy carrier.

The world's gas demand has doubled over the last 30 years. It will continue to increase strongly until 2030 and will then eventually peak in 2034 at 186 EJ/year, which is 33% higher than today's level. Thereafter, gas consumption will decline towards 2050 to a level 6% greater than today, as illustrated in Figure 4.3.10, its share of the overall energy demand will increase from the current 24%, reaching a peak of 28% in the mid-2030s, and be back at 25% in 2050.

FIGURE 4.3.10

Natural gas demand by region

Units: EJ/yr



Regional annual production rates and trends illustrated in Figure 4.3.11 will not change dramatically. Several regions, notably North America, have seen increasing gas production levels in recent years (we discuss this in more detail in our Oil & Gas companion report - DNV GL 2018b). Also, Middle East and North Africa, and North East Eurasia, show steep rises until the mid-2030s, thereafter experiencing a gradual decline.

Gas use will continue to grow earliest and strongest in the power sector, where it will peak in 2034 at levels two-thirds higher than today (Figure 4.3.12). A similar peak will be seen in gas use for transportation, but at far-lower consumption levels. The use of gas in buildings will remain essentially flat, while manufacturing gas use appears to increase throughout, with a forecast peak mid-century.

Separate forecasts for offshore gas, onshore gas, and unconventional gas are included in our supplementary report on the implications of the energy transition for the oil and gas industry (DNV GL 2018b).

The annual rate of gas capacity additions, illustrated in Figure 4.3.13, will increase over the next decade, thereafter reducing back to a pace similar to that of today. The regional variations are relatively small, with the dominant contributions coming from Middle East and North Africa, North America, and North East Eurasia.

FIGURE 4.3.11

Natural gas production by region

Units: Gm³/yr

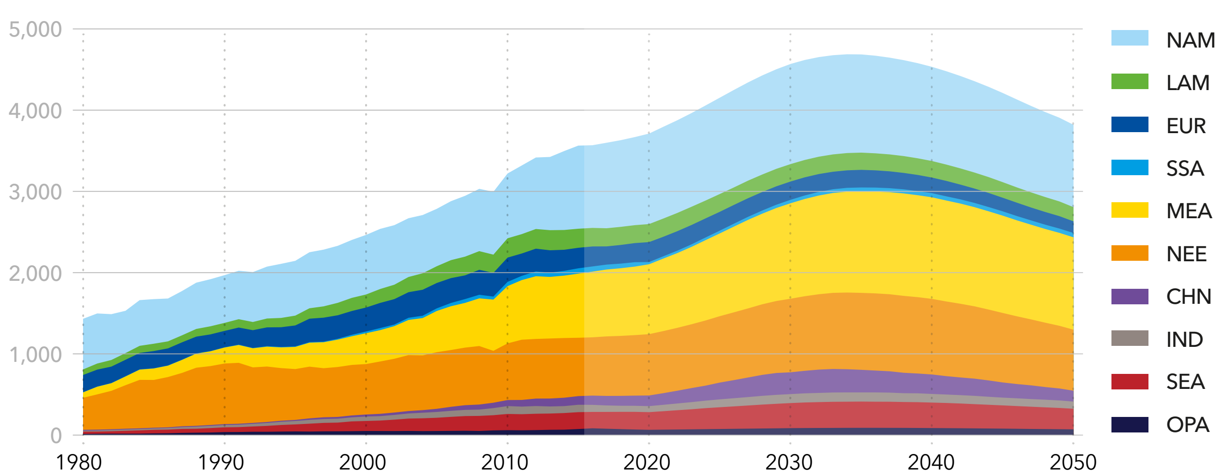


FIGURE 4.3.12

World natural gas demand by sector

Units: EJ/yr

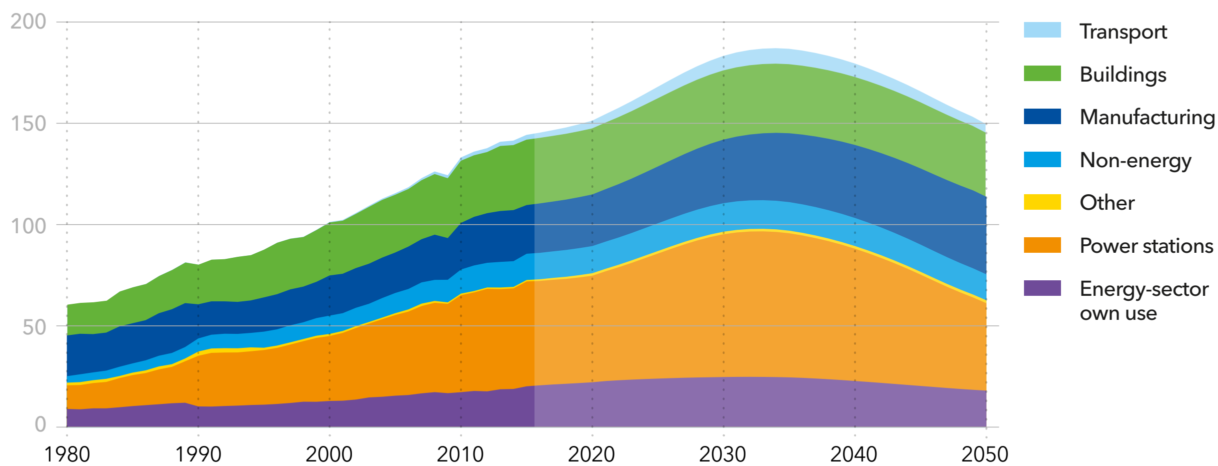
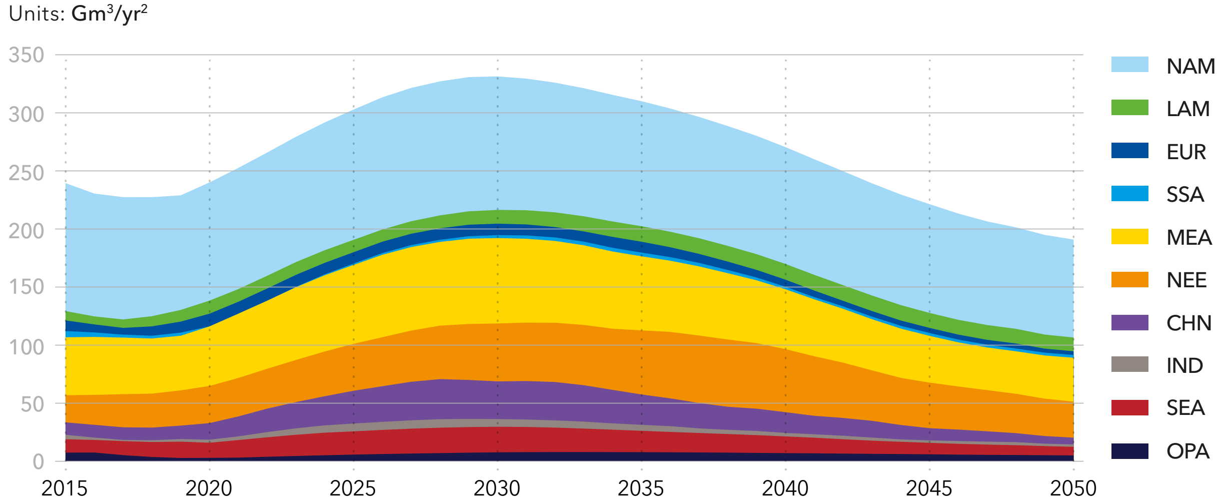


FIGURE 4.3.13

Natural gas production capacity additions by region

Units: Gm^3/yr^2



4.3.4 NUCLEAR POWER

Nuclear power is environmentally ambiguous. It is advocated in the context of climate change mitigation to meet future energy demands without emitting carbon dioxide (CO_2), other GHGs, and particulate matter, and can reduce or eliminate dependence on oil. Societal acceptance varies across regions, however; witness the opposition following the Fukushima disaster in Japan in 2011. Willingness to accept risk and carry costs – including for treating and storing nuclear waste, and decommissioning – will continue to vary in coming decades. Increasing competition from renewable energy technologies as a faster-to-market option for meeting growing energy demand in developing countries could be a game changer for nuclear. Added to environmental risk, it will reduce willingness to treat relatively expensive nuclear power preferentially, as has been the case in several markets until now.

World nuclear power output has grown almost fourfold since 1980. Figure 4.3.14 shows our forecast that before the peak in 2035, output will increase by two-thirds compared with today. By mid-century, it falls back to 2.6 PWh/year, 10% above current production. Due to the calculation method, where the heat content of nuclear fuel is considered as primary energy, a large proportion of the primary energy content of 28 EJ is lost in electricity production as the efficiency is only 35%.

North America and Europe are the two most nuclear-dominant regions today and will be joined by Greater China as a major nuclear power within a decade. Figure 4.3.15 illustrates that new nuclear will be built mostly in Greater China. In fact, no other region will add net new capacity in the future, and even China will see retirements exceeding capacity additions after 2041. At that time, Greater China's nuclear power output will be seven times higher than in 2016.

FIGURE 4.3.14

Nuclear electricity generation by region

Units: PWh/yr

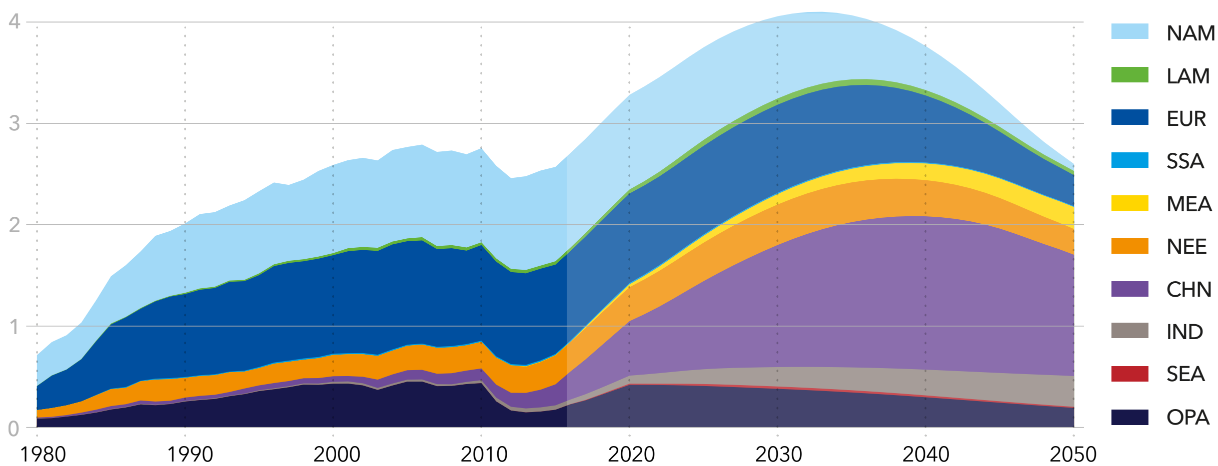
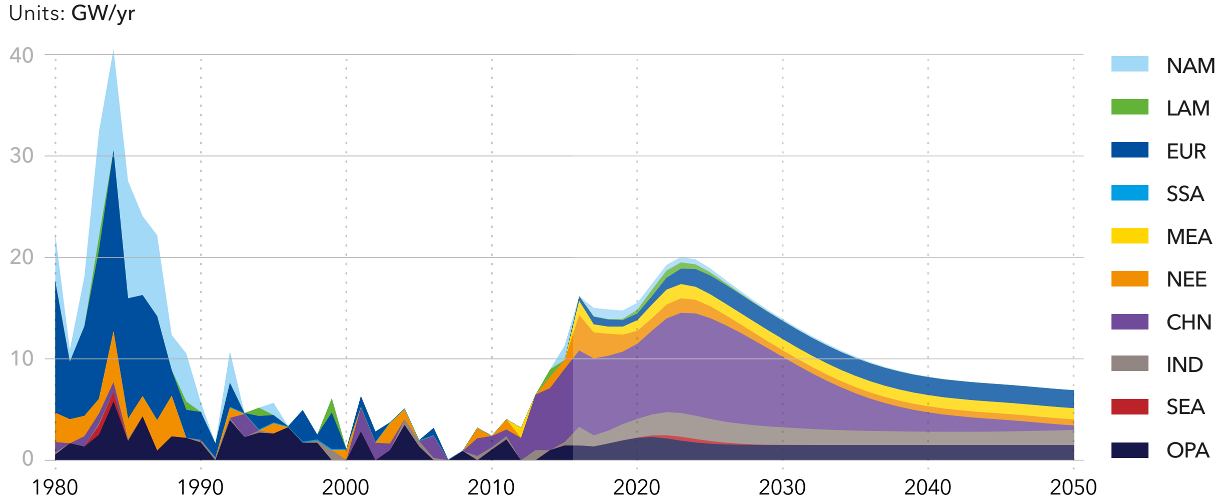


FIGURE 4.3.15

Nuclear capacity additions by region

Units: GW/yr



4.3.5 HYDROPOWER

Hydropower is at a policy crossroads as planning permissions for large dams must be balanced with protection of biodiversity and the livelihoods of residential communities. We expect broader environmental concerns to gain primacy in the hydropower debate, but countries will still want to exploit this formidable source of reliable renewable power. Variable renewable energy sources (VRES) will be a strong competitor for hydropower in large parts of the world. VRES will cause average electricity prices to decline, creating a harsh conditions regionally for hydropower. There is, however, an upside in services from hydropower in the form of flood damping, energy storage, and in balancing variable solar and wind generation. All things considered, we predict policy continuity for hydropower projects. In the initial decades, large hydropower developments will be supported in developing economies due to robust new demand for electricity.

Hydropower will be increasingly valuable for balancing load and generation, both for short-term daily variations and for medium-term seasonal variations. 'Pumped hydro', which increases reservoir volumes by harnessing surplus solar and wind energy to pump water back up to the reservoir, will be increasingly important. However, not all hydropower production is suitable for this. Pumped hydro requires new investments and involves energy losses; so, many areas will continue with traditional hydropower, both traditional reservoirs without pumping facilities, or run-of-river hydro.

World hydropower production has doubled during the last 30 years, and Figure 4.3.16 illustrates our prediction that it will continue to grow throughout the Outlook period. Towards 2050, most of the suitable resources in prime locations will be developed, and production will start to level off, providing 6.6 PWh/year or 11% of the world's electricity at the end of the forecast period.

Latin America, Greater China, North America, and Europe are the largest hydropower producing regions today. Greater China will continue to grow steeply, and Latin America will also increase during the first five years. The growth in Sub-Saharan Africa will occur slightly later during the forecast period.

Figure 4.3.17 shows how installation of hydropower capacity will peak around early 2030s, with South East Asia leading. Later in the period, additions will be at a much lower level, with Latin America and South East Asia attracting the greatest levels.

FIGURE 4.3.16

Hydropower electricity generation by region

Units: PWh/yr

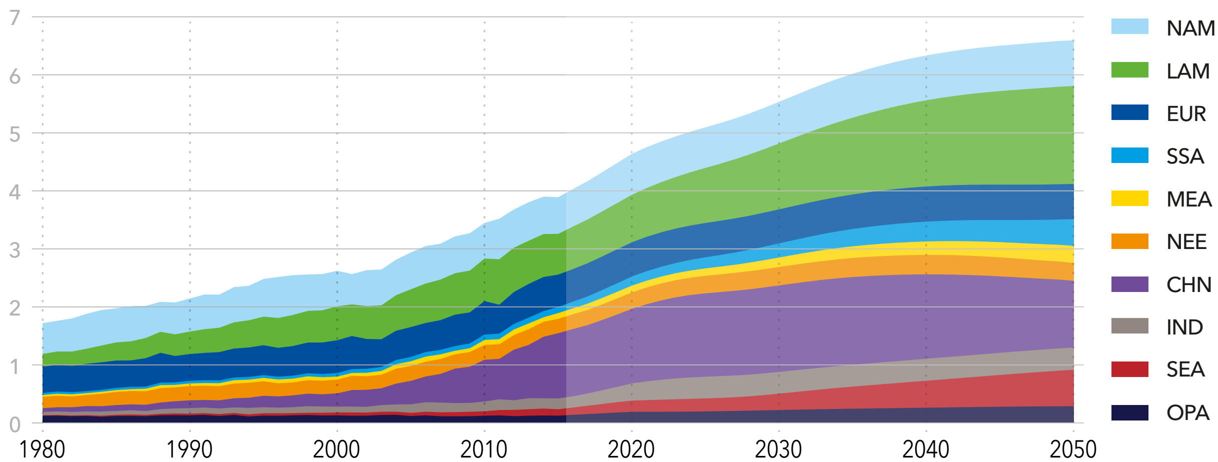
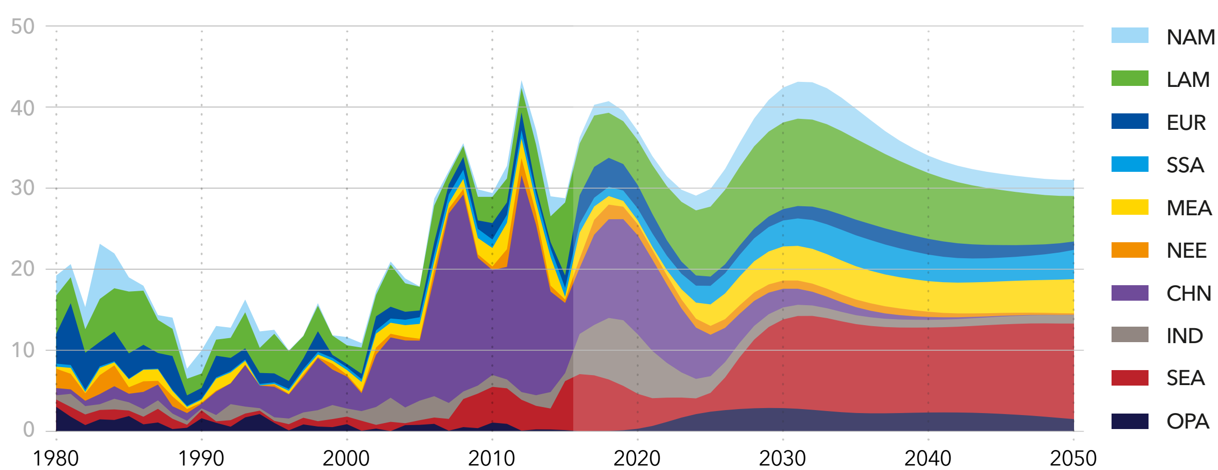


FIGURE 4.3.17

Hydropower capacity additions by region

Units: GW/yr



4.3.6 BIOMASS

Biomass is currently the largest source of renewable energy. Its carbon neutrality is debated, as described in discussion on biofuels in Section 4.8, where we provide a more comprehensive comment on biomass assumptions and sustainability. Loss of biodiversity tends to follow aggressive deforestation, for example. Consequently, policies tend to focus on better use of biomass residues and waste, hitherto left to rot and produce methane, a significant source of GHG. Support for such efforts will increase in many regions.

Biomass can take several different forms; for example, wood or charcoal used for heating and cooking, gas produced from waste, and liquid fuel produced from crops. We do not differentiate quantitatively between the various biomass forms, but use the gross energy output from its combustion as a metric. We do not model the sector's capacity other than in power generation, where we explicitly follow the building of biomass-burning power plants.

The world's use of biomass has grown 53% over the last 30 years. Figure 4.3.18 indicates that the growth will continue for the next two decades, thereafter levelling off. Although biomass has seen its share in energy supply declining until now, a gradual increase in its consumption implies that its current share of 10% will grow to about 11% in 2050. World biomass consumption is predicted to stay high, but will change composition considerably, from past poor efficiency associated with basic biomass use (for example, in cooking) to greater shares being derived from waste generation and modern crop-based biofuel.

In some regions, biomass is currently the dominant energy source in residential buildings. This will change, but direct biomass use will remain a considerable energy source in some regions.

Biomass contributes 6.4% of the energy mix in manufacturing, and this will decline to 4.1% in 2050, again with large regional variations (Figure 4.3.19). In electricity production, biomass usage will increase by 150%. However, the share is still small and will keep stable at around 2% of the global energy mix until 2050, but with large regional variations.

Transport's use, in the form of liquid biofuels, will experience the highest sector growth. It is set to increase by 280%, and will grow to be one of the major energy sources used for transport, especially in aviation and shipping. The major driver for this growth will be decarbonization policies, driven by CO_2 pricing. The regional composition will not change dramatically over the forecast period in our Outlook.

FIGURE 4.3.18

Biomass demand by region

Units: EJ/yr

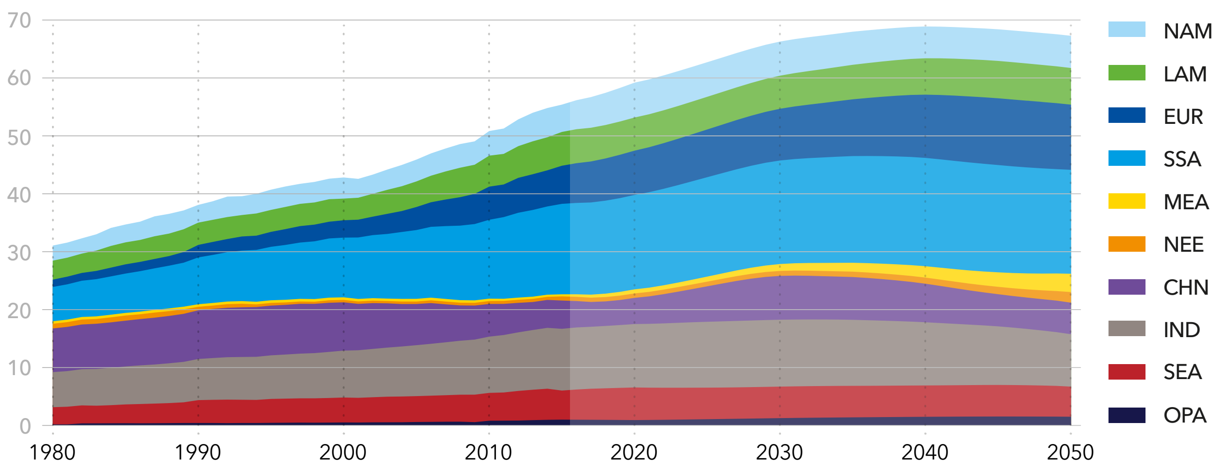
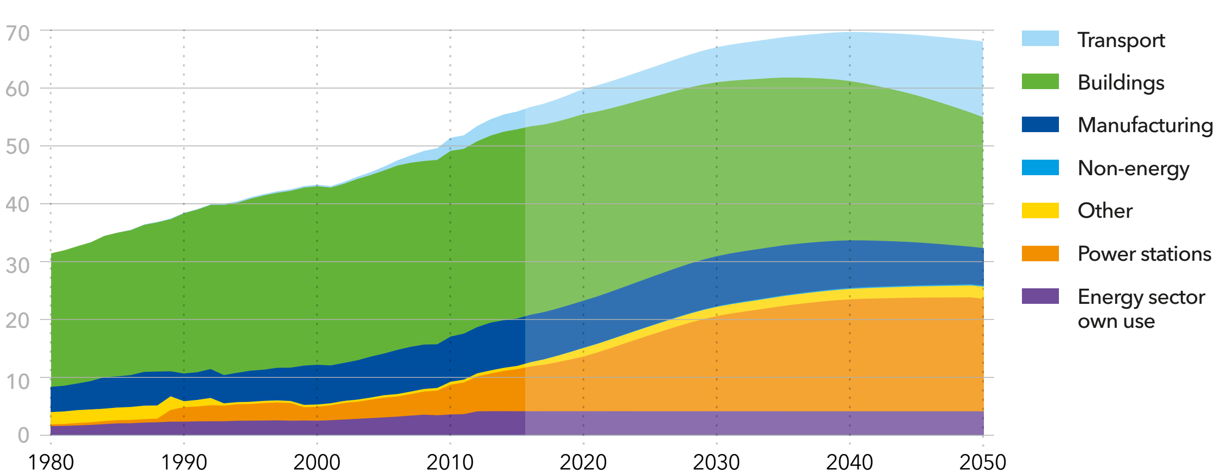


FIGURE 4.3.19

World biomass demand by sector

Units: EJ/yr



4.3.7 SOLAR PHOTOVOLTAIC

Solar PV has seen more rapid cost reduction than any other energy source over the last decade. Its initial uptake frequently reflects preferential treatment such as feed-in and net tariffing. Such support is unsustainable when solar PV grows in the coming years. Furthermore, it will not be needed.

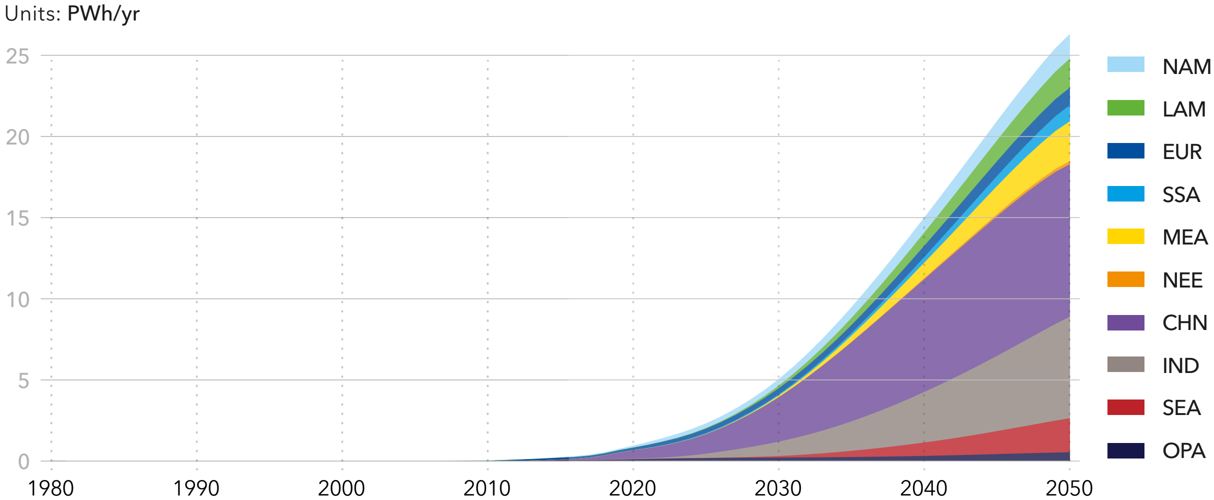
Increasingly, policies will require VRES to bear more of their own cost burdens to ensure reliable power systems. We see a bright future for small-scale local solar PV in housing and industrial facilities, generating electricity at the point of consumption, and thereby avoiding transmission losses and the need for infrastructure investment. We forecast that today's policies will remain in force, maybe even increasing incentives in some regions over the coming decade. We expect preferential treatment to decline beyond 2030 in most regions, and by 2040 in all, as solar PV becomes entirely cost competitive, even when storage and other costs are included. The market design in large parts of the world, typically designed for a dispatchable electricity world, is in flux. As we explain in our companion report (DNV GL 2018a), policies will have to accommodate a radically different generation system.

The rapid cost decline has resulted in solar PV now being the fastest-growing form of energy. However, it started from a very low base. Despite the strong rise over the last 10 years, it accounted for only 0.2% of world energy consumption in 2016. From 2016 to 2027, solar PV generation will increase by one order of magnitude, and then by almost another order of magnitude by 2050, as illustrated in Figure 4.3.20. This will bring generation up to 27 PWh/year (97 EJ/year), producing 40% of the world's electricity and 16% of its energy supply. While 27 PWh/year is connected to a grid in one form or another, 0.3 PWh/year is totally off-grid. Off-grid is a concept we

FIGURE 4.3.20

Solar PV electricity generation by region

Units: PWh/yr



have modelled only in the two regions with the lowest levels of energy access in 2016; the Indian Subcontinent and Sub-Saharan Africa. The uptake of off-grid solar in these regions is driven by the increasing cost competitiveness of a solar PV-battery combination versus grid extension and off-grid diesel generators. Long distances from the grid and low household consumption make it difficult for policy makers to justify economically central-grid extension to distant regions. Small-scale, off-grid solar can play a significant role in these regions, thus increasing electrification rates. The regional description of Sub-Saharan Africa in Section 5.4 gives more details of off-grid solar.

All regions, except North East Eurasia, achieve considerable solar PV generation in our forecast. Greater China is already (2016) overtaking Europe as the largest producing region, and will remain so for the entire forecast period, while the Indian Subcontinent will, within the next decade, take over as the second largest region.

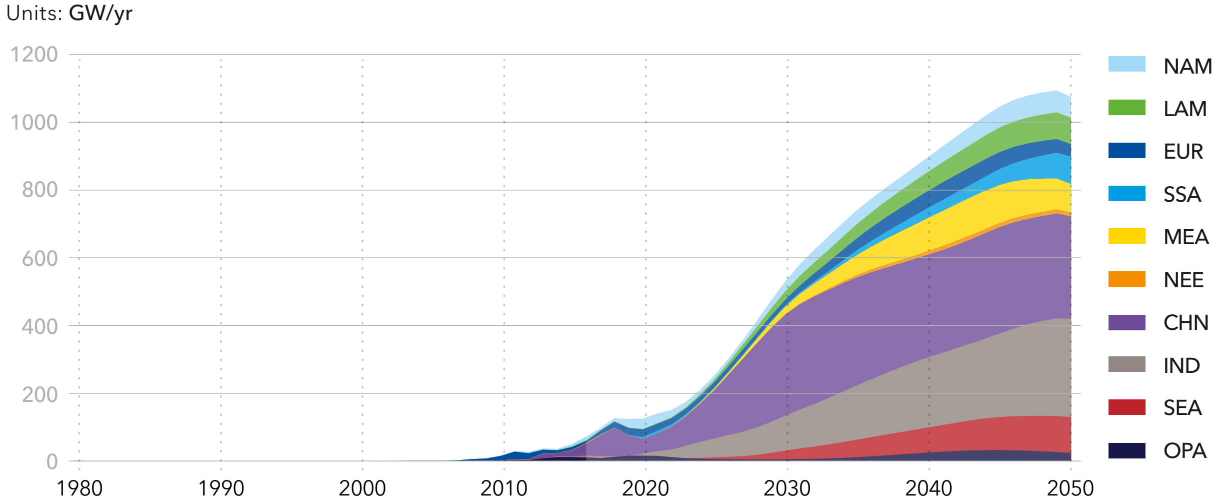
Newbuilds of solar PV obviously reflect those areas that will produce the energy. All regions except North East Eurasia will add a significant share of solar PV capacity. As illustrated in Figure 4.3.21, the absolute levels of installations will gradually increase to around 500 GW in 2030 and 1,000 GW towards the end of the period, around 10 times the current installations. Total installed capacity in 2050 is estimated to be 19 terawatts (TW), of which 7 TW is in Greater China and 5 TW in the Indian Subcontinent. The ETOM does not model offshore solar PV separately, but we can say that offshore solar PV is an opportunity near cities and for countries with high population densities.

As elaborated in our supplementary report, Power Supply and Use (DNV GL 2018a), we find that these high growth rates are consistent with the industry's capacity to expand, but we also elaborate on the challenges this creates for governments, regulators, and network operators.

FIGURE 4.3.21

Solar PV capacity additions by region

Units: GW/yr



4.3.8 SOLAR THERMAL

Solar thermal is used here as a placeholder for both solar water heating and for concentrated solar power (CSP), the latter being used only for power generation. Solar water heating has increased recently but is forecast to flatten out at about 1.5 EJ/year towards 2050.

As solar PV and wind costs continue to decline, CSP costs will not do so to the same degree. In addition, although some local uptake is expected – for example, in the Middle East and North Africa and Latin America – solar thermal is expected to provide only around 1.0 EJ/year of primary energy supply in 2050, a level similar to off-grid solar PV.

CSP, which includes the heating of liquids, involves implicit energy storage. This adds a dispatchable element to its electricity. Yet the technology remains so expensive that combinations of VRES and other storage and flexibility enhancements will provide less costly solutions to the VRES intermittency challenge.

4.3.9 WIND

Wind power shares some challenges with hydropower: loss of visual amenity and threats to wildlife. Nevertheless, we foresee policies favouring offshore wind strengthen in countries with limited land areas, and bypassing community opposition. Onshore wind will be more cautiously supported in some developed countries lacking the energy hunger of developing nations. As wind power spreads, costs will continue to decline for decades. Consequently, public subsidies will be reduced and disappear in many regions.

In our ETOM, we consider offshore and onshore wind separately. Although they are combined here, the split is evident under electricity generation, and in our companion report on Power Supply and Use (DNV GL 2018a), where offshore and onshore wind generation and production are analysed in more detail.

Wind generation has been growing steeply over the last few years, but from a very low base, and represented only 0.6% of the world's primary energy supply in 2016. Nevertheless, wind will continue to grow steeply, increasing tenfold in the next 20 years, and thereafter rising sharply towards the end of the forecast period. As illustrated in Figure 4.3.22, wind generation will represent 19 PWh/year (68 EJ/year) by 2050, 12% of the world's total primary energy demand and 29% of electricity production.

All regions will have considerable wind generation by 2050, with Greater China being by far the largest with 6 PWh/year, followed by Indian Subcontinent, and North America.

Wind installations are led by Greater China, and, compared with solar PV, are lower at the start of the forecast period but higher towards the end. As illustrated in Figure 4.3.23, annual capacity additions will reach 300 GW/year in 2030 and 500 GW/year in 2050, about ten times their 2016 levels. As explained in our companion publication (DNV GL 2018a), predicted growth rates are high, but are consistent with the industry's ability to expand. The total installed wind capacity in 2050 is 7 TW, with around one third being in Greater China. The companion publication also goes into the details of offshore wind and onshore wind, as the ETOM forecasts each separately.

FIGURE 4.3.22

Wind electricity generation by region

Units: PWh/yr

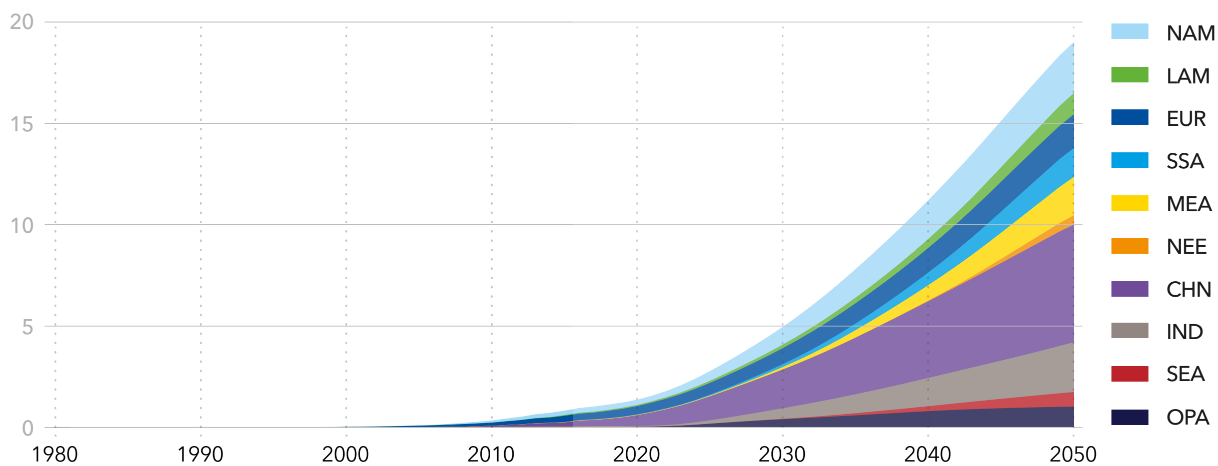
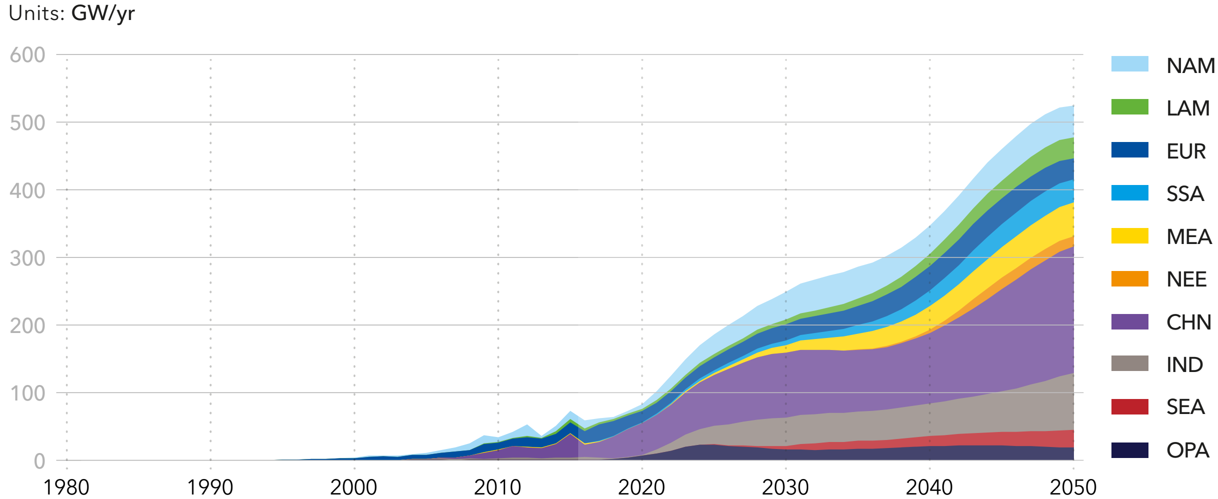


FIGURE 4.3.23

Onshore and offshore wind capacity additions by region

Units: GW/yr



4.3.10 GEOTHERMAL

Geothermal is a small energy source, accounting for only 0.5% of the world's energy use in 2016. A case could be made for oil and gas majors to explore geothermal projects as strategic synergies drawing on their drilling and large-project capabilities. In the absence of developments in this vein, or of other breakthroughs, little new development is expected, and geothermal energy will continue to be small throughout the Outlook period. It is largest in South East Asia and North America.

4.3.11 OTHER

Other energy forms, such as tidal and wave energy, are not quantified as part of the energy mix, but are discussed in Section 4.8 on technologies and their levels of maturity.

4.4 ENERGY INFRASTRUCTURE

With regards to energy infrastructure we have chosen to focus on electricity transmission and distribution grids and on LNG terminals. These reflect the growth necessary to facilitate electricity's increasing share of the supply mix, as well as gas becoming the dominant fossil fuel, with associated increased trading via the medium of LNG.

4.4.1 GRIDS

The energy transition entails a strong growth of electricity use. In our analysis, electrification implies 162% growth in electricity generation to 2050. Further, the move from a fossil based 'conventional' power production system to a system with orders of magnitude more (variable) renewables has implications for the grid. In our Power Supply and Use report (DNV GL 2018a), we define the many types of grid, including where cables are drawn (overhead, underground and underwater) and five classes of voltage that goes through them, and whether the current through them is direct or alternating.

Solar PV is frequently used close to where it is generated, and some argue that the net result of the electricity transition to renewables would entail less relative grid need because of this increased decentralization. However, there is also the opposite effect, that the many decentralized power sources will benefit from connections in times of surplus electricity, so as to sell it to the grid. We find this second effect much stronger and the grid expands faster than electrification and so – using our integral metric of gigawatt-kilometre (GW-km) – grows by 254% to 2050. The reason is that variable renewables are a particularly strong force for grid growth; a grid is needed that can handle its intermittence (the peak-to-average transmission load is far higher than for traditional generation), and thus dispatch power from areas that are in electricity surplus to areas that find themselves in shade and/or devoid of wind. Even with much fortified battery storage, peak shaving from demand response, and peaking plants, variable renewable energy sources (VRES) will benefit from being able to dispatch surplus electricity to faraway places. The expansion of the grid is shown in Figure 4.4.1, and the main expansion happens in Greater China and on the Indian Subcontinent. Further refinement of these results is given in the Power Supply and Use report (DNV GL 2018a). One interesting development discussed there is the rapid increase in the use of direct current (DC) power lines beyond 2030.

Global grid costs reflect the mixture of grid additions that come from the exponential growth in VRES supply as shown in Figure 4.4.2. Such grid reinforcements are negligible today, but will take off within a decade, and amount to about a sixth of the combined grid operational expenditure (opex) and capital expenditure (capex) costs by 2050. Note that after 2045, the grid starts to mature: capex costs are declining sharply, reflecting less demand-related grid capacity additions in such a slow grid-growth environment.

FIGURE 4.4.1

Grid capacity by region

Units: PW-km

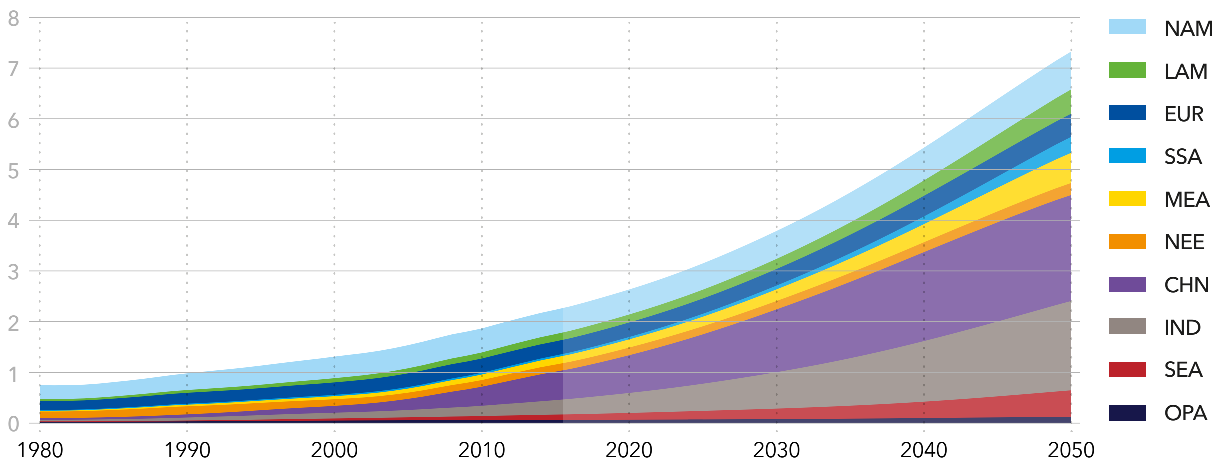
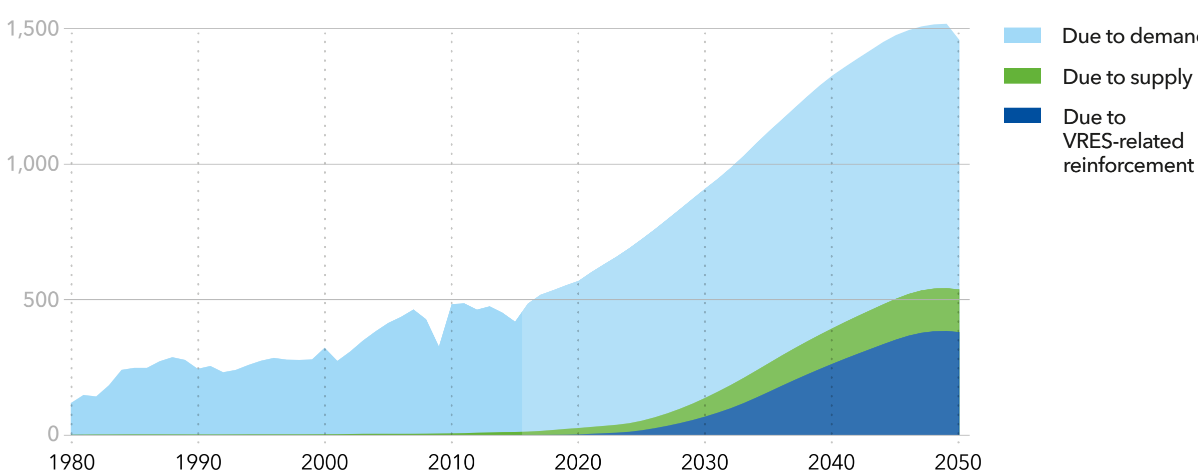


FIGURE 4.4.2

World grid cost by driver

Units: Bn$/yr



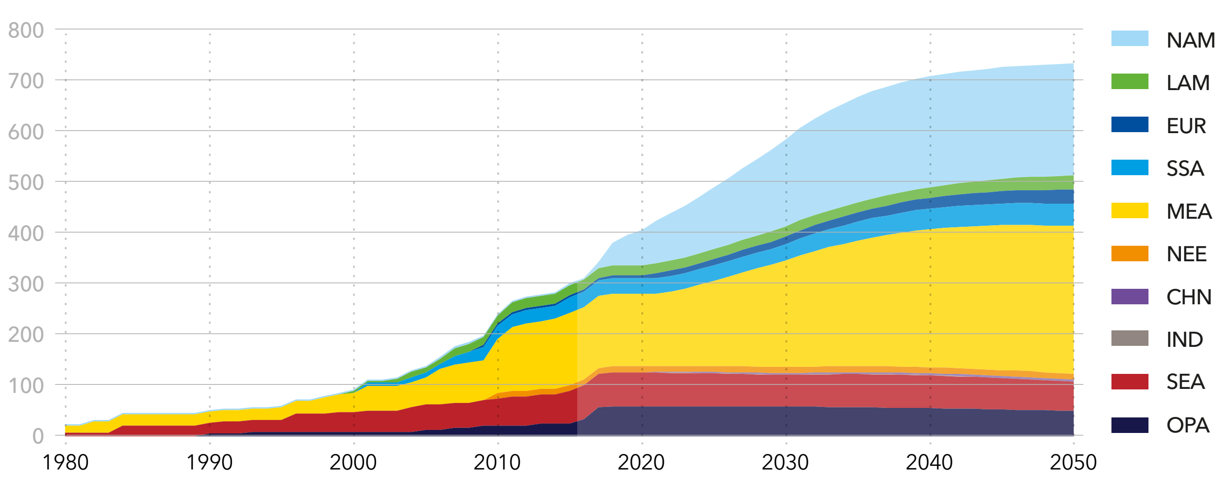
4.4.2 LNG TERMINALS

In 2016, global natural gas liquefaction capacity was about 310 Mt/year. This will grow quickly to plateau at about 707 Mt/year in 2040. Middle East and North Africa is currently where the main capacity resides. However, as shown in Figure 4.4.3, by 2040 North America will have grown from almost zero today to almost rival the capacity of the Middle East and North Africa. This reflects the phenomenal growth in North American gas output, where net additions will come almost solely from shale gas production.

FIGURE 4.4.3

LNG liquefaction capacity by region

Units: Mt/yr



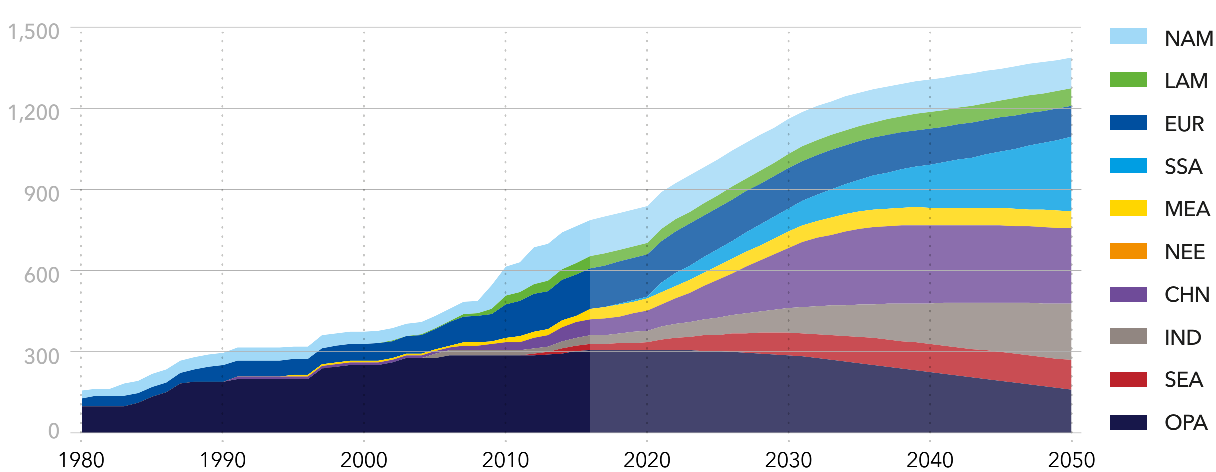
Global regasification capacity will also surge, doubling its capacity to 1390 Mt/year in 2050. Currently, OECD Pacific has about 40% of the global regasification capacity, almost all of which is in Japan. As illustrated in Figure 4.4.4, most regions will experience significant regasification-capacity growth in the period. Chinese capacity will increase more than four-fold, to about 280 Mt/year capacity, a level rivalling that of Sub-Saharan Africa and OECD Pacific.

In comparing liquefaction and regasification capacities, the latter is about twice the size of the former. This partly reflects unit investment costs, which are five times higher for a liquefaction plant than for a regasification plant. Thus, it is economical to have lower average annual capacity utilization, i.e. higher redundancy for regasification plants.

FIGURE 4.4.4

LNG regasification capacity by region

Units: Mt/yr



4.5 EFFECTS OF DIGITALIZATION ON THE FUTURE OF ENERGY

Digitalization is not a new phenomenon, but it is accelerating across all industries and intensifying as an integrated part of the energy system and the energy transition.

Although it is not possible to state precisely how digitalization will contribute to increasing the pace of the transition by a specific factor, this chapter includes a general overview of the effects of digitalization, and provides some specific examples of these.

Digital technologies will make power systems around the world more connected, intelligent, efficient, reliable, and sustainable. Smart grids are already improving the safety, productivity, accessibility, and sustainability of power systems, allowing utilities to deliver energy at the right time, in the right place, and at the lowest cost. In the next few years, emerging technologies, like data analytics, artificial intelligence, mobile- and cloud-based systems, and blockchain, will add layers of software and applications on top of the grid, making the grid ever smarter. This will bring more predictability and scalability, and new business models and services to grid operators, while also driving change in markets, businesses, and employment. As new business models are emerging, others may be on their way out.

Digitalization will lower costs of monitoring and control of all kinds of energy generation (fossil, nuclear, and renewables). In transmission and distribution networks, digitalization will help realize efficiency gains and a lower level of losses, for example through remote monitoring of assets, allowing them to be operated closer to their optimal conditions.

In asset-intensive energy value chains, digitalization will drive improved planning and more efficient predictive maintenance of assets, leading to lower investment requirements and operating costs.

In the power sector, digitalization is an important enabler of the energy transition. Smart metering and demand response will better match power demand and supply. This partly compensates for the variability of renewable power sources and is a key to our forecast of double-digit capacity growth of solar PV and wind power.

On the effect of demand response, we find a likely annual reduction in peak-to-average electricity demand of 4% by 2050. Our expectation was that this would improve the competitiveness of variable renewables and boost their uptake. However, with less peak demand, the total need for capacity will decline. This will reduce additional uptake of capacity, i.e. reduce the need for new renewables - a result that initially seemed counter-intuitive in our model, but logical in hindsight.

In electricity also, better and fully digital monitoring and subsequent management of grid capacity utilization will significantly reduce power losses. Thus, by 2050 such losses will decline by 25% from today's rate to only 3% in the most grid-efficient region (OECD Pacific) and 13% in the region with the highest losses (Indian Subcontinent).

Although ever-faster computers and other digital devices typically see declining energy use per computational operation for every new generation, the growth in volume is so strong that their total energy consumption will still increase. A particular case in point is bitcoin and other computationally intensive cryptocurrencies. Although next generation cryptocurrencies may be less computationally intensive, their proliferation will rely on power-consuming cooling. Similarly, the move to cloud-based solutions is also dependent on mountains of computing power, with corresponding electric-cooling needs. Although Moore's law enables computing power to grow much faster than corresponding energy needs, we forecast that recent energy consumption growth rates of about 4%/year (Sverdlik 2016) will be sustained. We thus expect a quadrupling of energy used for computational purposes to 2050.

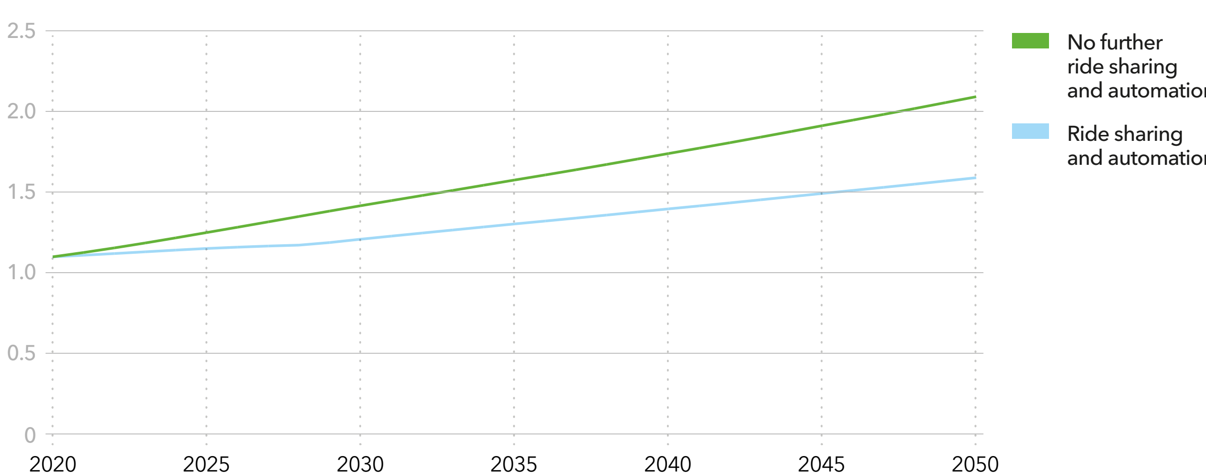
Digitalization will also impact transport. We have already witnessed ride-sharing with companies such as Lyft and Uber, both totally dependent on Global Positioning System (GPS) solutions matching vehicles with nearby transportation needs. Maritime transportation will experience better fleet utilization through similar applications. The short-term energy savings will be substantial.

Less common is the discussion of longer-term effects: greater asset utilization will shorten asset life expectancy and thus influence replacement rates towards faster asset renewal and uptake of new and ever–more energy-efficient technologies. This will be somewhat offset by the fact that greater asset utilization will also reduce the size of asset fleets, which will require less resource and energy use in their production.

FIGURE 4.5.1

The effect of digitalization on the global light vehicle fleet

Units: Billion vehicles



The combined effect on the light vehicle fleet of both increasing car-fleet automation (partially or fully replacing the driver with a robot and sensors) and widespread ride-sharing is an example of increased asset utilization. As explained in more detail in Section 4.1 on road transport, the effect of digitalization is about half a billion fewer light vehicles on the road in 2050, as illustrated in Figure 4.5.1.

Increased asset utilization will result in fewer vehicles, their average lifetime will shrink, and new and more fuel-efficient cars will be introduced faster. More rapid fleet rejuvenation results in a slower growth in energy consumption, as shown in Figure 4.5.2.

The improved availability of automated ride-sharing may, however, have unintended energy side-effects. Endpoint access to electric and automated cars, as currently piloted in many European cities, might not only replace energy-consuming passenger car use with energy-saving trains; it might also reduce walking and the use of energy-saving buses.

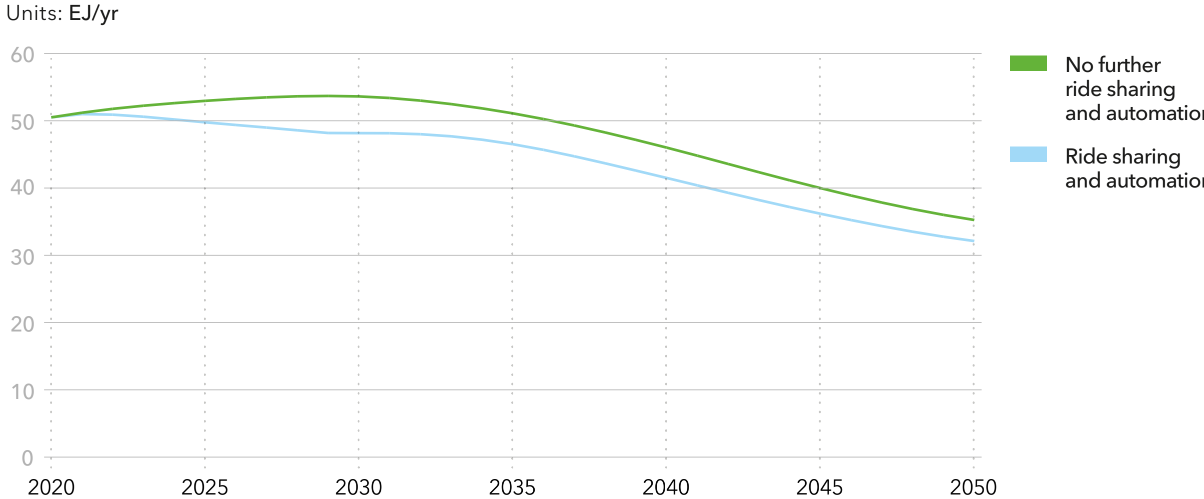
In maritime transport, we foresee a similar increase in fleet utilization. Better planning will reduce average sailing distances for a shipload by 3% from 2016 to 2050. More importantly, better information about when a vessel can on- and offload will significantly reduce time in port, and thus result in growth in fleet utilization by 11% over our forecasting period. In practice, part of this will be countered by slow steaming when possible, and also by relatively smaller fleets. All things considered, these trends point to an increased likelihood of achieving the IMO's target of reducing shipping GHG emissions by at least 50% over the period 2008–2050.

In the sections on the energy demand from buildings, we explain in greater detail about the energy requirements from data storage and communication.

FIGURE 4.5.2

The effect of digitalization on the global light vehicle energy demand

Units: EJ/yr



4.6 ENERGY EFFICIENCY

ENERGY INTENSITY

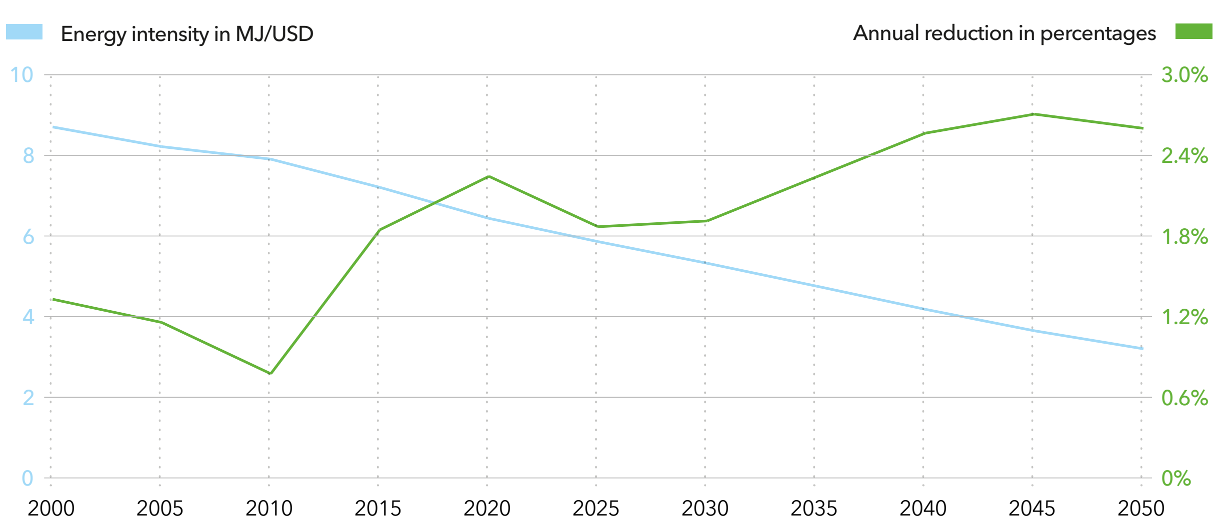
Energy efficiency can be measured in several ways, but we have focused on the world's energy intensity – units of energy per unit of GDP. This has been reducing on average by 1.1% per year for two decades. This decline has not been smooth, with spikes along the way. A case in point is the large reduction in energy intensity over the last five years, mainly driven by developments in China, where the economy continued to grow while growth in energy use slowed down considerably.

Over our forecast period, for which we foresee a 130% increase in global GDP and a 1% increase in overall primary energy consumption, energy intensity more than halves from 7.1 MJ/USD in 2016 to 3.1 MJ/USD in 2050. Thus, we forecast a shift from an historical annual improvement rate in energy intensity of 1.1% per year to an average of 2.3% per year over the Outlook period. Figure 4.6.1 shows how the annual improvement rate will vary, with continued high improvements, but highest towards the end of the forecast period. This average energy intensity rate is a result of a combination of sector-specific energy-efficiency inputs provided to the model.

The main reasons for accelerated intensity improvements are faster electrification of the energy system and the increased share of renewables in the power mix. In a steadily electrifying energy system, efficiency is greater and losses less, so less energy is needed to produce the same services. As the renewable share of electricity accelerates, energy intensity benefits from smaller losses in power generation. The acceleration in energy efficiency is underway: developments over the last five years prefigure our forecast for the Outlook period.

FIGURE 4.6.1

World energy intensity



Based on our results, the third measure of UN Sustainable Development Goal (SDG) #7 – to double the rate of improvement in energy efficiency – will not be met, although we are approaching those levels. More specifically, our estimates do not see the world more than doubling its energy efficiency to 2030, as our forecast 2.0% per year improvement in 2015–2030 is close to, but not double, the historic 1.3% per year in 2000–2015.

Over recent decades, developed countries have decoupled economic growth from increased energy use. More recently, China has followed suit as it enters a new stage of development. In our Outlook, the world follows the same overall trend, although some of the poorest regions will still be growing their energy use at the end of the forecast period.

SECTORAL ENERGY EFFICIENCY

Table 4.6.1. shows forecast energy-efficiency trends by sector, aggregated from regional estimates for each sub-sector.

Road transport will see a significant increase in energy efficiency, with the dual effect of steadily improving efficiency for combustion cars and introduction of highly efficient EVs. The average energy use per kilometre driven reduces linearly by 3.4%/year over the forecast period, giving a total reduction in energy use per km of 70% over the forecast period. This is obviously only possible if our forecast fleet electrification materializes, as the electric engine has far higher efficiency than the combustion engine. In aviation and maritime, there are also considerable efficiency gains of 2.0%/year per passenger trip and 1.0%/year per tonne-mile, respectively.

TABLE 4.6.1 ENERGY EFFICIENCY IMPROVEMENTS BY SECTOR

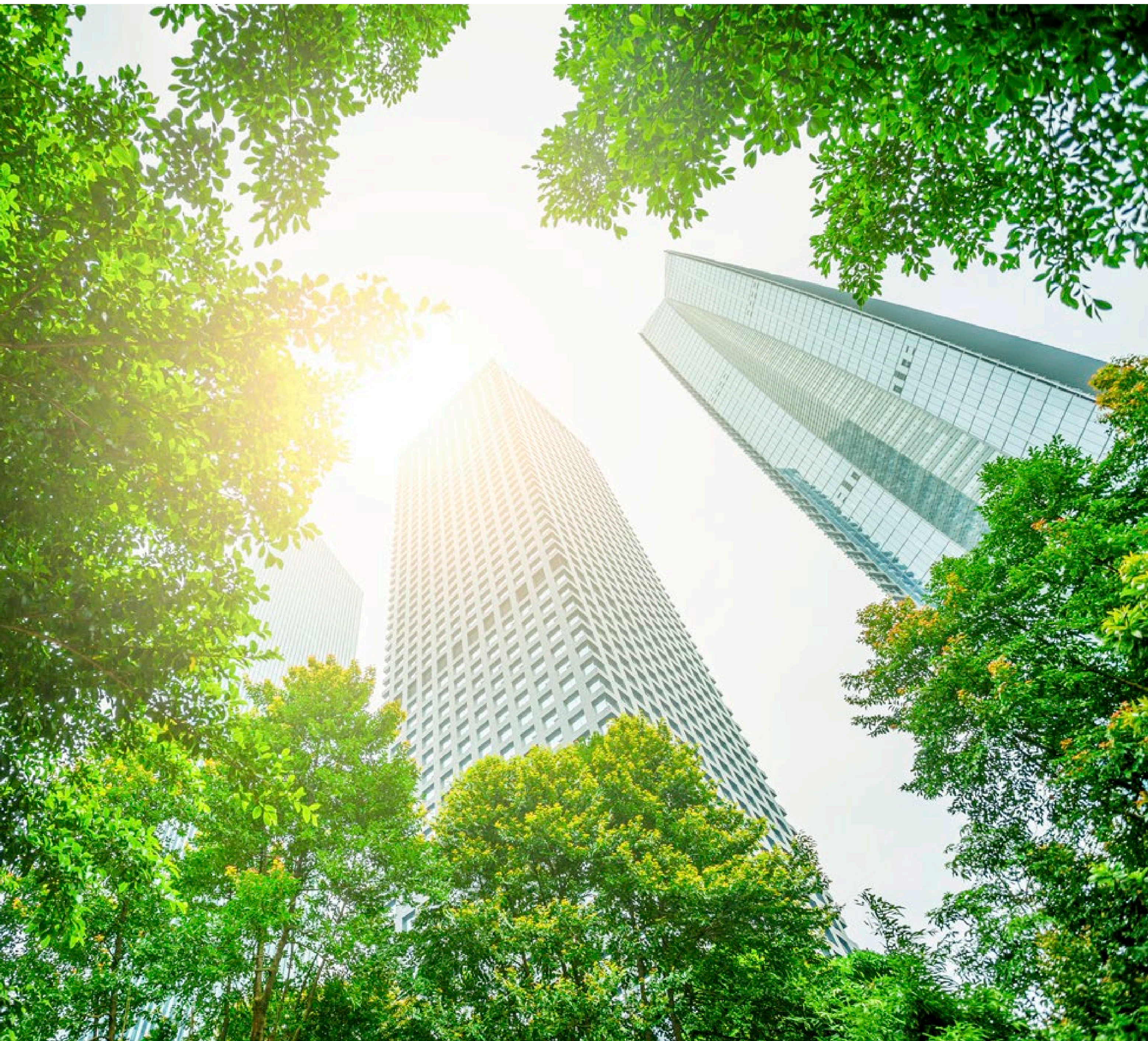
SECTOR	SUB-SECTOR	SECTORAL OUTPUT		ENERGY USED		IMPROVEMENT PER YEAR (2016-2050) CAGR*
		2016	2050	2016	2050	
Transport	Road	25T km	57T km	85 EJ	62 EJ	3.4%
	Aviation	3.6G pass-trips	8.8G pass-trips	12 EJ	15 EJ	2.0%
	Maritime	55T tonne-miles	76T tonne-miles	11 EJ	11 EJ	1.0%
Buildings	Space heating	1.9 EJ	2.5 EJ	45 EJ	40 EJ	1.2%
	Space cooling	0.5 EJ	2.6 EJ	5 EJ	17 EJ	1.5%
	Water heating	0.9 EJ	1.9 EJ	19 EJ	25 EJ	1.5%
	Cooking	1.5 EJ	2.3 EJ	24 EJ	16 EJ	2.4%
	Appliances & lighting	1.2 EJ	2.9 EJ	24 EJ	47 EJ	5.5%
Manufacturing	Base materials	31G tonnes	51G tonnes	79 EJ	77 EJ	1.6%
	Manufactured goods	13G tonnes	30G tonnes	46 EJ	79 EJ	0.9%

* CAGR: compound annual growth rate

SI prefixes G (giga-): a billion, T (tera-): a trillion, E (exa-): a quintillion

Energy use in buildings will increase by 23% from 2016 to 2050 while end-use services grow by 102%, so that energy efficiency rises 1.5% per year. The biggest efficiency improvement is in cooking, with an average improvement rate of 2.4% per year, mostly thanks to transition from traditional cooking. Water heating and space heating will experience growth rates of 1.5%/year and 1.2%/year, because of electrification, fuel switching, and technological improvements. The efficiency improvement in space cooling is expected to stay strong, with an average improvement rate of 1.5%/year. Finally, the overall efficiency improvement of appliances and lighting is expected to be 0.5%/year, although the rate for lighting on its own is believed to be much higher. These figures reflect many factors, including the fact that some of the economic growth will be used for improving comfort; through air conditioning and new appliances, for example. Nevertheless, the main driver for efficiency improvement the use of more efficient energy sources, such as electricity replacing the inefficient use of biomass for cooking and heating.

Energy use for production of base materials is almost flat, while output increases by more than 60%, representing an annual efficiency gain of 1.6%. The efficiency improvement of manufactured goods production is less, at 0.9%/year, but this includes a change in composition of manufactured goods. This occurs as increased wealth and new technologies push towards more production-intensive electronics and other appliances requiring more energy to produce than say, textiles, furniture, or general machinery.



4.7 ENERGY EXPENDITURES

THE GLOBAL EXPENDITURE PICTURE

Energy has a price tag. Two critical questions are whether the projected transition is an expensive one; and whether the total expenditures are affordable.

We calculate fossil expenditures by considering upstream and power-related capital expenditure (capex) and operating expenditure (opex) for oil, gas, and coal. For non-fossil energy expenditures, we calculate capex and opex related to power stations. "Power stations" here is used as a term that includes wind parks, solar PV – including everything from rooftop to utility scale parks – dammed or run-of-the-river hydropower stations, nuclear plants, and solar thermal and geothermal plants. Grid costs are not attributed to either fossil- or non-fossil, and consist of expenditures related to power lines, substations, and transformers.

We forecast global fossil expenditures to drop significantly from around USD 3.4 trillion in 2016 to USD 2.1tn in 2050 (measured in 2005 US Dollars). Non-fossil energy expenditures will exhibit a reverse trend, more than tripling from USD 0.69tn in 2016 to USD 2.4tn in 2050. The year 2044 will be the last when fossil energy expenditures will be higher than non-fossil expenditures. Due to rapid electrification of the energy system, grid expenditures will increase from USD 0.49tn in 2016 to USD 1.5tn in 2050.

Global energy expenditures will increase by 33%, from USD 4.5tn in 2016 to USD 6.0tn in 2050. But as GDP will grow by 130% over the same period, the energy fraction of world GDP will decline from 5.5% in 2016 to 3.1% in 2050, as shown in Figure 4.7.1.

> "By 2050, capex for renewables and grids will be 47% of global energy expenditures, up from 17% in 2016.

FIGURE 4.7.1

Energy expenditures as fraction of world GDP

Units: Percentages

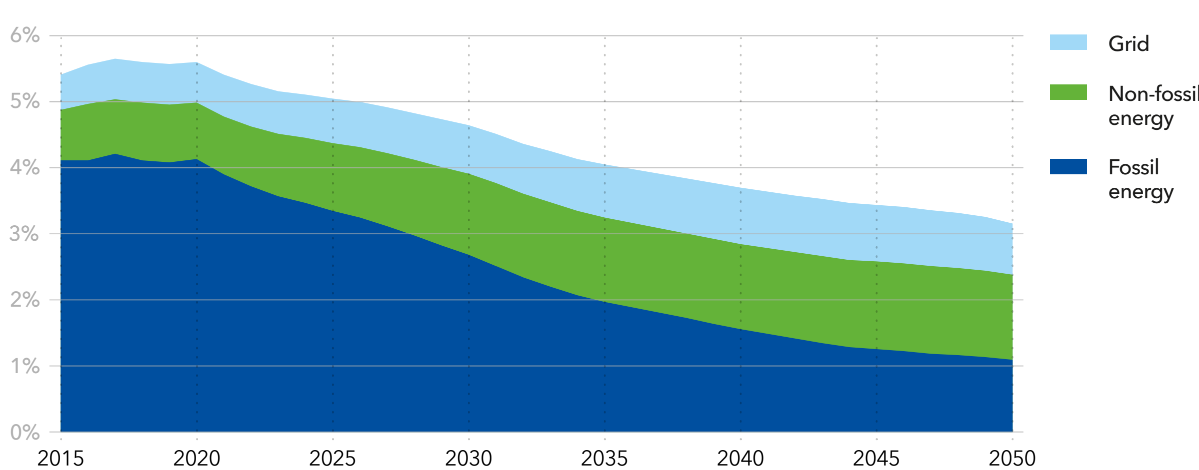


FIGURE 4.7.2

World energy capex by source

Units: Bn$/yr

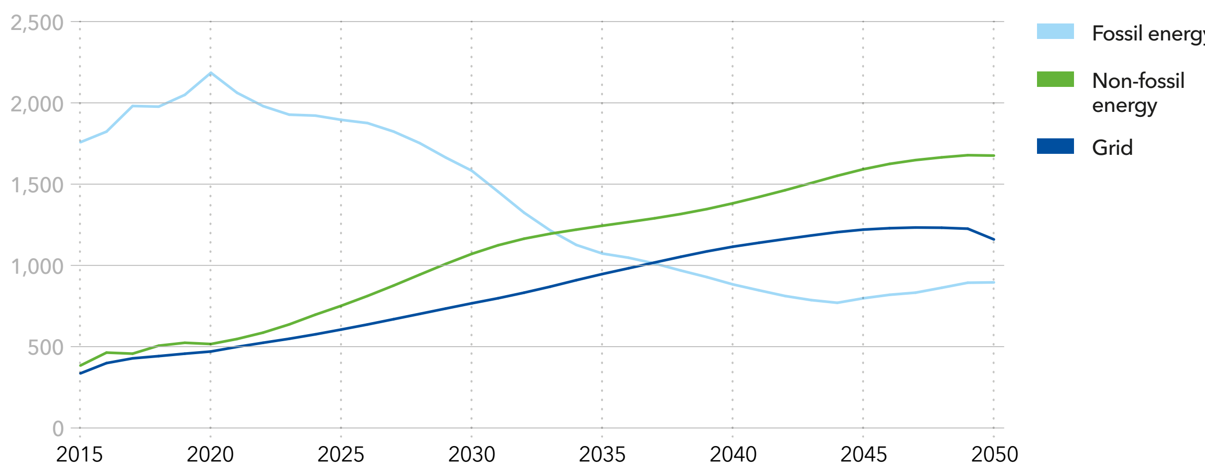


FIGURE 4.7.3

World energy opex by source

Units: Bn$/yr

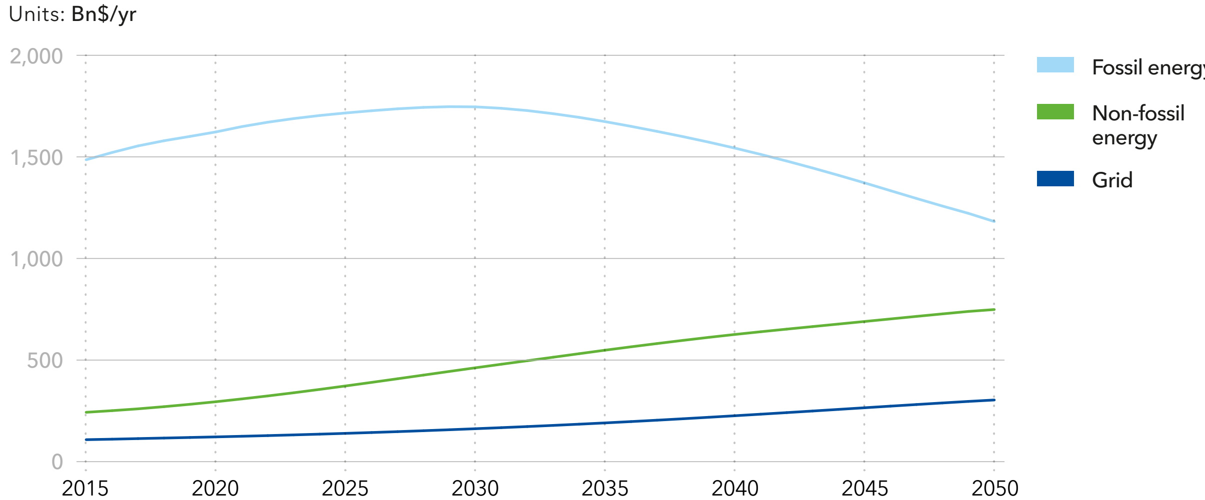


Figure 4.7.2 shows that fossil capex will peak in 2020. By 2034 non-fossil capex will be larger than fossil capex. Grid capex will also increase, although at a slower pace than non-fossil capex.

Fossil opex will peak nine years later than capex, as shown in Figure 4.7.3. Opex for non-fossils and grids will increase, but unlike capex they will never surpass or come close to fossil opex.

POWER EXPENDITURES

Power capex is calculated by multiplying capacity additions for each electricity source, with the unit investment cost. Figure 4.7.4 provides the global power capex by power station type.

Global capex in renewable power has lately been USD 250-300 billion (in 2005 USD) annually, with the lion's share going to wind and solar. Capex in fossil-based power has been USD 150-250bn annually, with the largest share going to new coal plants.

We forecast the world's electricity output to almost triple by 2050. However, power-station capex will grow even more, as expenditures associated with wind and solar – still experiencing declining unit costs – are mostly capital expenditure. Fossil power stations, in contrast, have substantial operating costs that are reflected in their LCOE, notably the fuel costs of the coal, gas, and oil that they burn. Figure 4.7.5 shows how global power-station opex start to decline beyond 2032 as the share of renewables in the power mix increases. Gas and coal will remain responsible for most of the power-sector opex, even by 2050, when their role in power generation is significantly reduced.

Figure 4.7.6 considers in more detail the regional outlook for capex in renewable power stations. Greater China is by far the largest regions in terms of renewable power-station capex, passing USD 200bn/year by 2024.

FIGURE 4.7.4

World power station capex by power station type

Units: Bn$/yr

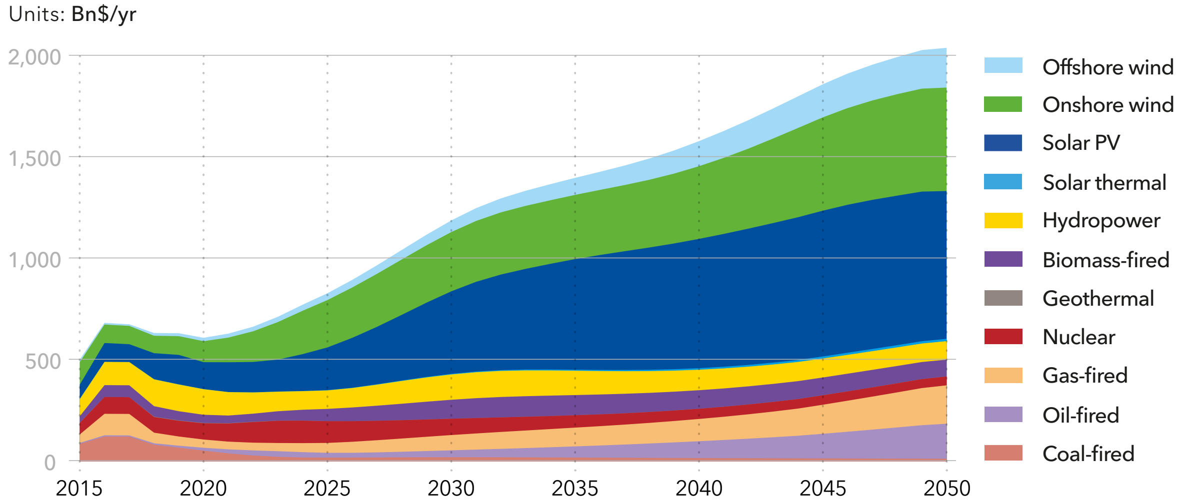


FIGURE 4.7.5

World power station opex by power station type

Units: Bn$/yr

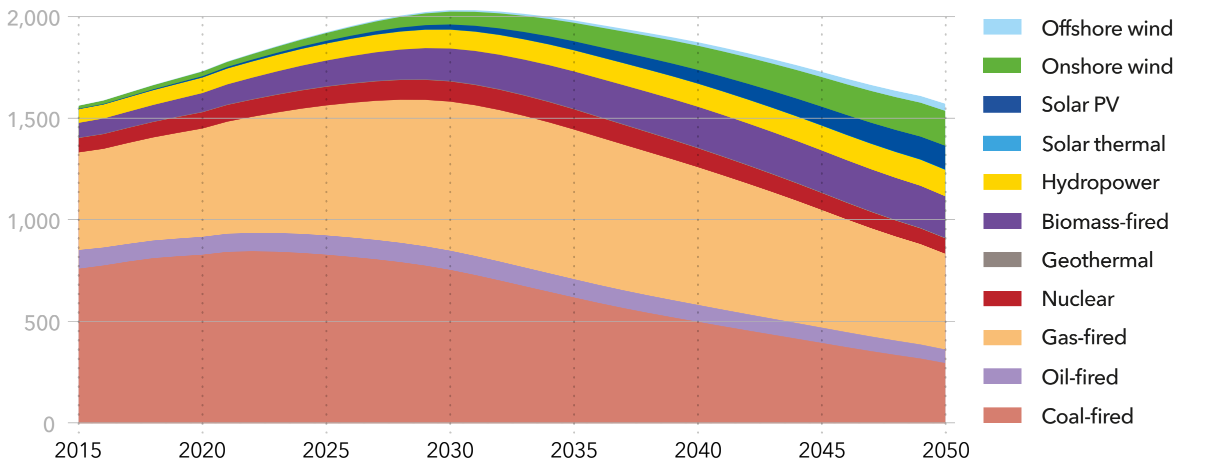
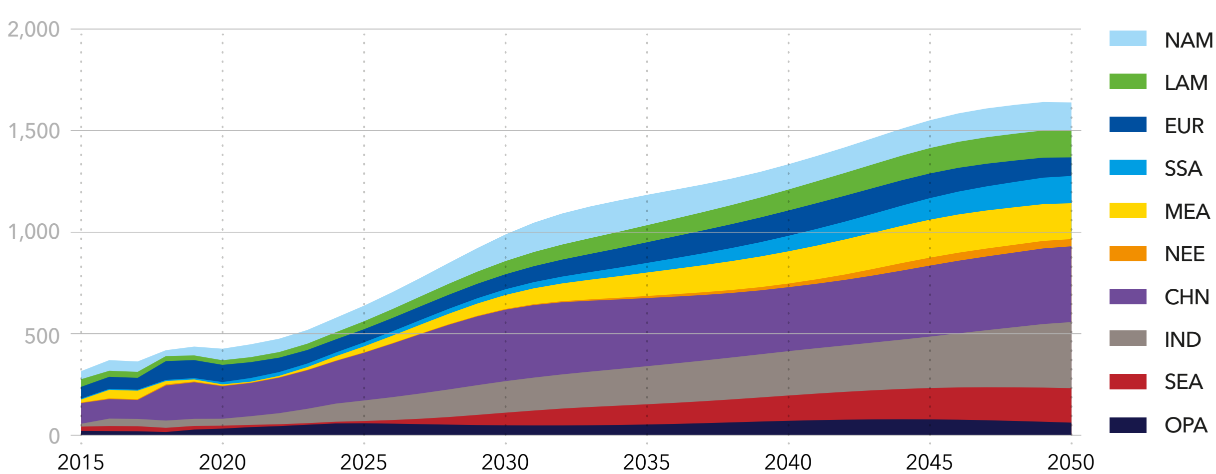


FIGURE 4.7.6

Renewable power station capex by region

Units: Bn$/yr



GRID EXPENDITURES

Due to rapid electrification of the global energy system, the infrastructure for supply must grow disproportionally, as VRES require grid reinforcements and must respond to higher peak loads.

Figure 4.7.7 shows the growth in grid expenditures for different types of voltage levels. These represent average values from a global perspective, and differ slightly by region: UHV is ultra-high voltage; eHV, extra-high voltage; HV, high voltage; MV, medium voltage; and LV, low voltage. The faster growth in expenditures on LV and MV power lines beyond 2030 is the result of the rapid growth in VRES supply, of which a significant share will not require a connection to higher-voltage transmission lines. Electrification of heat is another key driver here.

As can be seen from Figure 4.7.8, Greater China and the Indian Subcontinent will be responsible for 40-50% of global grids capex. Towards to the end of the century, capex starts to decline due to a slowdown in manufacturing electrification rates.

By 2038, Greater China will reach its peak of power-grid capex at USD 300bn. Grid capex on the Indian Subcontinent will also reach USD 300bn, but only in 2050. Power-grid opex will be significantly lower than capex, as can be observed in Figure 4.7.9, with the largest growth in Greater China and the Indian Subcontinent.

FIGURE 4.7.7

World grid expenditures by voltage level

Units: Bn$/yr

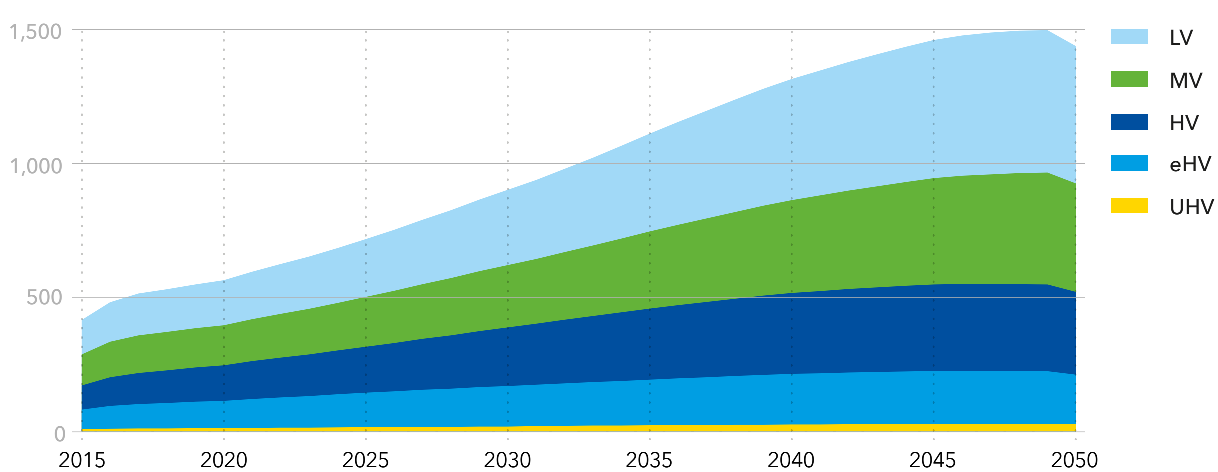


FIGURE 4.7.8

World grid capex by region

Units: Bn$/yr

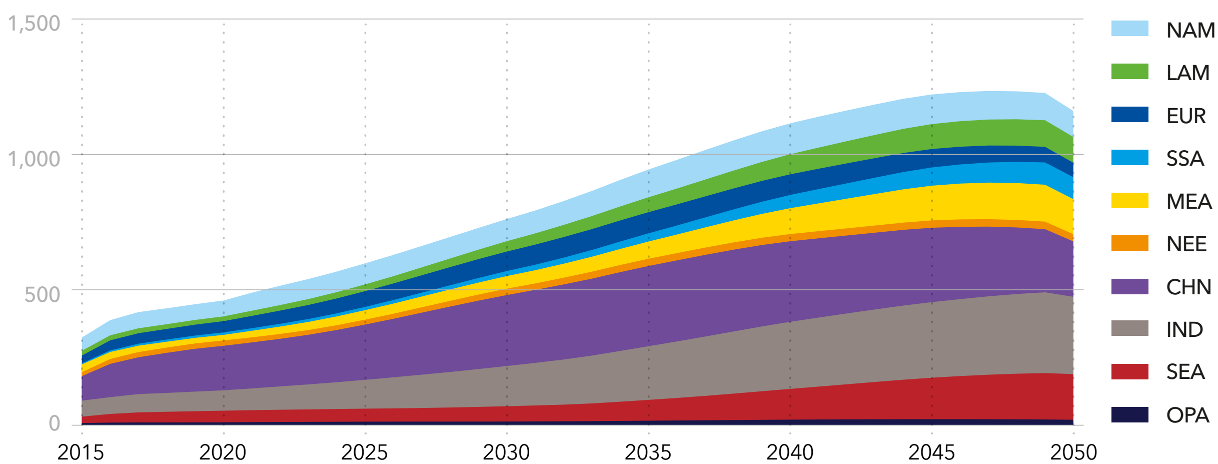
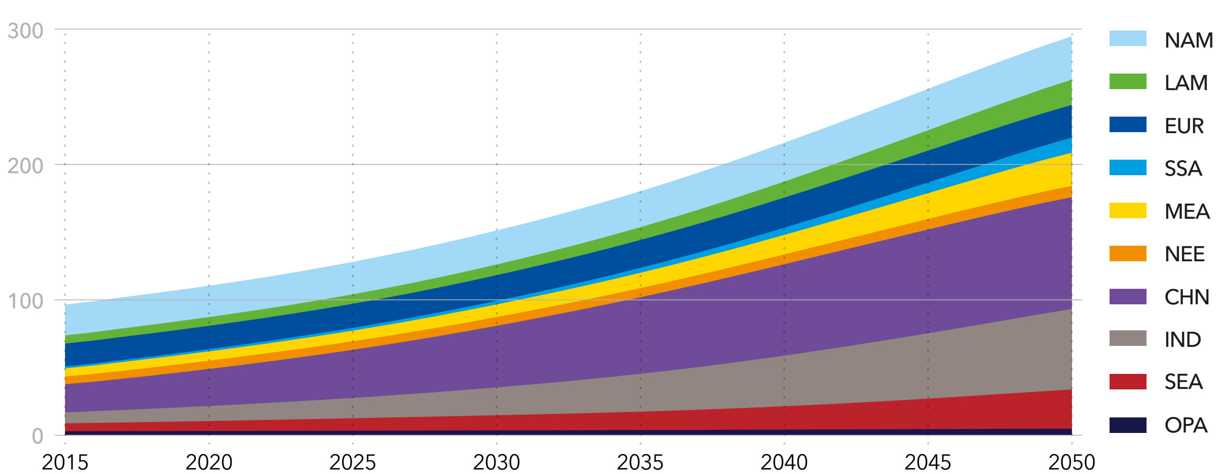


FIGURE 4.7.9

World grid opex by region

Units: Bn$/yr



4.8 TECHNOLOGIES AND THEIR MATURITY

The production, use, and carbon intensity of the energy system will be dependent on the development of energy technologies. In this section, we describe carbon capture and storage (CCS), biomass, emerging PV technologies, nuclear fusion, and ocean energy.

In our companion publications, we provide more details on industry-specific technologies. For example, energy storage, a key technology for the energy transition, discussed in detail in our Power Supply and Use report (DNV GL 2018a).

We base our forecast on proven technologies that have a certain maturity and commercial readiness for practical operation. Over the course of the next 35 years, we are likely to see breakthroughs in new technologies. Such advances could occur within nuclear fusion, superconductivity, synthetic fuels or other unknown areas. We have not accounted for such breakthroughs in our Outlook, and do not discuss them in detail here. We do, however, include two emerging technologies that do not have wide prevalence today: CCS and hydrogen. We include these in our model to understand their interplay with other parts of the energy system driven by market mechanisms.

HYDROGEN

Hydrogen (H_2) is already produced for various applications, notably in the manufacture of fertilizers from fossil sources, primarily natural gas. Indeed, the production of H_2 by electrolysis driven by hydropower was the basis of the growth of Norway as an industrial society (Ursúa et al. 2012). Yet H_2 use as an energy carrier is only just emerging. Several trends are contributing to this. One is increasing deployment of intermittent renewable energy sources, such as wind and solar PV. There will be times when supplied power will exceed underlying demand, and so prices will be very low. Battery storage, grids that connect to faraway places and users, as well as demand response will be used, and electrolytically-produced H_2 will complement this picture. This relatively cheap H_2 from electrolysis will play a key role in H_2 becoming an energy carrier by itself.

A second energy-supply change is the emergence of cost-effective removal of carbon dioxide (CO_2) in the steam methane reforming (SMR) process, whereby natural gas is converted to hydrogen. This process lends itself well, and some argue better than gas-fired power plants, to CO_2 removal.

Decarbonization of energy use is another driver for hydrogen as an energy carrier. We forecast significant uptake of H_2 in heavy vehicles, for example. Such use typically represents a halving of energy use per kilometre, compared with fossil combustion. If the manufacture of the H_2 thus used is emission-free, so is the propulsion. Moreover, the fuel-cell combustion afforded by H_2 is also free of local emissions. Both the global and local emission aspects also count currently when shipowners contemplate H_2 use for short-haul ferries.

Though a fuel cell electric vehicle (FCEV) is more efficient than traditional petrol or diesel vehicle propulsion, it is still not as efficient as a battery electric vehicle (BEV). Furthermore, FCEVs still require many moving parts, reducing the technology's advantage over conventional vehicles. Hence, we forecast a much more aggressive uptake of BEVs than of FCEVs, as all sales of light vehicles and short- to medium-haul heavy transportation will be battery electric by 2050. But the much higher energy density will afford H_2 a decarbonized niche in long-haul vehicle transportation.

Similarly, we foresee decarbonization of fossil heating, notably natural gas, by piping H_2 through existing gas infrastructure. The switch from distributing natural gas to H_2 is by no means trivial. Hydrogen combustibility is very different from that of natural gas, optimal piping is different, and appliances need to be replaced in homes. Heat processes in industrial sites will need to be redesigned, and equipment and machinery exchanged.

As H_2 is still an embryonic energy carrier, it is hard to validate our assumptions about future cost (reductions) and uptake. Our analysis has limited the uptake because we believe that three criteria must be met simultaneously for a region to embark on the H_2 journey:

- The existence of a recent, high-quality distribution system for natural gas that can also be used for hydrogen

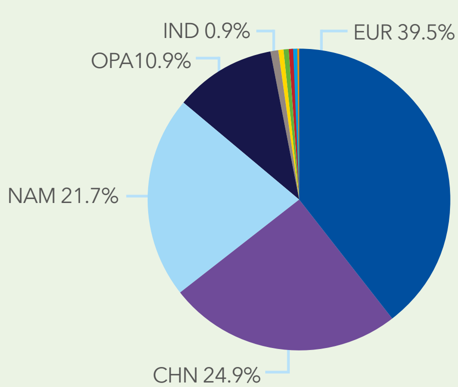
- A significant use of natural gas for heating
- A decarbonization push, as evidenced by expected growth of carbon prices.

We see four regions as meeting these criteria. In addition to the OECD-regions of North America, Europe, and OECD Pacific, parts of Greater China will also field a combination of H_2-based heating in buildings (including hot water, space heating, and cooking), and H_2-fueled long-haul vehicle use. Penetration will typically be in the 5–15% of energy consumption range in the relevant regions and sub-sectors. In addition, ships will also use H_2, but shipping penetration will be even lower. Based on DNV GL's Low Carbon Pathways model (2017), we forecast H_2 to reach a 3% share for short-sea shipping by 2050 (see DNV GL 2018c for the details of maritime fuel mix projections). As we show below, however, the H_2 growth from 2040 to 2050 is significant. In line with others (Shell, 2018), we would have forecasted a significant growth in H_2 production and use towards 2100. Over a longer timeframe, however, we would have had to investigate the conversion of industrial heat processes from fossil to H_2 or electric sourcing. We do not think such technologies will be implemented until the end of our forecast period.

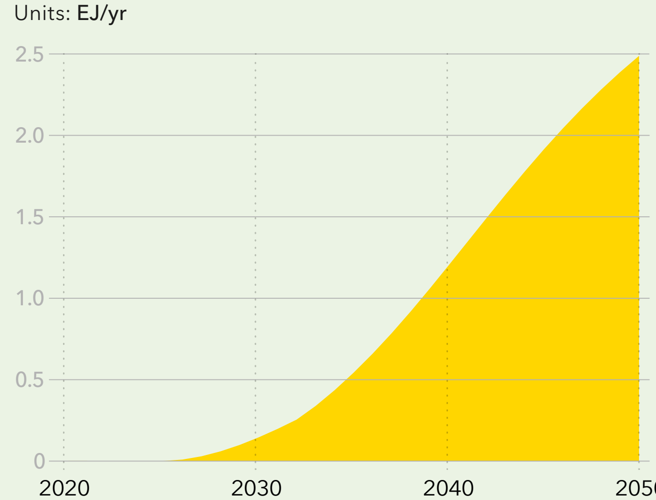
FIGURE 4.8.1

World hydrogen energy demand

Regional share in 2050



Units: EJ/yr



CARBON CAPTURE AND STORAGE

Carbon Capture and Storage (CCS) reduces emissions from large point-sources in energy production from fossil fuels and can capture CO_2 from industrial processes with high emissions as part of their production, such as the steel, iron, and cement industries. The development and use of CCS technology will depend on technical, economic, and policy incentives.

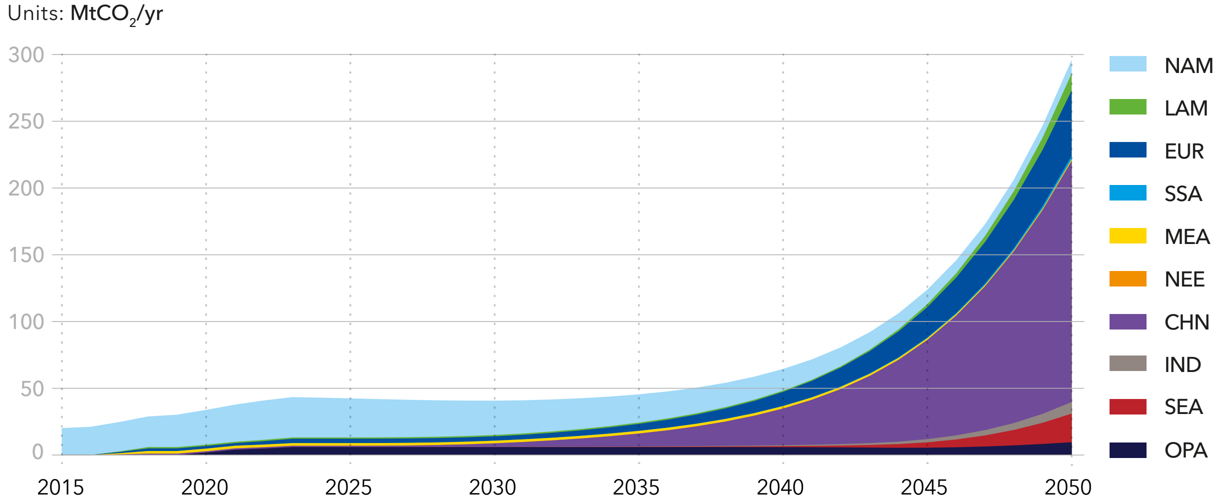
Combining the learning curves with current and upcoming plausible policy incentives, we forecast a globally installed capacity sufficient to capture 0.31 Gt CO_2 in 2050, corresponding to 1.5% of the global emissions that could potentially be captured. As described in Section 4.9, the uptake of CCS is sensitive to carbon prices and policies directed to reduce cost and increase implementation of CCS projects. Deployment will depend on growth in cumulative installed capacity, which will reduce costs through learning and scale effects. However, CCS will need an initial push to support pilot installations, which, combined with an increasing carbon price, will enable the growth take off after 2040, as indicated in Figure 4.8.2.

In our companion publication on Oil & Gas implications (DNV GL 2018b), we have included more details on CCS from the technology point of view, and more detailed results on CCS uptake.

FIGURE 4.8.2

Carbon emissions captured by region

Units: $MtCO_2/yr$



BIOMASS

Biomass used for energy production can take several different forms. Examples include wood or charcoal used for direct heat and cooking, gas produced from waste, and liquid fuel produced from crops, algae, or genetically-modified organisms.

The debate on biomass encompasses several dilemmas. Biofuels potentially contribute to food scarcity when productive agricultural land is used to produce energy crops, and biofuel can also potentially create local air pollution when it is burned. We forecast biofuel uptake to be limited to instances where energy uses are difficult to decarbonize through electricity, such as in aviation, deep-sea shipping, and long-distance trucking.

Combustion of biomass, including biofuels, is considered carbon neutral, and thus we count no carbon emissions from this. This is in line with Intergovernmental Panel on Climate Change assumptions where carbon contained in biomass is eventually absorbed from the atmosphere by photosynthesis if the burned plants are replaced with new plants.

Biomass used in the future will be different from today, and third and fourth generations of biofuels are likely to be subjected to close examination before they are approved for use, and labelled as sustainable and carbon neutral. Between now and 2030, it is likely that biofuels produced from unsustainable sources will be used, while the next generation of biofuels is being developed. Although this is a concern, this is accounted for under agriculture, forestry, and other land-use emissions. We therefore maintain the view that biomass, including biofuel, is carbon neutral, but we will follow the subject closely and update our calculations if research concludes otherwise.

EMERGING PHOTOVOLTAIC TECHNOLOGIES

Solar PV technology has matured significantly in the last decades. There has been a lot of focus on the reduction in price, but a related and relevant development is the increased efficiency of capturing sunlight. Initial efficiencies were below 10% in the 1970s and have now moved to about 45% for some multijunction cells. Recent developments in emerging PV technologies could transform the outlook and potential for solar PV to take an even bigger share of the global energy market. For instance, perovskite cells have been incorporated into solar cells only since 2009, but have moved quickly into high efficiencies. A point of additional relevance for the energy transition is that these cells can be produced at lower cost, printed thinly on materials, and can be manufactured at much lower temperatures compared to most common crystalline cells. Perovskite cells also use abundant and commonly available raw materials. While no industrial-grade perovskite solar PV cells yet exist, there is a lot of focus on being able to solve the major challenge of stability and durability. If these challenges can be overcome, then the technology holds transformational potential for rapid deployment at terawatt scale. As we note in our Chapter 6 - 'The Next Five Years' - developments in perovskite technology should be monitored closely for forecasting purposes. The image below is of Oxford PV's 156 mm x 156 mm perovskite-silicon tandem solar cells at the company's industrial pilot line, Germany.

OCEAN ENERGY

Several technologies for capturing energy from the oceans are currently being pursued (OES 2018), such as:

- Wave energy (shore line and open-sea devices)
- Tidal energy (stream and range devices)
- Ocean currents
- Ocean thermal energy
- Reverse osmosis

These technologies have been demonstrated, but none has progressed sufficiently to push the technology cost/learning curve down to a level at which ocean-energy technology has achieved significant deployment. During the period covered by this Outlook, one or more of these technologies may achieve a breakthrough such that they become cost competitive. However, to have any material impact on our predictions for our forecast period, they would have to grow at faster rates than other renewables, which is unlikely. They are often confined to areas where conditions are particularly favourable to the technology's operation, which makes the solution cost effective, but not enough to scale. Thus, we estimate that the global contribution from emerging ocean-energy technologies will be very small, and they are not included in our forecast.

NUCLEAR FUSION

For several decades, nuclear-fusion technologies have been discussed as a potential breakthrough, carbon-free nuclear energy source. Several promising research projects currently focus on smaller fusion systems being piloted. None has progressed very far, and no plant has yet produced more energy than is required to initiate and sustain a fusion reaction.

The potential lies in high power-generation density and uninterrupted power delivery with a small carbon footprint. The availability of fuel – primarily deuterium – is almost limitless. It is believed that at least 10 years are needed before a breakthrough may be achieved, and hence there is a minimum of 20 years before such solutions could scale. Our nuclear forecast are therefore confined to traditional fission technologies.

4.9 FORECAST SENSITIVITIES

We acknowledge that the energy future that unfolds may be different from the one we envisage. We have consequently analysed how our forecast will deviate from the base-case prediction under differing parameter assumptions.

The assumptions analysed are summarized in Table 4.9.1 below, where we sort uncertainty into three classes: macro, technology, and behavioural. Our description of sensitivities is limited to the nine model inputs that we emphasize in bold text. The choice is based on a combination of quantitative significance and qualitative assessment of the uncertainty of the model inputs.

Our approach is to vary assumptions by increasing or decreasing them by a third (33%), except for population, for which we use two UN forecasts for comparison. The 33% has been chosen as a value that is large enough to have a significant impact on model outputs, while still being within a realistic uncertainty range. We do not test multiple sensitivities at the same time as the permutations are too numerous.

As a reference for this chapter, Table 4.9.2 summarizes several important model outputs from our Outlook. In later tables discussing sensitivities, we present the table values as percentages representing the fraction of deviation from the base case by the end of the reference period.

For some parameters, a 33% variation compared with the base assumption is more likely than for others. The absolute changes, therefore, say more about the model sensitivity to changes in assumptions than about which parameters are most likely to alter the transition that we currently forecast.

TABLE 4.9.1
Model inputs sensitivity test

Macro	Technology	Behavioural
Population	**Energy efficiency**	**Electric vehicle uptake**
Productivity	Learning rates: oil and gas	**Electrification rates**
Carbon price	Learning rates: batteries, solar, and wind	Lifetime of power plants
Renewables subsidies	**Learning rates: carbon capture and storage**	**Lifetime vehicles**
Coal price	Plastics recycling	Lifetime buildings
Share of secondary sector in economy		Lifetime building equipment

TABLE 4.9.2
Energy Transition Outlook 2018: Our base forecasts

	2016	2050
Final energy demand (EJ/year)	403	451
Electricity	75	205
Primary energy supply (EJ/year)	581	586
Coal	163	60
Crude oil	168	86
Natural gas	140	149
Nuclear	30	28
Biomass	56	67
Hydropower	14	24
Solar photovoltaic	1	96
Wind	3	68
CO_2 emissions (Gt/year)	36	20
CCS (tonnes CO_2 removed and stored)	21 million	300 million
Fraction of emissions captured	0.1%	2.6%
EV share light vehicles	0.1%	88%
EV share heavy vehicles	0.1%	62%

MACRO ASSUMPTIONS

POPULATION

The 2017 UN update on population includes a median forecast of 9.77bn people in 2050. However, as explained in Section 2.2, our base case foresees a lower population than this, at 9.18 billion people. The difference is due mainly to our belief that increased female education and urbanization will lower fertility rates faster than in the UN forecast. The UN further provides a low projection for each country in the world, and these add up to 8.75 billion in 2050. In our view, the UN's median forecast is a high one. Therefore, we test the UN low projection as our low case and the UN median projection as our high case.

– ETO low case: Population grows to 8.75bn in 2050 (UN low estimate)

– ETO base case: Population grows to 9.18bn in 2050

– ETO high case: Population grows to 9.77bn in 2050 (UN median estimate)

As seen in Table 4.9.3, a 4.7% reduction in population by 2050 will result in a 5% lower energy demand, and this decrease will be split quite evenly between all energy sources, except for nuclear and hydropower. This is because not all regions' populations are adjusted with the same rate and regions' energy mixes vary. A 6.4% increase in population results in 5% more energy demand by 2050. Solar PV is twice as sensitive (+9%) as most other power station types.

TABLE 4.9.3
ETO Model Sensitivity to Population (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	-5%	+5%
Electricity	-5%	+5%
Primary Energy Supply	-5%	+4%
Coal	-5%	+3%
Crude oil	-5%	+4%
Natural gas	-5%	+4%
Nuclear	0%	+1%
Biomass	-6%	+4%
Hydropower	-2%	+0%
Solar PV	-7%	+9%
Wind	-4%	+4%
CO_2 emissions	-5%	+4%

>> Bigger or smaller populations will result in an energy system demanding proportionally more or less energy, respectively, but will not change the pace of transition or the energy mix significantly.

PRODUCTIVITY

Besides population, productivity is the main driver for economic activity, as it is the output achieved per worker, measured here in GDP per capita. Our base-case forecast predicts GDP/capita growth rates to decrease as the GDP/capita of respective regions increases. There is a decline in productivity growth as there are larger possible automation and other productivity gains within the primary and secondary sectors than in services, the tertiary sector. Over the forecast period, the tertiary sector's share of economy will grow faster in more regions, with correspondingly slower GDP growth.

- ETO low case: Regional GDP/capita forecast is 33% lower than base case by 2050
- ETO base case: Regional trends (Figure 2.3.1, page 74)
- ETO high case: Regional GDP/capita forecast is 33% higher than base case by 2050

As seen in Table 4.9.4 below, a 33% reduction in productivity growth compared with our base-case estimate leads to a 6% reduction in energy demand by 2050. Crude oil use is 8% lower than in our base case, which could be explained by fewer people globally being able to afford car ownership. Solar PV is the energy source most impacted by the lower demand for electricity. Productivity growth being 33% higher than base case will have the opposite effect; it will increase energy demand by 6% and primary energy supply by 7%. Again, solar PV is very sensitive to a GDP/capita increase, growing a full 13% in the high case.

TABLE 4.9.4
ETO Model Sensitivity to GDP/capita (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	-6%	+6%
Electricity	-8%	+8%
Primary Energy Supply	-6%	+7%
Coal	-7%	+8%
Crude oil	-8%	+8%
Natural gas	-5%	+5%
Nuclear	-1%	+1%
Biomass	-1%	+2%
Hydropower	-1%	+1%
Solar PV	-12%	+13%
Wind	-7%	+7%
CO_2 emissions (Gt/year)	-7%	+7%

>> The effects of a change in GDP/capita growth are like those seen for population, with lower or higher growth resulting in an energy system that demands a little more or less energy respectively, but will not alter the pace of transition or the energy mix in unexpected ways.

SHARE OF SECONDARY SECTOR IN ECONOMY

There are large differences in energy use between different sectors within the economy. The secondary sector is the most energy intensive, requiring large amounts to produce industrial goods. We assume a decreasing share of the secondary sector as a region becomes richer. In our model, we expect this trend to continue and henceforth to impact all regions accordingly. This shift can be seen already in the Greater China region, where the secondary sector declines in relative terms as the tertiary sector grows.

- ETO low case: Regional share of secondary sector forecast is 33% lower than base case by 2050
- ETO base case: Regional trends (see Figure 4.1.20, page 134)
- ETO high case: Regional share of secondary sector forecast is 33% higher than base case by 2050

As seen in Table 4.9.5, a reduction in the share of the secondary sector in the economy will have a large impact on energy demand and CO_2 emissions in 2050, as compared to the base case. There will be significantly lower demand for fossil fuels, especially coal and natural gas, which are the most important energy sources in industry. A higher share for the secondary sector will have the opposite effect and leads to the forecasting of a much more energy-intensive world by 2050. The most surprising finding is that solar PV is, again, very sensitive.

CARBON PRICE

The world might be more concerned with emissions as policy makers pursue a climate change outcome of 'well below 2°C'. If so, carbon prices could grow faster than we assume. We therefore investigate the sensitivity of the energy system to higher-than-expected growth rates of regional carbon prices. In the same way, we also test for a

TABLE 4.9.5
ETO Model Sensitivity to Share of Secondary Sector (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	-14%	+14%
Electricity	-14%	+13%
Primary Energy Supply	-13%	+13%
Coal	-15%	+15%
Crude oil	-11%	+11%
Natural gas	-15%	+15%
Nuclear	-2%	+2%
Biomass	-8%	+8%
Hydropower	-2%	+2%
Solar PV	-21%	+22%
Wind	-11%	+10%
CO_2 emissions	-14%	+14%

>> A 33% shift in size of secondary sector is considered a large shift, and it is not surprising that this will cause large changes and can alter the pace of the energy transition.

situation in which climate change is less important to regional leaders, and decrease the expected trends.

- ETO low case: Regional carbon price forecast is 33% lower than base case by 2050
- ETO base case: Regional trends (see Figure 2.6.1 , page 91)
- ETO high case: Regional carbon price forecast is 33% higher than base case by 2050

As seen in Table 4.9.6, modestly lower or higher carbon prices will not impact energy demand by the end of our reference period. There is an important change in the energy mix, however. In the case of lower than expected carbon prices, coal use will be 8% higher and CO_2 emissions 4% greater than in the base case. With higher than base-case carbon prices, coal use will be only 4% lower, but CO_2 emissions decrease by 9%. That is the result of a large increase in CCS capacity, capturing a higher proportion of emissions. The amount of carbon captured shows large variations with carbon price. In the low case, it is only a twelfth of the amount captured in the base case. In the high case, it is seven times that which is captured in the base case. It is worth noting that a 33% change in carbon price is not seen as a large deviation, and that a much larger deviation could happen. In Chapter 8, we discuss how a doubling of carbon price would not be enough to close the gap towards 2°C, but it would certainly have a large influence on the energy mix and overall emissions.

TABLE 4.9.6
ETO Model Sensitivity to Carbon Price (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	0%	0%
Electricity	0%	0%
Primary Energy Supply	0%	+1%
Coal	+8%	-4%
Crude oil	-1%	+2%
Natural gas	+1%	0%
Nuclear	-1%	+1%
Biomass	-4%	+4%
Hydropower	-1%	+1%
Solar PV	-3%	+2%
Wind	+1%	-1%
CO_2 emissions	+4%	-9%
CCS (in tonnes of CO_2)	-92%	+600%
Fraction of total emissions captured compared to base case	-92%	+669%

>> The effects of a modest change in regional carbon prices will not alter energy demand much, but there will be a change of the energy mix.

TECHNOLOGY

ENERGY EFFICIENCY

Our base case foresees significant improvements in energy efficiency; for example, in vehicles, ships, trains, airplanes, buildings and the manufacturing sector. In our sensitivity test, we have systematically decreased or increased these different energy efficiency improvements moving towards the end of our reference period.

- ETO low case: Regional energy efficiency forecast is 33% lower than base case by 2050
- ETO base case: Regional energy efficiency trends (see Table 4.6.1, page 184)
- ETO high case: Regional energy efficiency forecast is 33% higher than base case by 2050

As seen in Table 4.9.7, energy efficiency is hugely important for total energy use. This is partly because it applies to many different sectors within the economy. Final energy demand increases by 32% when we vary our assumption for growth in energy efficiency by 2050 by reducing it 33% compared with the base case. This also means that there will be more demand for all types of energy, except for nuclear and hydropower. In the case of higher than expected energy efficiency, the effect is not symmetrical; we will only see a 17% decline in final energy demand. This asymmetry can be easily explained by means of a simple calculation. For any process, decreasing the energy efficiency by a third, will result in an energy use that is 4/3 times the original energy use. However, the energy necessary when the energy efficiency is increased by a third is only 2/3 times the original. So, while the energy demand increases by 25% in the first case, it decreases by 50% in the second. Since we only gradually adjust the energy efficiencies towards a 33% change in 2050, the overall effects are smaller. It should be added that a 33% adjustment in energy efficiency is large and would require a significant change in assumptions from our base case.

TABLE 4.9.7
ETO Model Sensitivity to Energy Efficiency (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	+32%	-17%
Electricity	+35%	-18%
Primary Energy Supply	+30%	-16%
Coal	+25%	-13%
Crude oil	+26%	-13%
Natural gas	+31%	-17%
Nuclear	+4%	-3%
Biomass	+29%	-16%
Hydropower	+5%	-4%
Solar PV	+53%	-27%
Wind	+29%	-15%
CO_2 emissions	+27%	-14%

>> If the energy efficiency improvement is increased by another 33% compared to our current forecast, the world will need 17% less energy by 2050. Although this will have a very significant impact, the energy mix would not change considerably.

CCS LEARNING RATES

CCS uptake is low in our Outlook, and it is relevant to ask what it would take to increase it. There is considerable uncertainty regarding cost-learning rates for CCS. Except for the oil and gas sector's reinjection of CO_2 into wells to increase production, most CCS capacity is in pilot installations. As with other technologies, costs will decline as cumulative installed capacity increases, due to learning effects. In our base-case forecast, we have calibrated CCS learning rates based on historical data on related technologies for the removal of sulphur dioxide (SO_2) and nitrogen oxides (NO_X).

In our sensitivity test, we have decreased and increased base-case CCS learning rates for both capital and operating and maintenance (O&M) related costs.

- ETO low case: Cost learning rates 33% lower from the year 2018
- ETO base case: Capital cost learning rate of 17% and O&M cost learning rate of 6%
- ETO high case: Cost learning rates 33% higher from the year 2018

As seen in Table 4.9.8, the model outputs are not sensitive to lower learning rates, which is logical as the technology already struggles to become competitive with current learning rates. Higher learning rates do not alter energy demand towards 2050, although there is a small change in the energy mix, with coal use increasing by 3%. This coal use happens in parallel with a 7% reduction in CO_2 emissions.

The amount and proportion of CO_2 captured is greatly affected by CCS cost learning rates, capturing as little as a fifth and as much as seven times more than in our base case when we vary our assumptions as described.

TABLE 4.9.8
ETO Model Sensitivity to CCS Learning Rates (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	0%	+1%
Electricity	0%	+3%
Primary Energy Supply	0%	+1%
Coal	0%	+1%
Crude oil	0%	0%
Natural gas	0%	0%
Nuclear	0%	0%
Biomass	0%	0%
Hydropower	0%	0%
Solar PV	0%	0%
Wind	0%	0%
CO_2 emissions	+1%	-7%
CCS (in tonnes of CO_2)	-80%	+600%
Fraction of total emissions captured compared to base case	-80%	+592%

>> Higher CCS learning rates would increase the capture of CO_2 dramatically, but starting from a low level, the impact on overall emissions is limited.

BEHAVIOURAL CHANGE

ELECTRIFICATION RATES OF BUILDINGS AND MANUFACTURING

There is significant potential in improving energy intensity through electrification. Although it is less than through a decarbonized power mix, even without renewables penetration, it will lead to a lower-carbon footprint, health benefits, and reduced emissions. There could be stronger drivers for faster electrification than we envisage in our forecast; for example, if wholesale electricity prices are reduced as a result of the larger volumes of zero marginal-cost renewables and electricity becomes more competitive against natural gas or coal. On the other hand, the uptake of electricity that we forecast might meet resistance. It could be argued that the base case is uneconomic because, for example, it puts a significant proportion of gas grids to households out of business. Similarly, electrification of manufacturing might not be technically or economically viable for large-scale industrial processes. If so, electrification rates could be significantly lower.

- ETO low case: Regional electrification forecast is 33% lower than base case by 2050
- ETO base case: Regional Electrification trends (see Figure 4.1.16 and 4.1.25 , pages 128 and 139)
- ETO high case: Regional electrification forecast is 33% higher than base case by 2050

As seen in Table 4.9.9, lower or higher electrification rates do not have a significant impact on energy demand and use in our model. In reality, there would certainly be an impact on demand because of the higher efficiency of electricity compared to fossil fuels, but this is not reflected here because we model the share of energy carriers independently from energy-efficiency gains. In the test results, we do,

TABLE 4.9.9
ETO Model Sensitivity to Electrification of Buildings and Manufacturing (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	+1%	-1%
Electricity	-15%	+15%
Primary Energy Supply	0%	0%
Coal	+11%	-11%
Crude oil	+4%	-4%
Natural gas	+12%	-12%
Nuclear	-3%	+2%
Biomass	+2%	-2%
Hydropower	-3%	+2%
Solar PV	-23%	+24%
Wind	-12%	+11%
CO_2 emissions	+9%	-9%

>> Higher electrification rates in buildings and manufacturing would increase the pace of the energy transition and alter the energy mix, so that by 2050 much more natural gas and coal will have been replaced by solar PV and wind.

however, see a significant impact on the energy mix. In a future with low electrification of buildings and manufacturing, there will be much more demand for fossil fuels, most notably natural gas and coal. In contrast, a future with high electrification will see much faster uptake of renewables, especially solar PV and, to a lesser extent, wind.

UPTAKE OF ELECTRIC VEHICLES

The most dramatic decarbonization of the energy system will occur through the conversion of road transport to electric propulsion. In our base case, we forecast 50% of new light vehicles to be electric in Europe by 2027. North America, Greater China, Indian Subcontinent and OECD Pacific will follow by 2032 and the rest of the world by 2037. For all regions, we forecast the EV share of heavy vehicles to reach 50% three years later than for light vehicles. There is, of course, the possibility that EVs will take off more slowly than we expect. Many consumers may remain sceptical and play down the known cost advantages, while emphasizing charging challenges and performance disadvantages, such as much-longer charging times and shorter ranges than for petrol vehicles. On the other hand, the share of EVs in vehicle markets could potentially reach 50% earlier than we assume. That could be the result of public policies in which only zero-emission vehicles will be allowed after a certain year, or implementations following policy ambitions to a higher degree than we have anticipated.

- ETO low case: In all regions, the market share of EVs reaches 50% by 2037 for light vehicles, and in 2040 for heavy vehicles
- ETO base case: Regional trends for when the market share of EVs reaches 50% (see Figure 4.1.3 and 4.1.4 , pages 114 and 115)

TABLE 4.9.10
ETO Model Sensitivity to EV Uptake (as deviation from base case)

	Low Case 2050	High Case 2050
Final Energy Demand	+1%	-2%
Electricity	-2%	+2%
Primary Energy Supply	+3%	-3%
Coal	+5%	-5%
Crude oil	+12%	-15%
Natural gas	+4%	-4%
Nuclear	+4%	-3%
Biomass	+4%	-3%
Hydropower	+2%	+1%
Solar PV	-9%	+10%
Wind	0%	-2%
CO_2 emissions	+6%	-7%
EV share light vehicles	-14%	+12%
EV share heavy vehicles	-20%	+20%

>> A slower uptake of EVs will first and foremost influence the consumption of oil and it will lower the pace of electrification and decarbonization in the transport sector.

- ETO high case: In all regions, the market share of EVs reaches 50% by 2027 for light vehicles, and in 2030 for heavy vehicles

As seen in Table 4.9.10, a slower uptake of EVs leads to slightly higher energy demand by 2050, and 12% greater oil consumption, than in our base case. It could be added that a slower uptake, or an uptake where the entire fleet will never be converted to EVs are considered possible by some other forecasters. This is not tested here.

VEHICLE LIFETIME

Vehicle lifetime is an important indicator of the amount of inertia in the road transport system. In our forecast, for different regions and car types, it will take 12–18 years for a vehicle to be replaced.

- ETO low case: Vehicle lifetime 33% less than base case from the year 2018
- ETO base case: Regional lifetimes for vehicles
- ETO high case: Vehicle lifetime 33% higher than base case from the year 2018

As seen in Table 4.9.11, a lower lifetime would lead to a significant increase in the share of EVs, both for heavy and light vehicles, and would reduce oil consumption. A higher-than-assumed lifetime would have an even higher, but negative, impact on EV uptake, most notably the light ones, and oil consumption could be 10% higher than in our base case by 2050.

TABLE 4.9.11
ETO Model Sensitivity to Vehicle Lifetime (as deviation from base case)

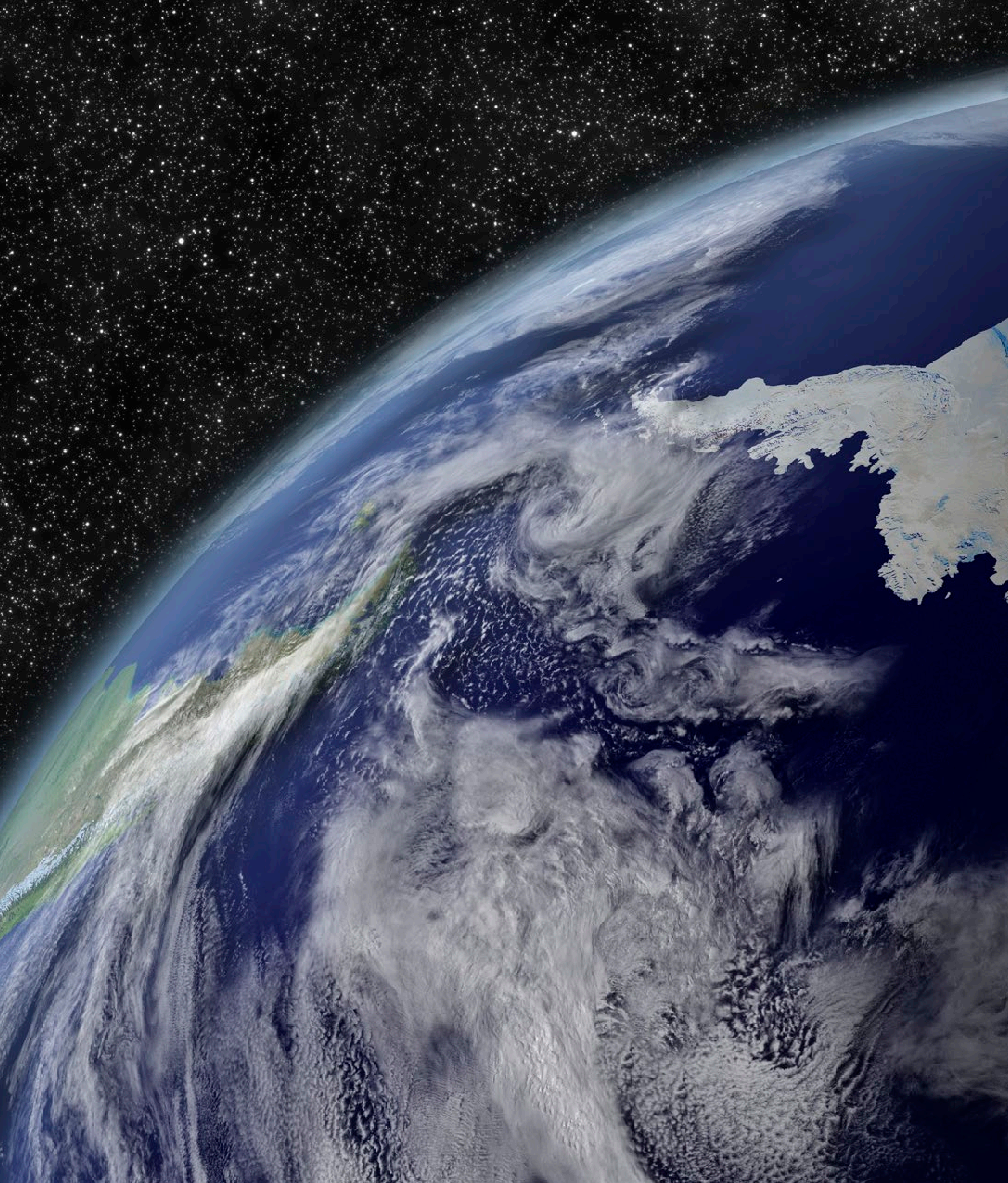
	Low Case 2050	High Case 2050
Final Energy Demand	-1%	+2%
Electricity	+1%	-2%
Primary Energy Supply	-2%	+2%
Coal	-2%	+1%
Crude oil	-9%	+10%
Natural gas	-2%	+2%
Nuclear	-1%	+1%
Biomass	-2%	+2%
Hydropower	0%	0%
Solar PV	+4%	-3%
Wind	0%	-1%
CO_2 emissions	-4%	+4%
EV share light vehicles	+8%	-11%
EV share heavy vehicles	+8%	-8%

>> The lifetime of vehicles is an important mediating factor that could impact how fast the road transport sector can be electrified. New technologies such as autonomous vehicles and ride-sharing, could lead to faster fleet turn-arounds due to higher car usage.

SUMMARY OF SENSITIVITY ANALYSIS

Although some changes in our assumptions could slow down the pace of transition, none of the sensitivities discussed can alter the main conclusion, that a rapid energy transition is underway with electrification and decarbonization as key pillars. The transition will lead to a very strong growth of wind and solar, and a decline first in coal use, and later oil, then natural gas.

The climate implications of the model sensitivities are discussed in more detail in Chapter 8.



CHAPTER 5

REGIONAL TRANSITIONS

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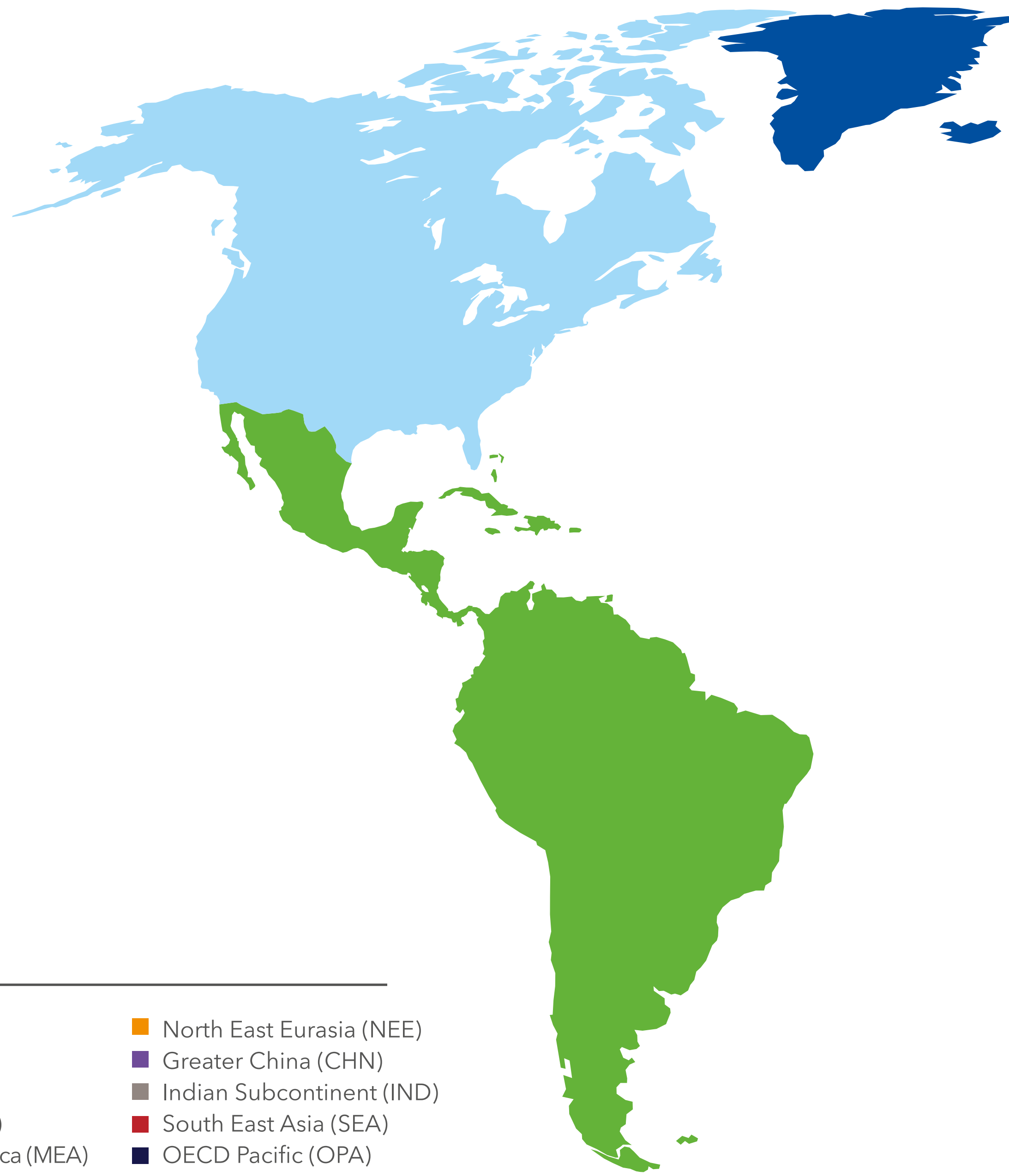
WE ANALYSE 10 GLOBAL REGIONS



REGION

- North America (NAM)
- Latin America (LAM)
- Europe (EUR)
- Sub-Saharan Africa (SSA)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- Indian Subcontinent (IND)
- South East Asia (SEA)
- OECD Pacific (OPA)

The US and Canada are mature, highly industrialized economies. Playing a key role in world economics, the region's policies have global impact; it also plays a leading role in energy technology innovation and is a large provider of funds worldwide.

Shifts in US federal policy have created uncertainty over future energy developments, environmental protection, and central government support for climate change mitigation.

In the US, owing to an absence of supportive federal regulations, the energy transition is driven forward by global energy-efficiency trends, technological developments, and pioneers at the subnational level.

Decentralized decision making by US individual states, Canadian provinces, and some large cities is equally important in determining the rate and direction of the region's energy transition. These are maintaining strong climate policies and have publicly linked recent extreme weather events and drought to climate change. Hurricanes Harvey, Irma, and Maria revealed the scale of damages and costs.

Various energy transitions are unfolding: adoption of renewable energy, retrenchment of fossil fuel usage, and the emergence of abundant unconventional hydrocarbon production. Energy intensity is improving and the region is decarbonizing the energy sector at a healthy pace. Greenhouse gas emissions (GHGs) have fallen partly due to substituting gas for coal.

NORTH AMERICA (NAM)

AREA

19.8 MN KM^2

THIS REGION CONSISTS OF
CANADA AND THE UNITED STATES (US).

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	359 MN	440 MN
GDP	16.0 TN USD	25.2 TN USD
GDP/PERSON	44,500 USD	57,400 USD
PRIMARY ENERGY USE	107 EJ	60 EJ
PRIMARY ENERGY USE/PERSON	297 GJ	136 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

NORTH AMERICA

As shown in Figure 5.1.1, North America's primary energy consumption has been declining since 2014 and will continue to do so towards 2050, when the region's energy use will be some 43% lower than today. The reduction is the result of energy efficiency improvements in the transport sector (62% reduction in energy demand between now and 2050) and a continued shift of the economy towards the tertiary sector, with a 58% reduction in manufacturing energy demand. The demand for energy in buildings increases only modestly over the reference period.

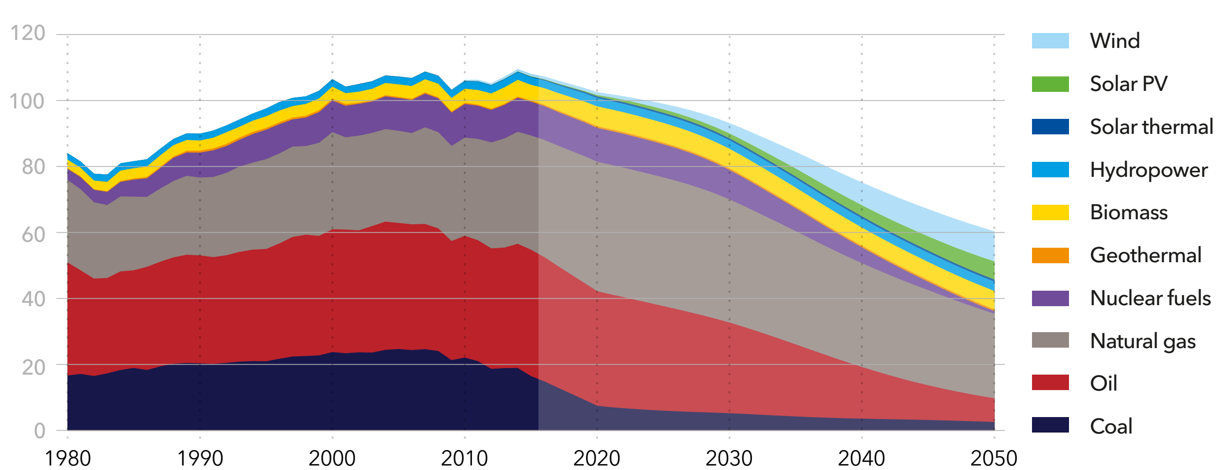
Coal use will continue to decline as it becomes increasingly uncompetitive as a fuel for power generation. Natural gas from domestic shale will continue to grow for the next few years, thereafter entering a slow decline. However, this initial growth spurt has seen natural gas overtake oil as the largest energy source in 2018, and it will remain the dominant source through to 2050. The use of oil is continuing to decline in the region, due to the increasing efficiency of the vehicle fleet and replacement by natural gas as a feedstock for the petrochemical sector. By 2030, the rapid uptake of EVs reduces oil demand drastically, eventually leaving it 80% lower in 2050 compared with today's use.

The growth in EVs will boost the pace of electrification in North America. Figure 5.1.2 shows electricity demand being 41% higher in 2050 than today. Most of the additional electricity demand will be met by growing capacities of solar and especially onshore wind, which will overtake natural gas as the largest power generator by 2040. Nuclear power will gradually decline in importance within the region.

FIGURE 5.1.1

North America primary energy consumption by source

Units: EJ/yr



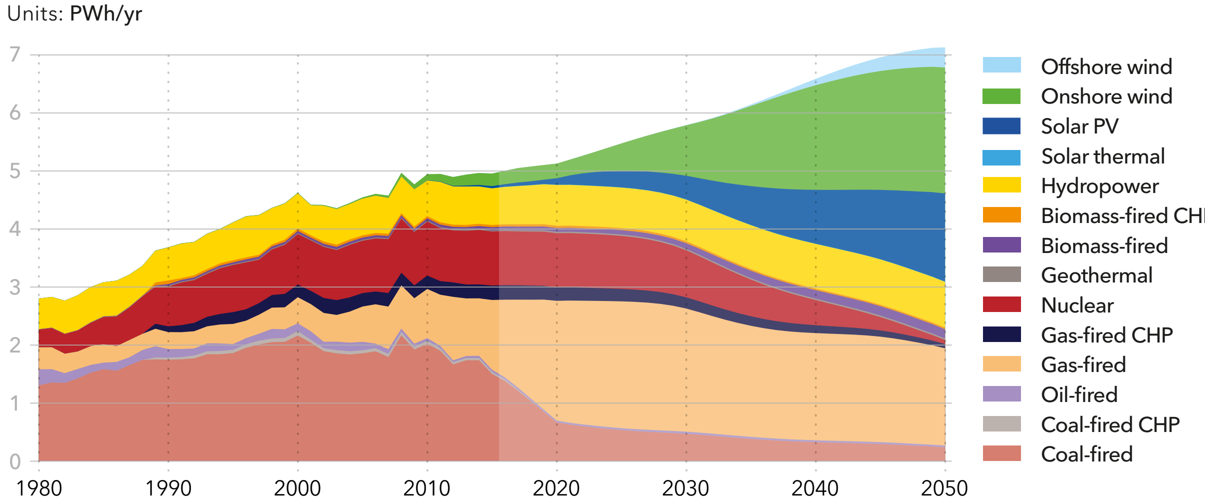
POINTERS TO THE FUTURE

- Large shale gas reserves have enhanced energy security, enabling substitution of gas for coal in power generation, complementing the shift to renewables. Liquefied natural gas (LNG) terminals and new liquefaction capacity will boost exports.
- The Climate Mayors initiative, backed by 405 US mayors, is committed to controlling local air pollution and backing climate action. Cities will control energy-efficiency measures, municipal transport systems, investment in renewable energy, and joint orders in EV purchasing.
- Corporate renewable energy procurement will continue, triggered by the falling costs of technology and the use of power purchase agreements to secure long-term energy price certainty. The direct procurement movement is pushing policy makers, regulators, and utilities towards cleaner energy supplies.
- Electricity market designs will evolve, led by the experiences of New York, California, and other states with high renewables penetration.
- Canada intends to reduce GHGs by 30% by 2030 compared with levels in 2005. In 2016, it committed to phasing out traditional coal-fired electricity. An economy-wide carbon pricing system was established in 2018, and will be in force from 2019.
- Carbon prices regionally will be shaped by the Regional Greenhouse Gas Initiative in northeast US. California and the Western Climate Initiative, and Canada's implementation of its national carbon pricing strategy. We expect linking of emissions trading systems, building on the 2017 Carbon Pricing in the Americas (CPA) declaration.

FIGURE 5.1.2

North America electricity generation by power station type

Units: PWh/yr



NORTH AMERICA

DECLINE OF BIG OIL

North America was the cradle for growth and innovation in the oil industry. A second revitalization of oil and natural gas production occurred with the boom in production from shale formations. Current production levels supply almost a sixth of the world's crude oil. This will continue for another decade. Yet the rate of capacity additions will decline, initially in the offshore oil sector and later in onshore unconventional oil extraction, resulting in output at half of today's level in 2050.

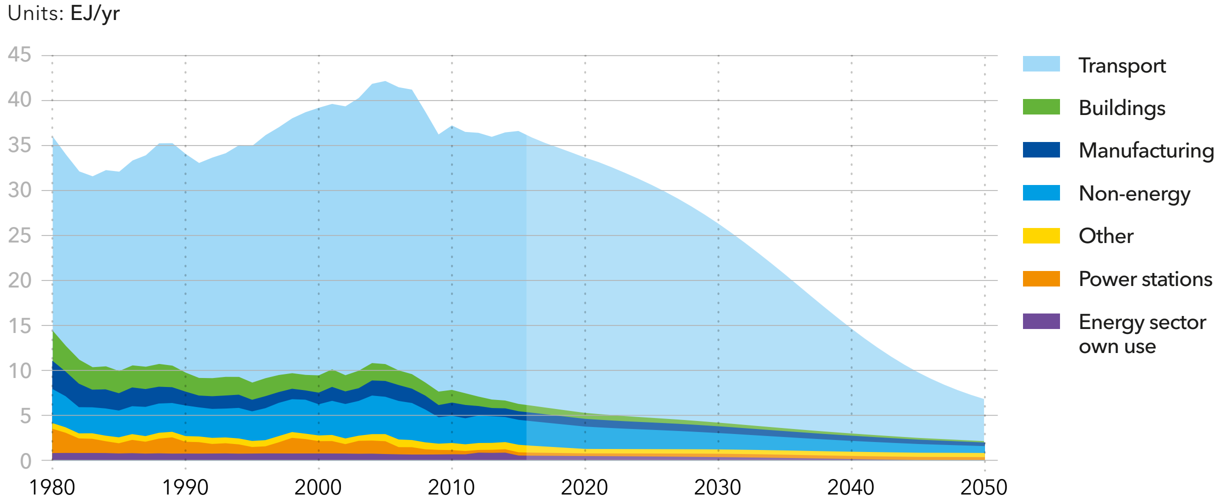
Driven by a mixture of transportation's transformation to electric propulsion, and technological and geopolitical changes, the North American oil and gas industry will change significantly by mid-century.

North America is big in both oil production and consumption. This is about to change. While oil demand in all sectors will reduce, the major reason for our forecast decline in oil demand, as shown in Figure 5.1.3, is the rapid decline of oil in the transport sector, driven by electrification. The land of the Model T Ford will see a boom in electric vehicles, reaching 180 million EVs in 2050.

FIGURE 5.1.3

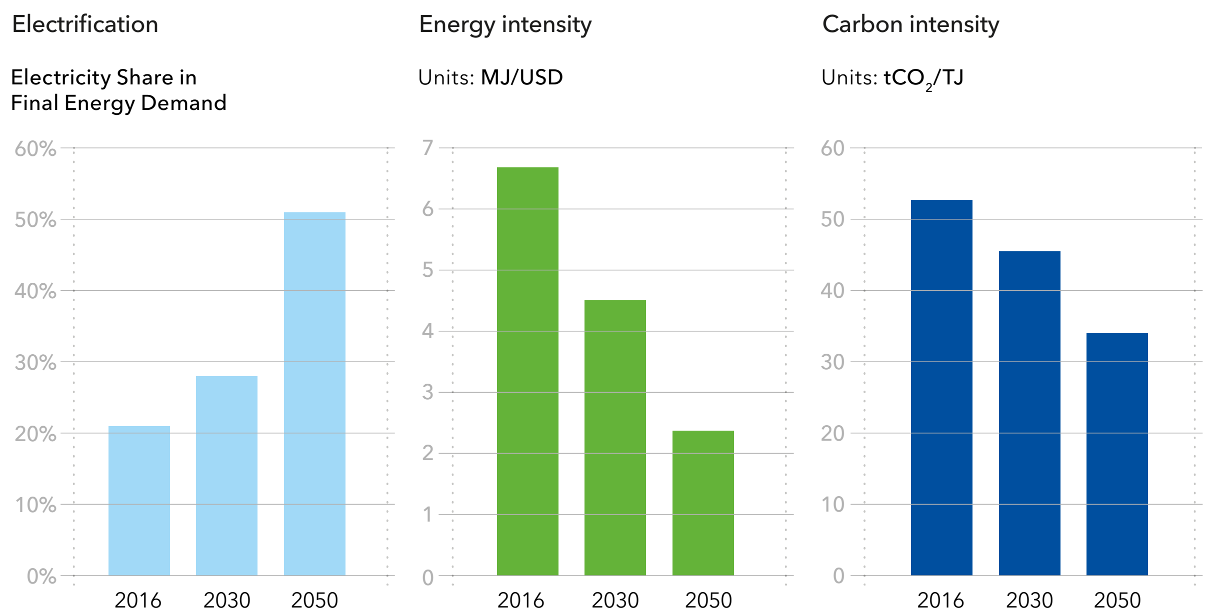
North America oil demand by sector

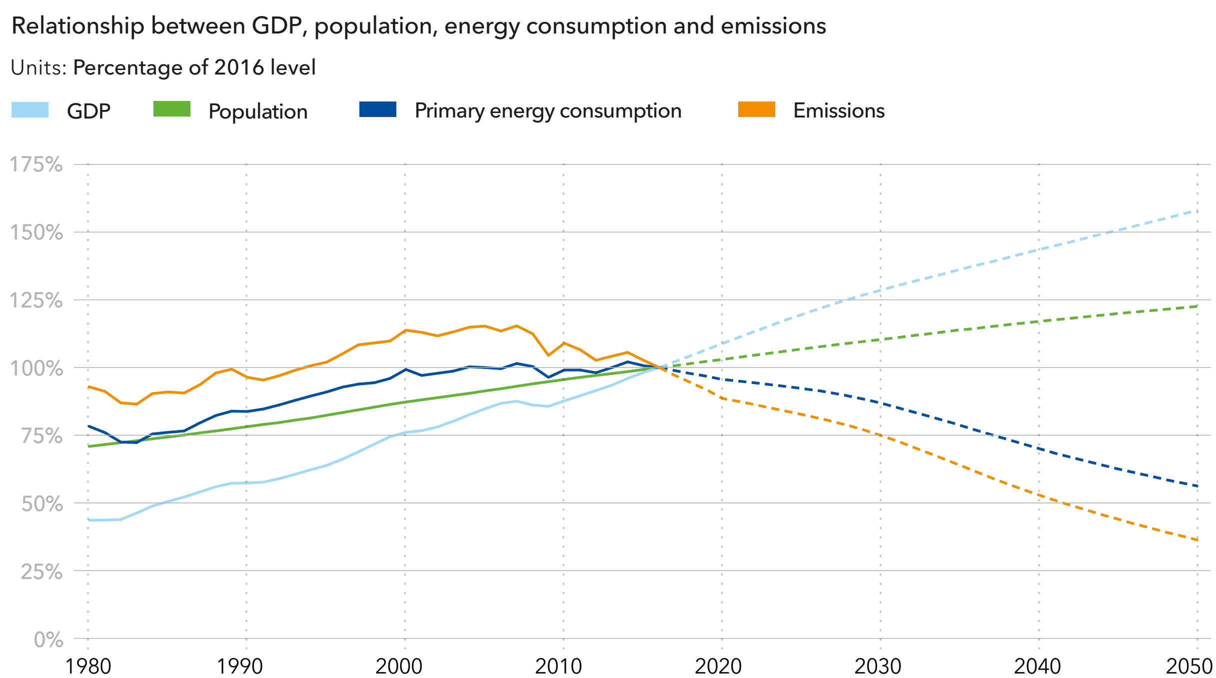
Units: EJ/yr



ENERGY TRANSITION INDICATORS – NORTH AMERICA

FIGURE 5.1.4





Energy priorities link everywhere to economic development agendas. Economies and populations keep growing and energy demand mirrors this. Changing and extreme weather are significant issues. Long periods of drought in Brazil, Colombia, Panama and Venezuela hamper security of supply and threaten blackouts. Air pollution and poor air quality in major cities are growing concerns. Transport is the fastest-growing source of energy-related emissions.

Latin America's energy sector is the least carbon-intensive among major economies in the developing world, mainly due to low coal demand.

Brazil, Mexico, and Venezuela lead regional oil production. Hydropower is longstanding in the region, but its 45% share in the electricity mix is declining and expansion is constrained by social and environmental considerations.

Latin America is rapidly transitioning from fuel oil and hydropower as main electricity sources to a diversified mix including natural gas, solar, and wind. Brazil, Chile, and Mexico are among the global top 10 renewable energy markets.

Non-hydropower renewables compete on price with fossil energy. For new capacities, the region has low, highly competitive costs for wind and solar. Most countries in the region support renewables in various ways. Blending mandates have created markets for biofuels in transport. Brazil's long-established biofuel economy and its world leading role in biofuel ethanol production, will translate into the world's largest fleet of flexible-fuel vehicles.

LATIN AMERICA (LAM)

AREA

20.4 MN KM^2

LATIN AMERICA RUNS FROM MEXICO TO THE SOUTHERN TIP OF SOUTH AMERICA, AND INCLUDES THE CARIBBEAN ISLAND NATIONS.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	637 MN	743 MN
GDP	6.6 TN USD	16.0 TN USD
GDP/PERSON	10,400 USD	21,500 USD
PRIMARY ENERGY USE	34 EJ	41 EJ
PRIMARY ENERGY USE/PERSON	54 GJ	56 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

LATIN AMERICA

Latin America's primary energy consumption will remain relatively flat in the coming decade, as shown in Figure 5.2.1, after which a period of rapid economic growth will drive it upwards. The increase is the result of greater energy use in manufacturing and buildings, mostly from appliances, lighting, and space cooling. Energy use for transport will decline modestly until 2030 and remain relatively flat afterwards.

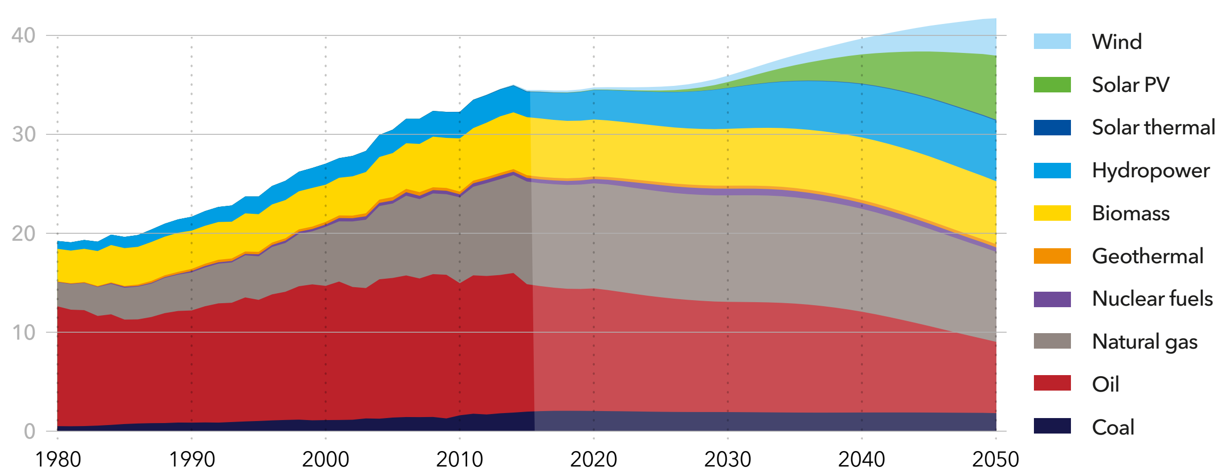
Most of the additional energy demand beyond 2025 will be covered by electricity, which in 2050 will account for twice its current share. By then, as shown in Figure 5.2.2, a combination of hydropower, biomass, solar, and wind will produce 94% of the region's power needs and meet 55% of its total energy demand. Solar PV and hydropower will each provide a third of the capacity in 2050, followed by onshore wind.

Coal use is and will remain low in Latin America. Due to rapid uptake of EVs in the region after 2030, oil will lose its leading position as an energy source by 2041, when natural gas becomes the largest supplier of energy.

FIGURE 5.2.1

Latin America primary energy consumption by source

Units: EJ/yr



POINTERS TO THE FUTURE

– Energy security will remain a challenge. With challenging topography, the region will focus on infrastructure investments, better integration of networks, and interconnections. Regional cooperation can unlock benefits and reduce the need for fossil baseload. However, country-specific initiatives will drive the extraction of unconventional oil and gas in the region where resources, especially in Argentina, are huge and promising.

– Diversification of energy sources will remain on the agenda. The region will host some of the most dynamic wind and solar markets, building on hydropower to balance electricity systems. Governments will increase focus on energy efficiency and distributed generation for the 6% of the population that still lacks access to modern energy services.

– Recognizing renewables as catalysts for industry and job creation, deployment policies will seek to maximize local value creation and foster community acceptance for renewable-energy projects through local-content provisions.

– Car ownership accelerates with stronger growth. Officials aim to reduce emissions and improve air quality by increasing fuel efficiency, public transit and alternative fuel availability. Electrification of transport will increase, with Chile and Colombia among the leaders.

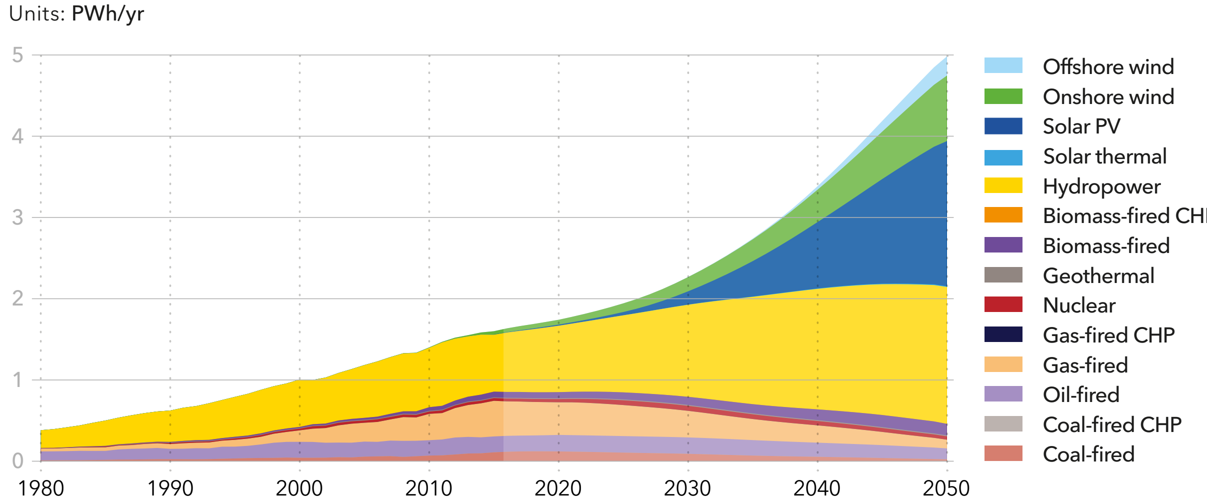
– With the combination of population increase and urbanization, urban planning is expected to adopt building standards and stimulate use of efficient technologies in building sector expansions.

– Chile, Colombia, and Mexico's introduction of carbon pricing will be a yardstick for the region, with alignment efforts through CPA.

FIGURE 5.2.2

Latin America electricity generation by power station type

Units: PWh/yr



LATIN AMERICA

THE NEXT SHALE REVOLUTION

Global oil production will peak in about five years, but unconventionals, mainly shale, will see a steadily growing share of output as comparative costs of shale continue to reduce. Global onshore unconventional oil production will peak a decade later at 17 Mb/d, as shown in Figure 5.2.3. By 2050, almost a quarter of all oil will come from unconventional fields. Up to the present, North America has been the main source of shale growth. But over the next decades, as shown in Figure 5.2.3, Latin America will become a main player, and by the mid-2030s will produce almost half of global shale oil. Even with sharply declining shale production thereafter, the region will continue to provide half of global shale output.

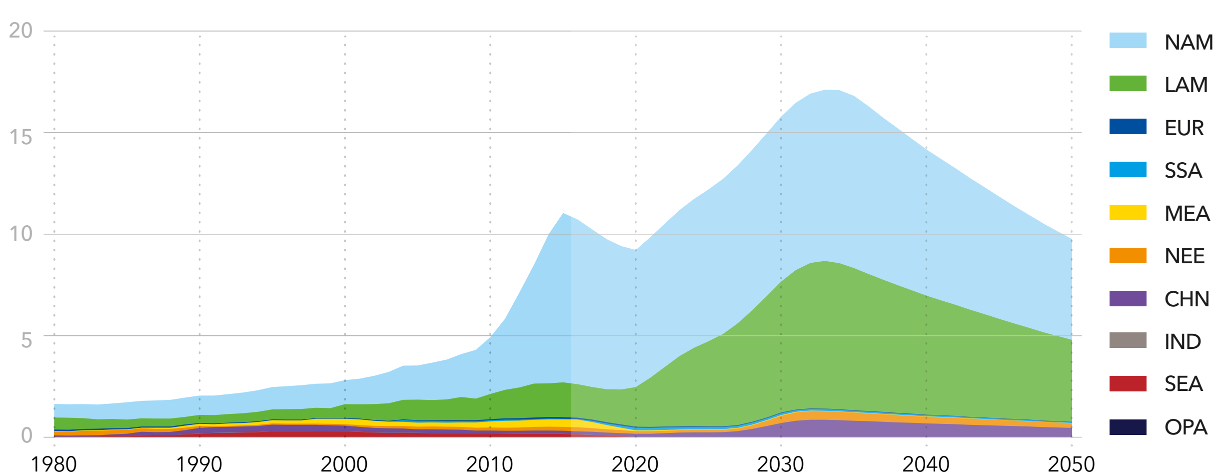
Brazil, Mexico, and Venezuela have been the main producers in the region up to now, with a 50/50 mix of on- and offshore production. But the shale revolution will spread to geological formations in other countries, and most strongly of course to nations where it finds conducive policies.

In Latin America, the combination will propel unconventional fields to provide more than the sum of the two other field types by the mid-2030s. Since shale formations are found further south, in particular in Argentina, the region's production centre of gravity will shift there in line with the decline in conventional and offshore production.

FIGURE 5.2.3

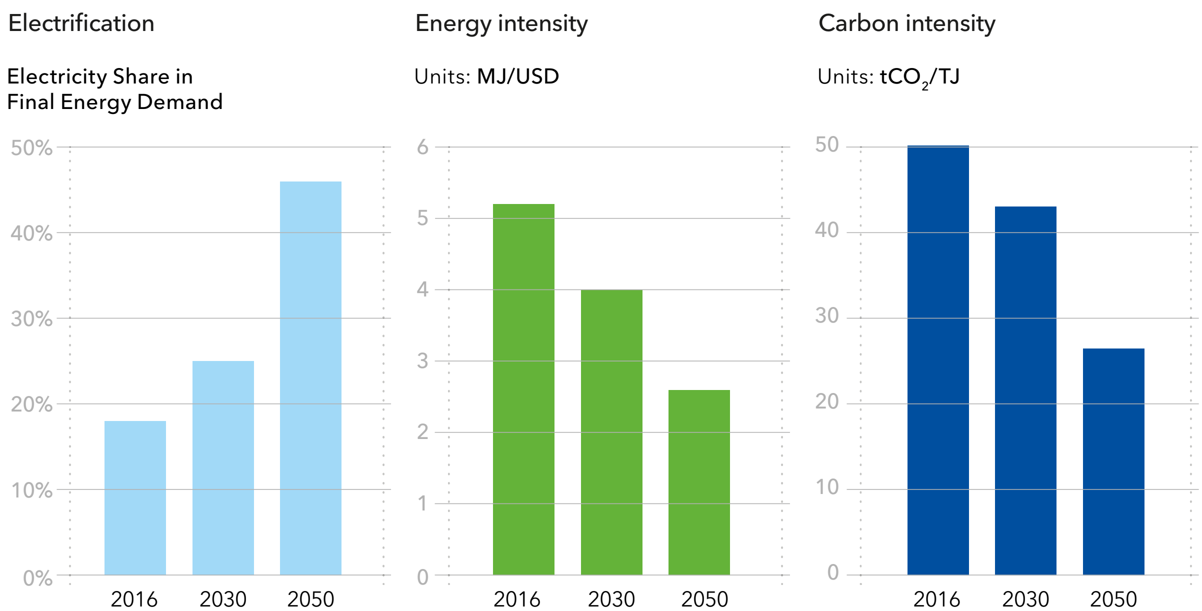
Unconventional crude oil production by region

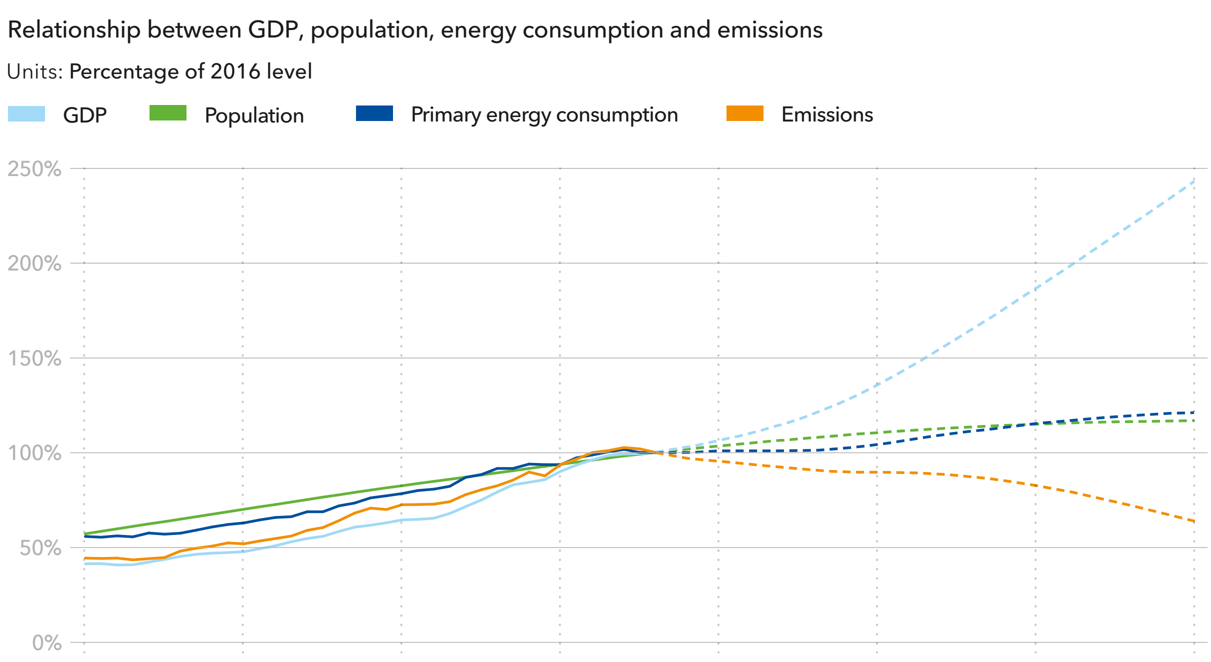
Units: Mb/d



ENERGY TRANSITION INDICATORS - LATIN AMERICA

FIGURE 5.2.4





Most countries are OECD members, but with considerable differences in wealth between the richer north and west, and the less-rich south and east. End-use energy demand is moderate considering the region's developed state. Energy demand has decoupled from economic growth thanks to improved energy intensity.

The European Union (EU) sets the direction for energy policy, and the region is a frontrunner in the energy transition. Indeed, a rapid transition is underway, but with individual country targets, and each country setting its own measures and timeframe to achieve energy and environmental targets.

Interests and opportunities vary widely, given legacy power systems and domestic resource endowments.

Denmark, Germany, Ireland, Italy and Spain have led the development and deployment of renewables. Norway is setting the pace in EVs. Coal retains the largest share in the power generation mixes of the Baltics and Poland.

Efforts to balance the energy trilemma focus simultaneously on energy that is clean, reliable and affordable. There is increasing attention on affordability given rises in household energy prices associated with a need for countries to reimburse costs caused by extensive grid refurbishment and investments.

EUROPE (EUR)

AREA

7.2 MN KM^2

THIS REGION COMPRISES ALL EUROPEAN COUNTRIES, INCLUDING THE BALTICS, BUT EXCLUDING RUSSIA, ALL THE FORMER SOVIET UNION REPUBLICS, AND TURKEY.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	541 MN	563 MN
GDP	15.5 TN USD	23.3 TN USD
GDP/PERSON	28,700 USD	41,400 USD
PRIMARY ENERGY USE	74 EJ	48 EJ
PRIMARY ENERGY USE/PERSON	137 GJ	85 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

EUROPE

Europe's primary energy consumption has declined during the last decade and, as shown in Figure 5.3.1, will continue to do so towards 2050, when the region's final energy demand will be 35% lower than today. The reduction is the result of electrification and energy-efficiency improvements in the transport sector (49% reduction of transport energy demand between now and 2050) and a reduction in manufacturing energy demand. The demand for energy in buildings decreases modestly over the reference period, driven by efficiency improvements in residential buildings.

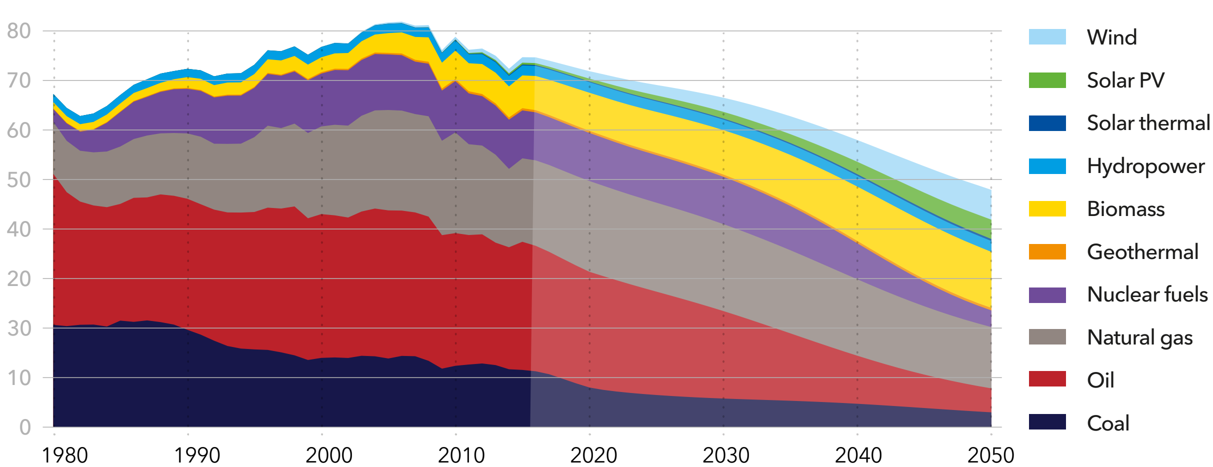
Coal use will continue to decline in Europe, driven by the EU decarbonization policy. The use of oil, currently the largest source of energy, will reduce even faster, by 82% over the forecast period, because of the rapid uptake of EVs. Natural gas use in the region will increase the next few years, after which it will stabilize for two decades and ultimately decline as the result of a reduction in industrial gas demand. The use of biomass in Europe almost doubles over the forecast period, while the use of nuclear energy remains relatively stable until 2030, and then rapidly declines.

The growth in EVs will drive electrification in Europe, with electricity demand in 2050 being 47% higher than today, as shown in Figure 5.3.2. Gas power will reach its peak in 2042, after which it slowly declines. In the 2040s, onshore wind and solar PV overtake gas as the largest power sources. By 2050, renewables will produce 75% of Europe's electricity.

FIGURE 5.3.1

Europe primary energy consumption by source

Units: EJ/yr



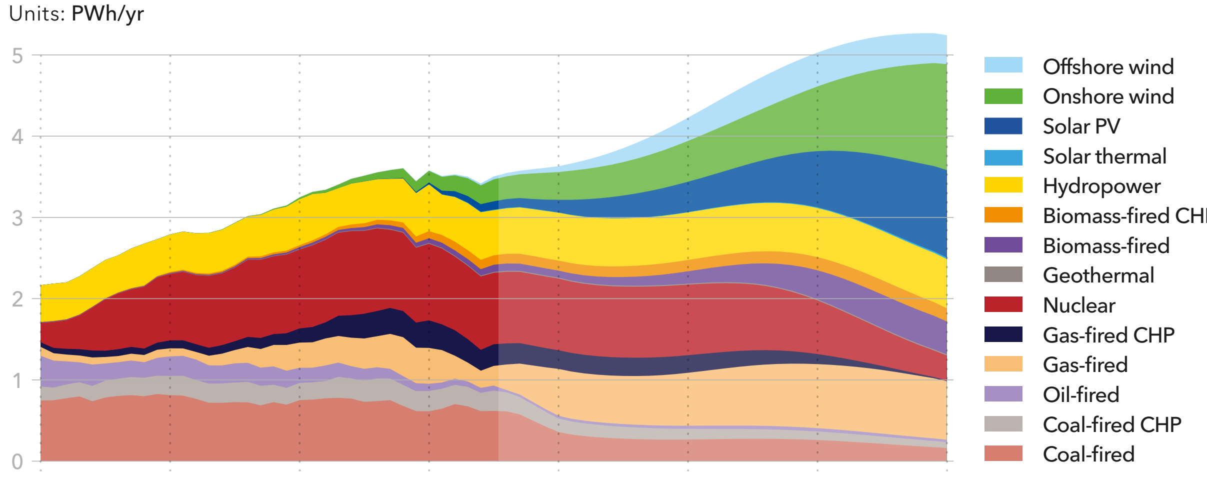
POINTERS TO THE FUTURE

- Europe will advance its longstanding leadership in forward-thinking energy and climate policies to achieve current targets and future revisions. It will strengthen regional dialogues with other leading climate-change players, notably China.
- A combination of its long-term, low-carbon investment signals and the reform, agreed in 2017, of the EU Emissions Trading System by 2030 will help to correct persistently low carbon prices.
- Priorities are a single energy market via the Energy Union, with secure, affordable, and climate-friendly energy. EU targets for 2030 include: reducing GHG emissions by at least 40% compared with 1990; raising renewables' share in gross final energy demand to 32%; a minimum of 14% renewable energy in transport; and, energy savings of 27% relative to the 2007 primary-energy baseline projections. These are likely to be strengthened due to the upwards revision clause by 2023.
- We forecast continual decline in European production of hydrocarbons. More LNG import terminals will be built as alternatives to reliance on piped gas from Norway and Russia. Large pipeline construction to support long-distance gas transmission will, however, continue. We expect a steady drive to increase renewable energy deployment, and greater energy efficiency to offset energy imports.
- Power system stability and security will become a key focus for operators, regulators, and energy policymakers. There will be continuously higher deployment rates of variable renewable energy at transmission and distribution level, also bringing further market and network integration through continental and subsea interconnectors.

FIGURE 5.3.2

Europe electricity generation by power station type

Units: PWh/yr



EUROPE

LOW CARBON TRANSITION – BUT STILL FALLING SHORT

Europe is navigating its energy transition at a steady pace and is continually revising its regulations and innovation mechanisms to achieve targets and keep up with a fast-evolving energy system. The region has earned a reputation as a global leader in setting the direction for climate policy.

Both at the national and EU level, the transition to cleaner energy remains a strong priority, although the Union faces uneven commitments among its members on the pace and extent of climate action and energy transition. Most noticeable is the debate on whether such efforts potentially undermine the competitiveness of European industry, and fears of carbon leakage (i.e., business transferring production to regions with lower emissions requirements), as the region faces high compliance costs and higher energy costs due to carbon pricing. Also, the lack of enthusiasm from several coal-dependent economies is holding back efforts.

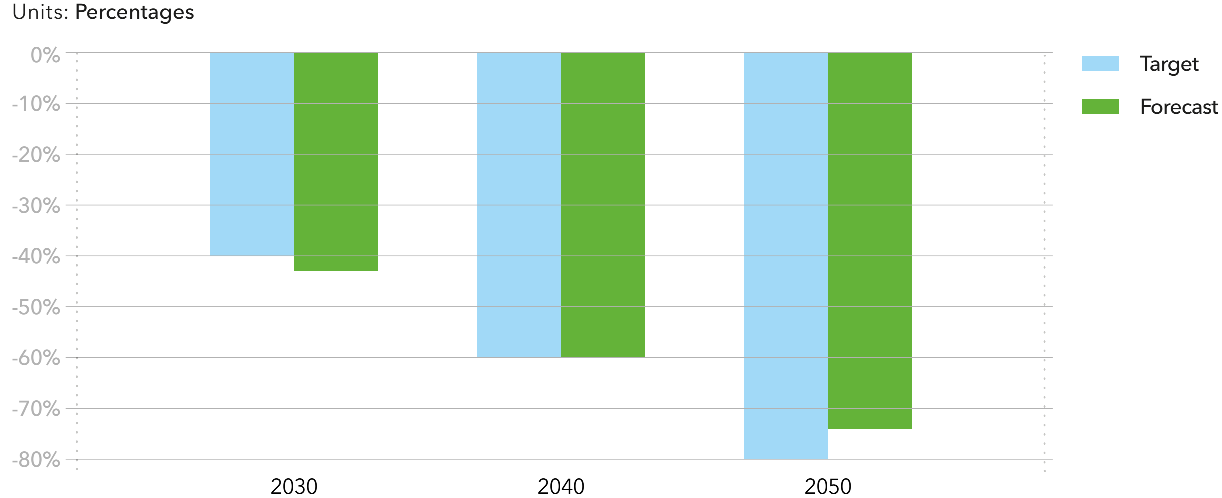
Nevertheless, the EU is committed to action based on the European Commission's roadmap for a low-carbon economy by 2050, which includes economy-wide goals. By 2050, the EU aims to cut GHGs to 80% below 1990 levels through domestic reductions alone. To achieve this, milestones for 2030 and 2040 have been set at reductions of 40% and 60% respectively. The legally-binding 2030 target is currently (mid-2018) under reconsideration for further strengthening.

In our forecast, as shown in Figure 5.3.3, Europe manages to meet its 2030 and 2040 low-carbon milestones. However, it will fall short of its 2050 target. Hence, even 'the best in class' on commitment to long-term emissions reduction and the energy transition agenda will struggle to achieve its decarbonization ambition.

FIGURE 5.3.3

European CO_2 emission reductions

Units: Percentages

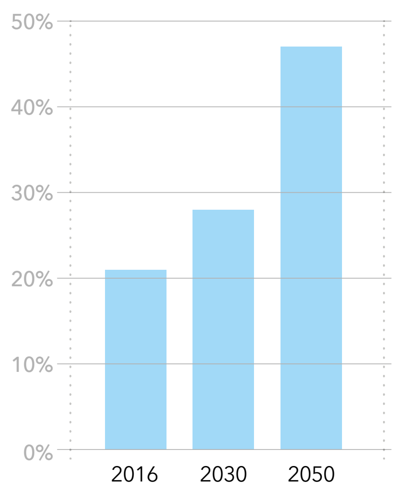


ENERGY TRANSITION INDICATORS - EUROPE

FIGURE 5.3.4

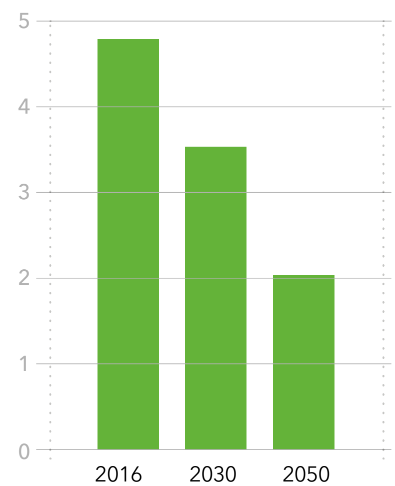
Electrification

Electricity Share in
Final Energy Demand



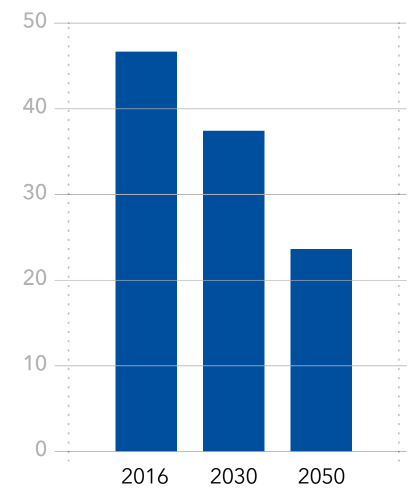
Energy intensity

Units: MJ/USD



Carbon intensity

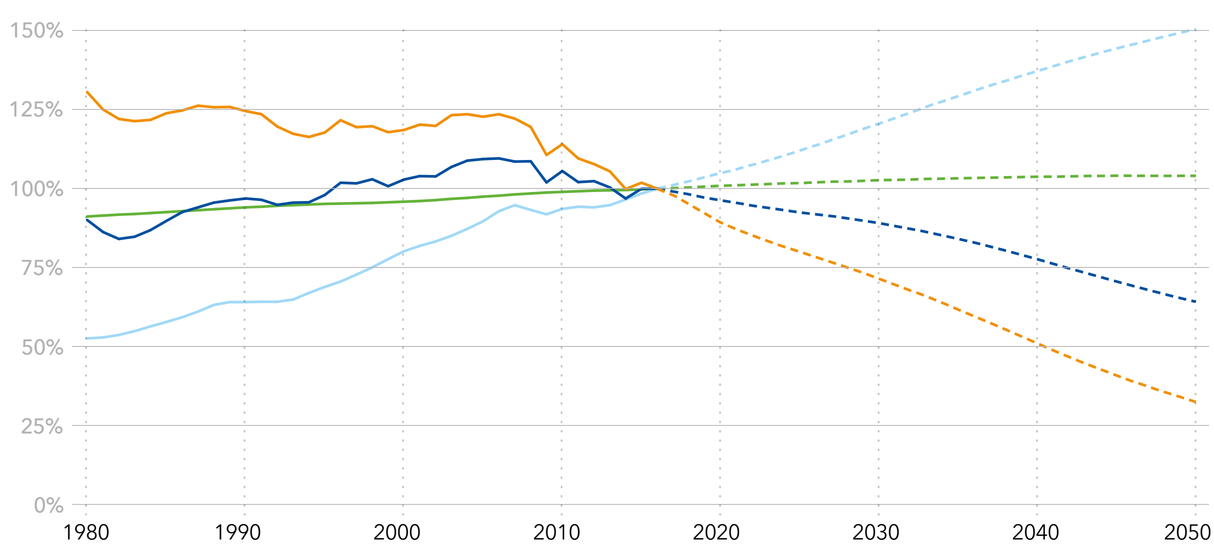
Units: tCO_2/TJ



Relationship between GDP, population, energy consumption and emissions

Units: Percentage of 2016 level

GDP Population Primary energy consumption Emissions



The region is diverse with respect to natural resources. Angola, Nigeria, the Republic of Congo, Sudan and South Sudan are the largest petroleum producers. Oil-rich Nigeria is the largest economy. South Africa, where coal is the main primary fuel for power generation and a major employer, mines 250mn tonnes a year, 90% of coal used in the Sub-Saharan Africa region.

Large parts of the region struggle with corruption and weak governance. Some suffer long periods of internal conflict.

This is the least-developed and least-electrified world region, and there is a link between these two facts. Most Sub-Saharan countries are poor and are challenged by energy poverty despite the region's rich resource potential. Only 43% of the region's people have access to electricity, and many countries have barely initiated policy measures to accelerate access.

Urbanization rates in Sub-Saharan Africa are regarded as the fastest in the world. In the next 30 years, urban dwellers will outweigh rural residents. Local value and job creation, including youth unemployment, are key challenges, but also, opportunities. The continent holds large potential for leapfrogging development stages through innovation and technology, and for charting new paths by leveraging the capabilities of the large generation of youth, digital technologies and connectivity as catalysts of entrepreneurial activity.

Energy deficiency is an impediment to economic development and progress. The region requires power generation and infrastructure to meet the basic energy needs of growing populations. Supply has hitherto not kept pace with population growth and industrialization.

SUB-SAHARAN AFRICA (SSA)

AREA

24.3 MN KM^2

COMPRISES ALL AFRICAN COUNTRIES EXCEPT MOROCCO, ALGERIA, TUNISIA, LIBYA AND EGYPT.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	1.04 BN	1.99 BN
GDP	2.3 TN USD	11.5 TN USD
GDP/PERSON	2,200 USD	5,800 USD
PRIMARY ENERGY USE	24 EJ	45 EJ
PRIMARY ENERGY USE/PERSON	23 GJ	23 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

SUB-SAHARAN AFRICA

Figure 5.4.1 indicates that Sub-Saharan Africa's consumption of primary energy will continue to grow and will be 85% higher in 2050 than today. The main driver for growth is the region's rapidly expanding population. Increased trade and access to vehicles leads to a bigger energy demand from the transport sector. Manufacturing energy demand will see the largest growth, while the increase in buildings is dampened by efficiency gains as large amounts of wood and manure used for cooking are replaced by modern energy.

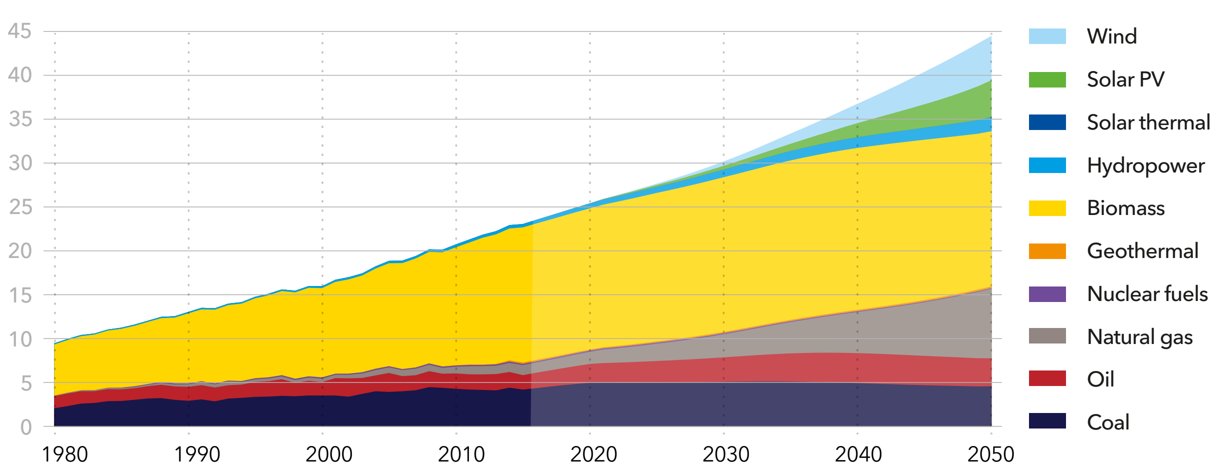
Biomass will remain by far the largest source of energy in the region by 2050, although it slowly loses position to fossil fuels and, later, to modern renewables. Coal use will remain relatively flat between now and 2050. Oil use will grow 73%, while natural gas use will grow fivefold to 2050 and overtake coal as the region's second largest source of energy.

Figure 5.4.2 illustrates how Sub-Saharan Africa's electricity consumption will continue to grow, and rapid electrification will be experienced from 2025 as the number of people with grid (or off-grid) access grows and economic growth drives consumption upwards. Beyond 2020, coal-fired power generation will start to decrease, and the electricity demand will be supplied by a combination of hydropower, natural gas, solar PV and wind, including offshore wind, which will provide 14% of the region's power in 2050. In addition, there will be strong growth of off-grid solar.

FIGURE 5.4.1

Sub-Saharan Africa primary energy consumption by source

Units: EJ/yr



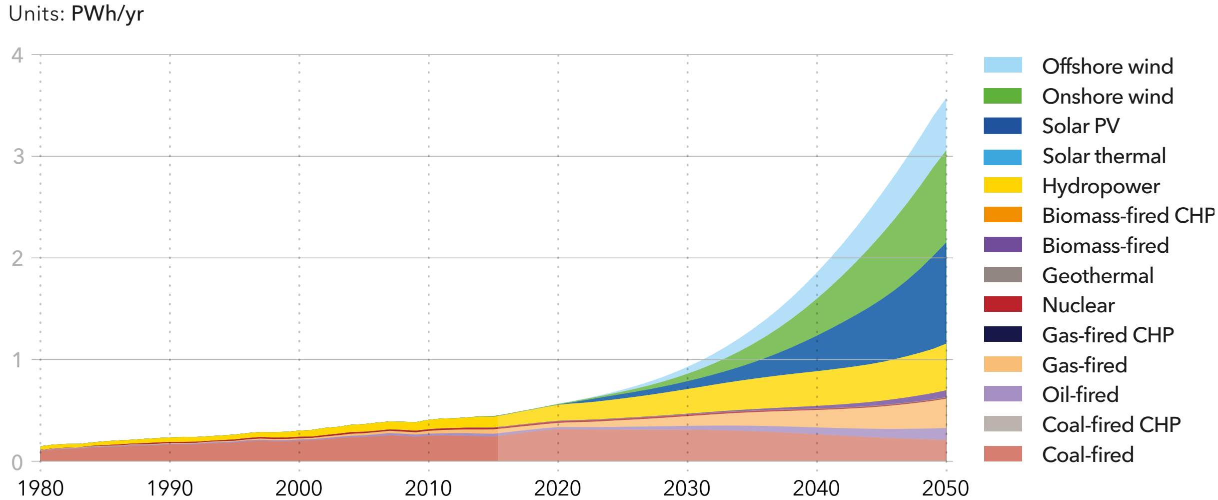
POINTERS TO THE FUTURE

- SDG goals #1 and #2, on poverty and hunger, remain paramount, as does SDG #7 on energy access.
- Partnerships and global funding, will play key roles in energy and infrastructure development. Leapfrogging old, costly, polluting production and transport will be a major focus.
- Lower renewable energy costs are creating new opportunities for Sub-Saharan Africa to afford its energy needs. Solar PV and onshore wind, and storage technologies will boom in the future.
- Future national energy plans will consider distributed solar PV, storage technologies, and mini-grids for rural electrification as the quickest and potentially least-cost option for energy access. We anticipate supportive national policies for the build-out, starting in non-oil-dependent economies.
- Pioneers include Ethiopia, with an ambitious off-grid access rollout plan for 35% of the population as part of achieving universal access by 2025. Kenya and Mozambique both aim to boost renewables through through new feed-in tariffs. Kenya aims to raise electricity capacity tenfold to 23 gigawatts (GW) by 2033. Its geothermal potential offers a vision of large-scale, on-grid renewables as baseload. Mozambique is targeting 2 GW each of wind, solar, and hydropower capacity, while aiming to double electricity access to 50% of the population by 2023.
- The region will have limited explicit carbon-pricing instruments; only South Africa has begun to introduce a carbon tax. A wider range of carbon-pricing policies are expected to be announced in nationally-determined contributions for 2025 or 2030 onwards.

FIGURE 5.4.2

Sub-Saharan Africa electricity generation by power station type

Units: PWh/yr



SUB-SAHARAN AFRICA

LEAPFROGGING TO ENERGY ACCESS THROUGH OFF-GRID SOLAR PV

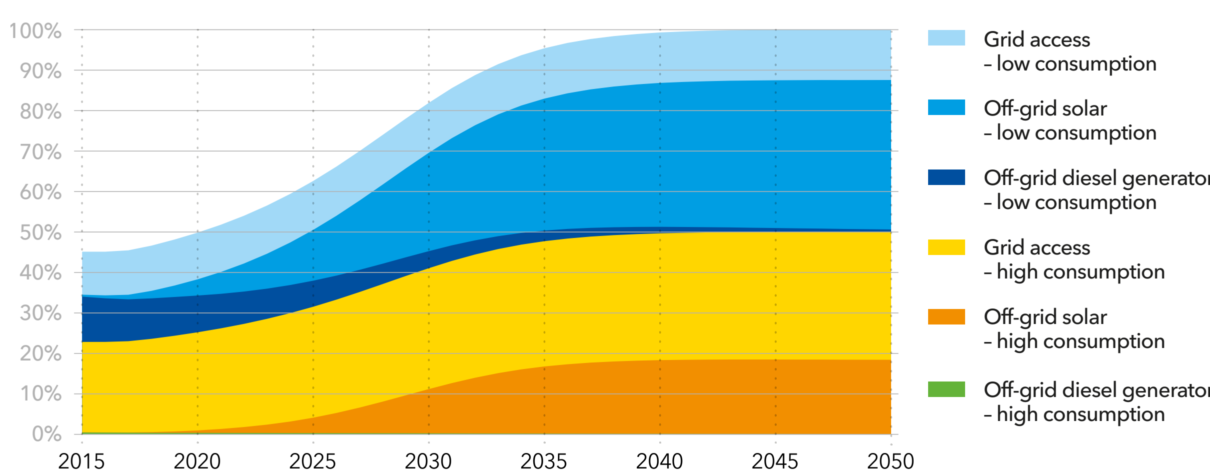
The two regions with the highest fractions of people without access to electricity are the Indian Subcontinent and Sub-Saharan Africa. Particularly-poor rural populations suffer from this, as no electricity also implies lack of access to mobile phones and the Internet, staples of modern society. We have therefore investigated the extent to which these two regions will benefit from inexpensive off-grid PV to leapfrog the grid. The conclusion from our modelling is that, because they are relatively better off, populations on the Indian Subcontinent will demand so much power that the cost advantage of off-grid solutions will be negligible, such that, by 2050, only 1% of the Indian Subcontinent's electricity will be off-grid solar PV. In contrast, the poorer Africans will typically use far less power, and for those users, off-grid solutions will imply inexpensive electricity access (Figure 5.4.3). Thus, a full 5% of the region's electricity will be delivered off-grid.

That 5% might sound insignificant; but, in terms of household access to electricity, the story is different. The off-grid solutions enable almost all Sub-Saharan Africa households to have electricity access by 2050 (Figure 5.4.3). We have classified households into two categories per their average annual power consumption: high (800 kilowatt-hours (kWh) per household per year in 2016) and low (110 kWh/household/year). Both categories see their average consumption increase by about two-thirds by 2050. The relative attraction of off-grid solutions is higher for low consumers, and 37% of such households will consequently have off-grid electricity access by 2050, while only 18% of the high power-consuming households will use such solutions. Without the advent of off-grid solar PV, more than a third of the poorest households in the region would have had to do without electricity.

FIGURE 5.4.3

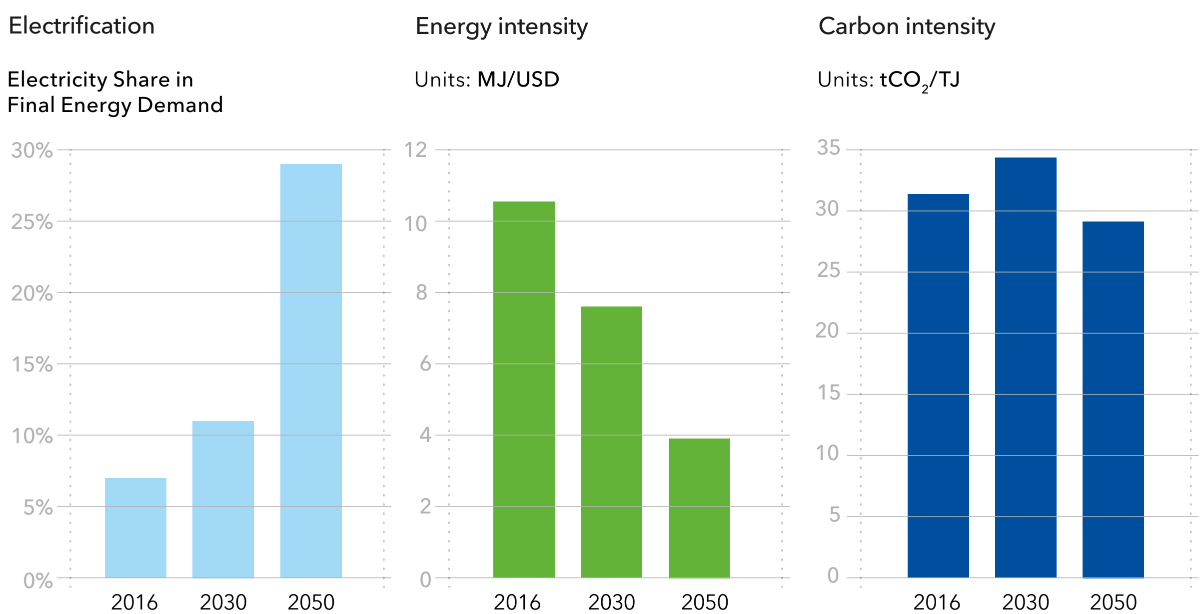
Sub-Saharan Africa population by electricity access and consumption level

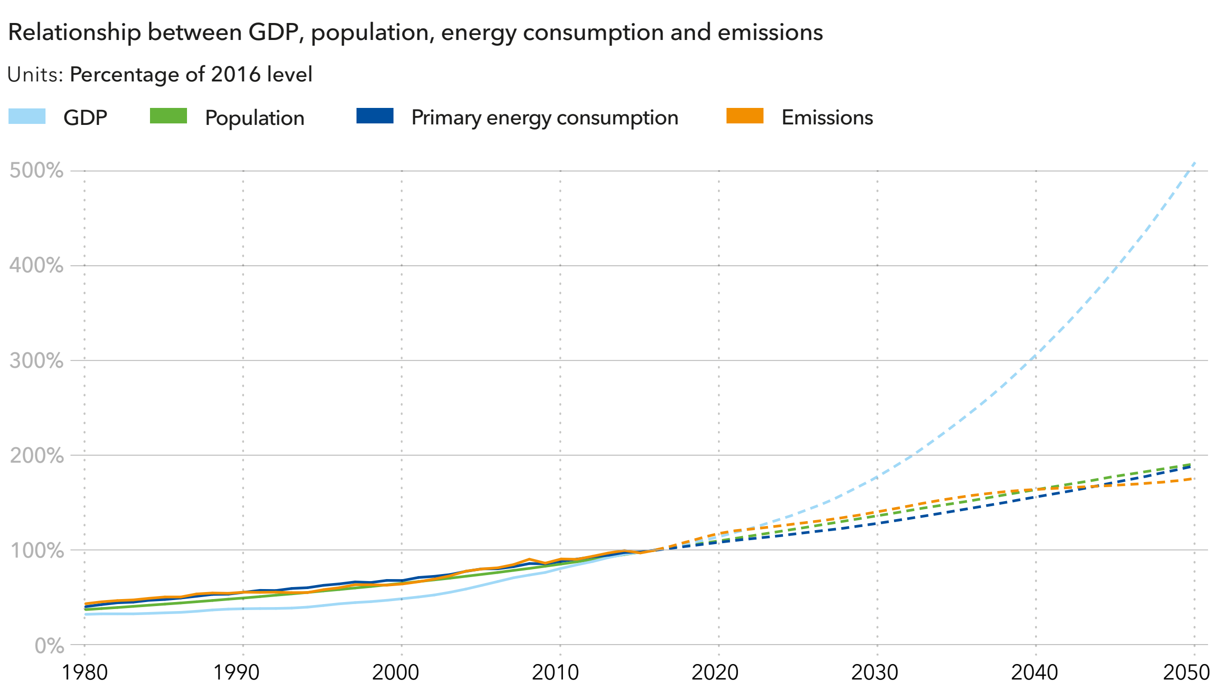
Units: Percentages



ENERGY TRANSITION INDICATORS - SUB-SAHARAN AFRICA

FIGURE 5.4.4





Economically and politically, the region is diverse and has vast petroleum resources, the largest being in Iran, Iraq, Qatar, and Saudi Arabia.

Lower oil prices since 2014, conflicts, and violence have hampered economic growth in recent years.

The region faces challenges from rising socio-economic development, youth unemployment, and the need to meet rapidly-growing energy demand while considering water and food security, climate change, and local air pollution.

Regarding the energy trilemma, the region performs well on energy access and affordability, but is challenged on environmental sustainability due to high energy intensity and GHG emissions given the dominance of fossil fuels.

Dominance of fossil energy resources drives policy in many of the region's nations. Electricity, gasoline, and water subsidies are widespread, driving high consumption per capita and draining government finances.

The region is taking serious steps to fulfil its renewable energy potential and diversify its energy sources. Jordan, Morocco, and Tunisia have set targets to transform their energy mixes. Egypt, Iran, and Turkey, which are the most populous nations in the region, have streamlined their policies to progress clean energy sectors and investment in renewable generation, and to attract foreign investors.

MIDDLE EAST AND NORTH AFRICA (MEA)

AREA

12.1 MN KM^2

THE REGION STRETCHES FROM MOROCCO TO IRAN AND INCLUDES TURKEY AND THE ARABIAN PENINSULA.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	514 MN	716 MN
GDP	5.4 TN USD	16.4 TN USD
GDP/PERSON	10,500 USD	22,900 USD
PRIMARY ENERGY USE	48 EJ	65 EJ
PRIMARY ENERGY USE/PERSON	94 GJ	91 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

MIDDLE EAST AND NORTH AFRICA

Figure 5.5.1 shows how primary energy consumption in the Middle East and North Africa will continue to grow moderately and increase 36% by 2050. Growth in energy use is driven by manufacturing, buildings, and transport up to 2040, the year when transport energy demand peaks and starts to decline. In buildings, there will be a large increase in the energy demand for appliances and space cooling as technologies become affordable for a larger share of the population and average temperatures in the region keep increasing.

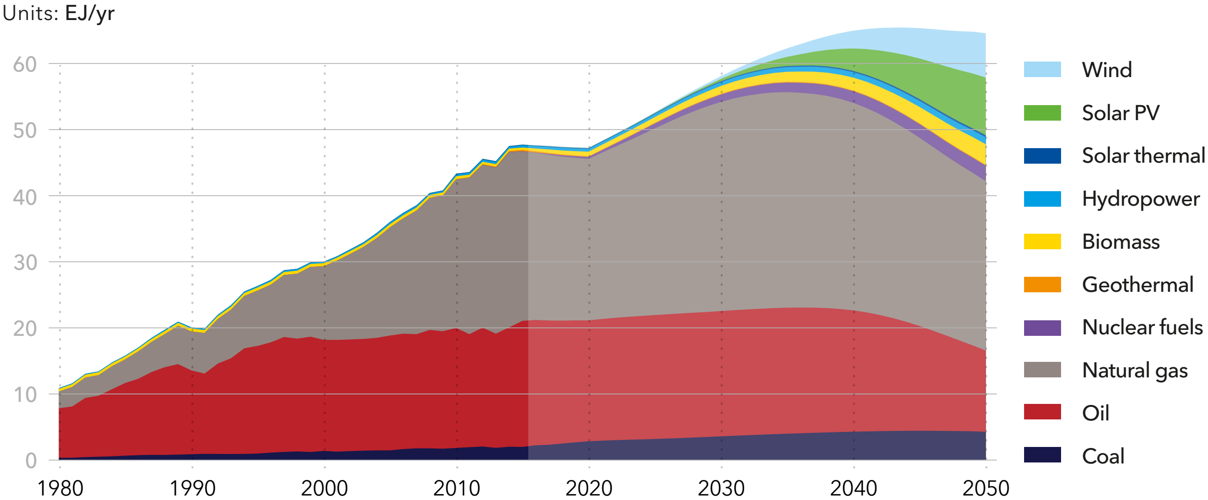
The energy mix is dominated by regional oil and gas resources, and this will continue throughout the forecast period. Oil use will peak in 2035 at only slightly more than its current level. Natural gas, already the largest energy source, will see a further increase until it peaks in 2035, 30% above its current level. In the mid-2030s, oil for road transport is increasingly challenged by the uptake of electric vehicles. Coal use will increase but will never become a significant energy source within the region.

The growth in natural gas use is primarily driven by the forecast increase in electricity demand, which will almost triple between now and 2050, as shown in Figure 5.5.2. Due to low-cost domestic gas reserves, the uptake of renewables starts later than in most other regions. In 2030, onshore wind starts to grow rapidly, followed by solar PV and offshore wind. By 2050, solar PV will be the main source of power, generating 39% of total supply. Onshore wind will then be second, with a share of 28%.

FIGURE 5.5.1

Middle East and North Africa primary energy consumption by source

Units: EJ/yr



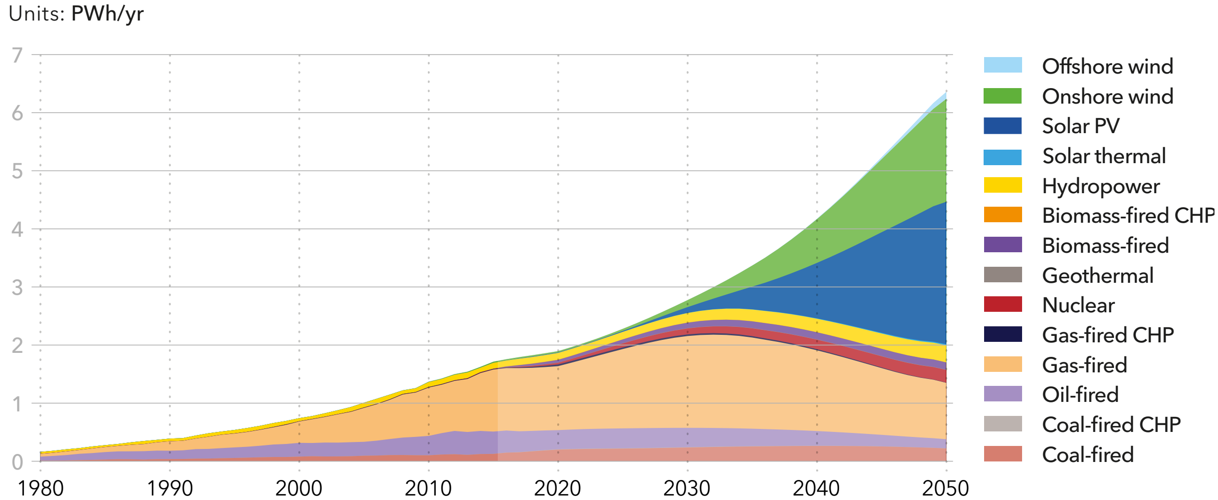
POINTERS TO THE FUTURE

- Systemic subsidization of energy and water is expected to reduce slowly with growing population, consumption, and budgetary pressures.
- Reduction of fossil-fuel subsidies is the first step towards a price on carbon, but we foresee slow adoption of, and low, carbon prices for the region.
- With these nations now feeling the effects of climate change, rising water scarcity, and a need to export fossil fuels while still meeting domestic demand, key policies will include reducing per capita energy consumption and greening supply chains.
- Conflicts in Syria, Libya, and Yemen are regional destabilizers. The disagreements between Iran and Saudi Arabia hinder regional cooperation towards common goals.
- The region has vast potential in renewables, particularly solar energy. It starts the energy transition from a very low base, however, and near- and mid-term renewables expansion will mostly be for satisfying growing domestic needs and to diversify from fossil fuel.
- Renewable energy investment and uptake will mature. For example, Egypt aims to get 42% of its electricity from renewables by 2025; Iran 5 GW by 2020; and Turkey 10 GW wind and 3 GW solar by 2019. Turkey is commissioning new hydropower. Saudi Arabia, with the largest petroleum reserves, sees renewables as a strategic priority and is investing in 9.5 GW of solar and wind by 2023. Its goal is for 30% of electricity to come from renewables by 2030. Israel aims to be reliant on natural gas and renewable energy for electricity generation and alternative fuels for transportation, also projecting the ambition to no longer import cars that run on gasoline and diesel fuels by 2030.

FIGURE 5.5.2

Middle East and North Africa electricity generation by power station type

Units: PWh/yr



MIDDLE EAST AND NORTH AFRICA

OIL POWERHOUSE IS DIVERSIFYING

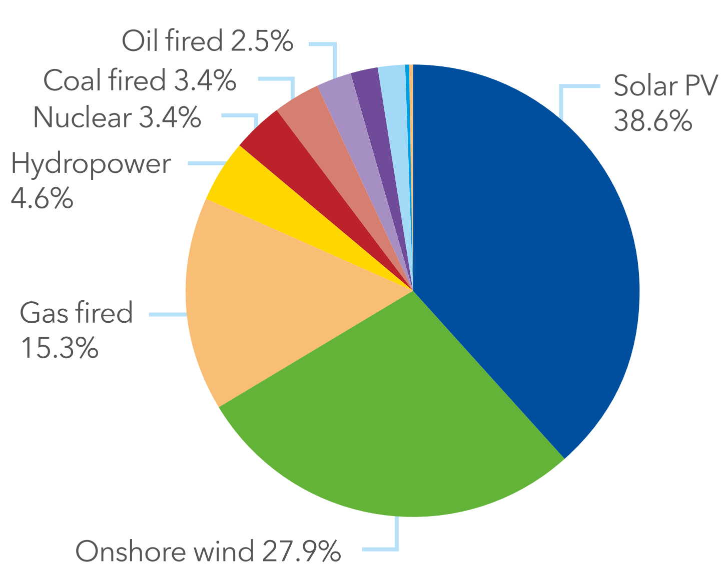
The region will remain the main global supplier of oil in our forecast. However it consists of a diverse set of countries. The three with the largest populations, Turkey, Iran, and Egypt, account for almost 50% of the region's present population, which is forecast to triple by 2050.

With growth in population, energy demand changes, and along with a cost reduction of renewables, the use of electricity will grow rapidly. Electricity, 60% of which is today generated from gas, will come primarily from wind and solar PV by mid-century, with increased support from hydropower and nuclear.

Variable renewables alone will provide more than 65% of the electricity by 2050, as shown in Figure 5.5.3. This means that even though oil and gas production will continue to play a significant role for the region, the shift to renewables will change the location of where energy is going to be produced, which in turn impacts on the region's economies and politics.

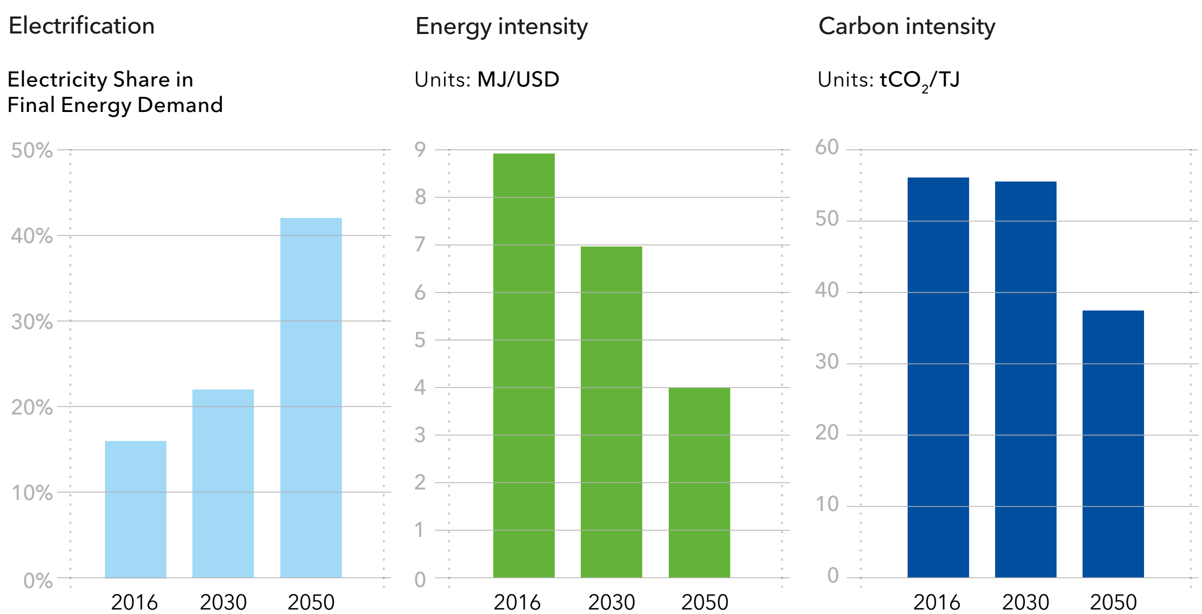
FIGURE 5.5.3

Middle East and North Africa electricity generation in 2050



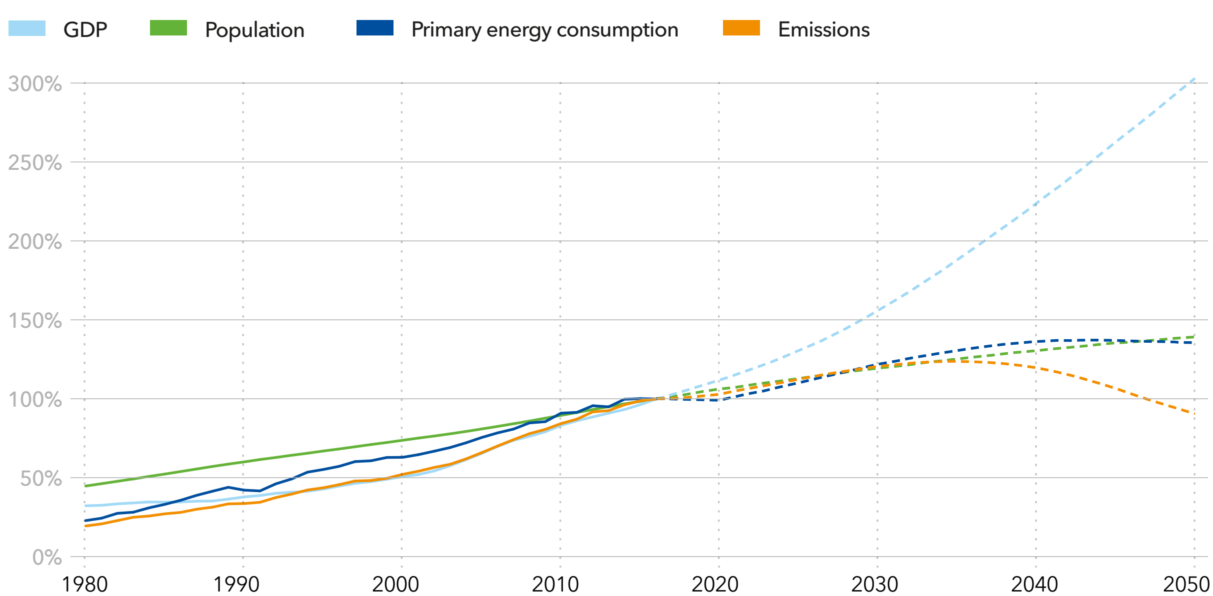
ENERGY TRANSITION INDICATORS - MIDDLE EAST AND NORTH AFRICA

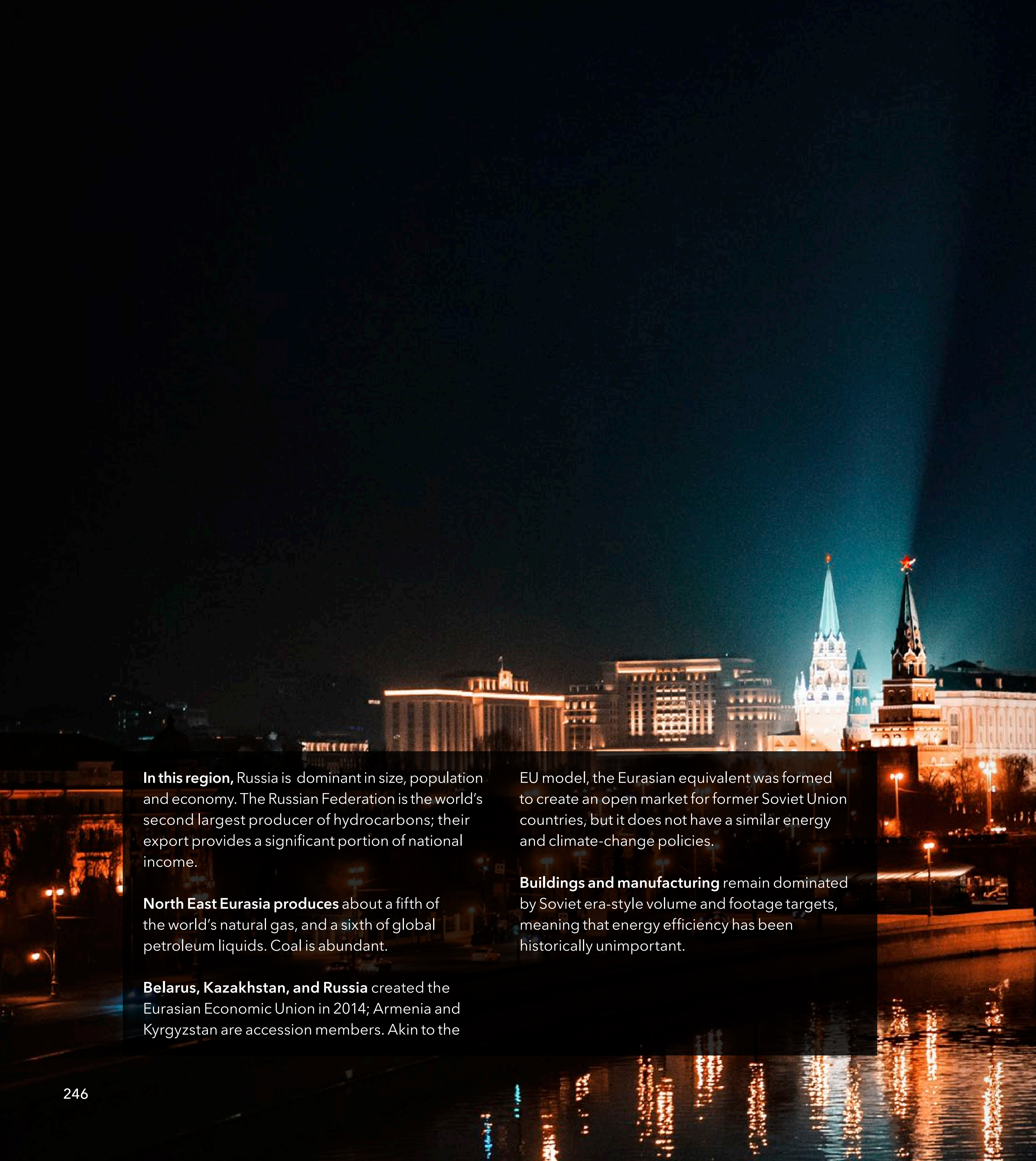
FIGURE 5.5.4



Relationship between GDP, population, energy consumption and emissions

Units: Percentage of 2016 level





In this region, Russia is dominant in size, population and economy. The Russian Federation is the world's second largest producer of hydrocarbons; their export provides a significant portion of national income.

North East Eurasia produces about a fifth of the world's natural gas, and a sixth of global petroleum liquids. Coal is abundant.

Belarus, Kazakhstan, and Russia created the Eurasian Economic Union in 2014; Armenia and Kyrgyzstan are accession members. Akin to the EU model, the Eurasian equivalent was formed to create an open market for former Soviet Union countries, but it does not have a similar energy and climate-change policies.

Buildings and manufacturing remain dominated by Soviet era-style volume and footage targets, meaning that energy efficiency has been historically unimportant.

NORTH EAST EURASIA (NEE)

AREA

23.8 MN KM^2

THE REGION CONSISTS OF RUSSIA AND ALL FORMER SOVIET UNION STATES EXCEPT THE BALTICS, TOGETHER WITH MONGOLIA AND NORTH KOREA.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	315 MN	302 MN
GDP	3.2 TN USD	6.4 TN USD
GDP/PERSON	10,100 USD	21,100 USD
PRIMARY ENERGY USE	49 EJ	30 EJ
PRIMARY ENERGY USE/PERSON	156 GJ	100 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

NORTH EAST EURASIA

Figure 5.6.1 shows how primary energy consumption in North East Eurasia will continue to decrease slowly and will be 37% lower by 2050 than today. The decrease in energy demand will be evenly spread among transport, manufacturing and buildings.

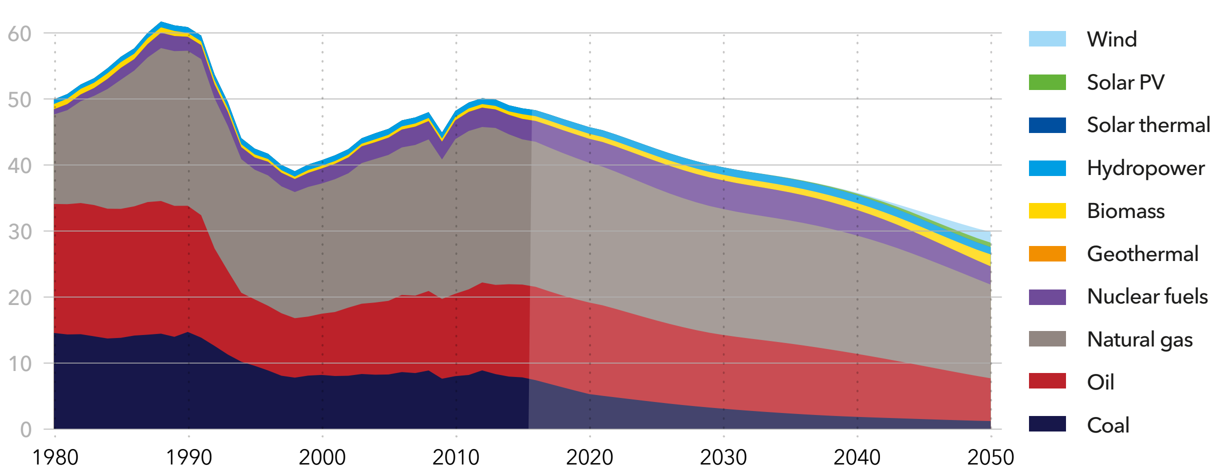
The regional energy mix will remain dominated by domestic oil and gas resources. Natural gas will see a slow decrease in absolute demand but remains the primary source of energy over the reference period, ending with a share of 47% by 2050. Oil remains the second largest source of energy but its demand will be halved through the forecast period, and nuclear has a stable position.

As in most other regions, electricity consumption in North East Eurasia will grow: Figure 5.6.2 indicates 53% growth between now and 2050. Most of that additional electricity consumption will be powered by natural gas. Coal use will become less competitive and it will play a minor role after 2025. Nuclear power and hydropower will be relatively stable throughout the forecast period. The uptake of new renewables will start later in the region than in most others: only from the mid-2030s will it start to play a larger role. By 2050, onshore and offshore wind will have a combined 19% share of power generation.

FIGURE 5.6.1

North East Eurasia primary energy consumption by source

Units: EJ/yr



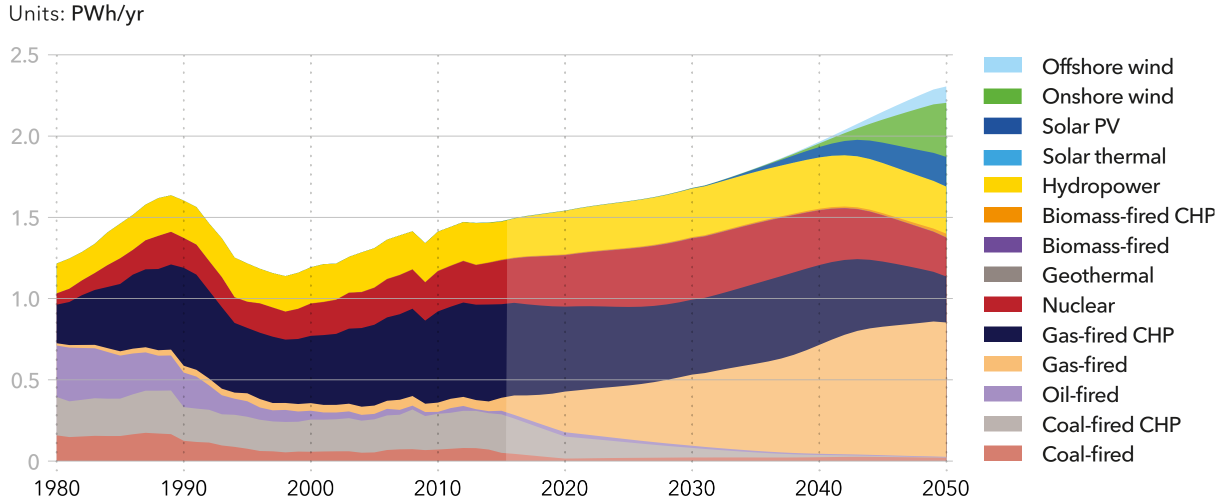
POINTERS TO THE FUTURE

- Due to abundant and cheap fossil-fuel reserves and substantial political will to develop these, the energy transition is less of a priority compared with other regions. The largest contribution to lower energy use and reduced CO_2 emissions will come from improved energy efficiency in all sectors.
- Russia has a modest target for renewables, excluding hydropower, to have a 4.5% share in electricity generation by 2020. Transmission and grid capacity to reach disconnected settlements and isolated regions are priorities.
- Kazakhstan aims to increase the share of renewables in power generation from today's 1% to 3% by 2020 and 50% by 2050. The government has implemented supportive regulatory improvements, although in tariff policies and enforcement challenges remain. Financial support from the European Bank for Reconstruction and Development will add to the likelihood of success of frontrunner projects.
- Russia proposes to have reduced GHGs by 70% over the period 1990–2030. Official announcements emphasize energy efficiency, reforestation, and carbon-free nuclear and hydropower. Policy now focuses on improved energy efficiency rather than widespread renewables.
- Slow adoption of, and low, carbon prices are expected, although Kazakhstan's Emissions Trading Scheme (ETS) will likely relaunch in 2018. Russia could embrace some form of carbon pricing to avoid carbon border-tax adjustments. Reduced fossil fuel subsidies will likely be another early step towards a price on carbon.

FIGURE 5.6.2

North East Eurasia electricity generation by power station type

Units: PWh/yr



NORTH EAST EURASIA

A NEW EXPORT MARKET

Historically, Europe has been the biggest market for gas exporters from North East Eurasia. This will remain so over the next decade, with new committed infrastructure investments to replace or supplement older infrastructure and decreasing domestic reserves in Europe.

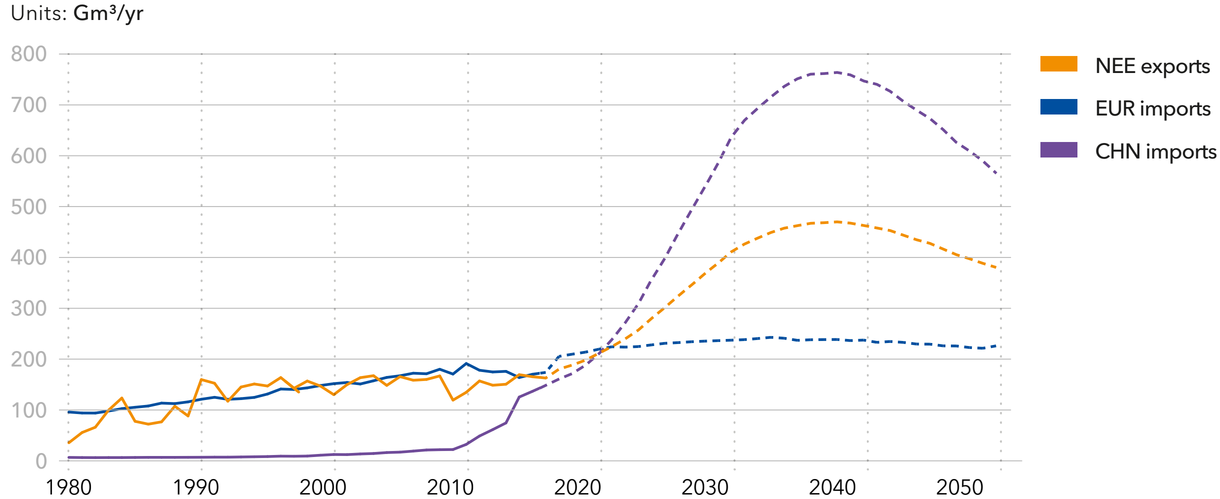
While we do not forecast a significant energy transition in North East Eurasia, it will be affected by transitions happening in neighbouring regions. Figure 5.6.3 shows that Europe's total net gas imports will increase only slightly, while its domestic production decreases at a faster pace. This can be explained by declining gas demand in Europe beyond 2020, the result of market penetration by renewables in the power sector, and because of reduced residential and industrial needs.

Another energy transition is bringing better news for North East Eurasia. As can be seen from Figure 5.6.3, Greater China's net gas imports will surge. Although domestic gas production in China will increase significantly, it will not be able to keep up with demand growth. Gas exporters from all over the world will compete to supply the fastest growing gas market in the world. We expect North East Eurasia to be a big winner through a combination of gas transported by pipeline and as LNG.

FIGURE 5.6.3

Net gas imports in Europe and Greater China vs. net gas exports from North East Eurasia

Units: Gm³/yr

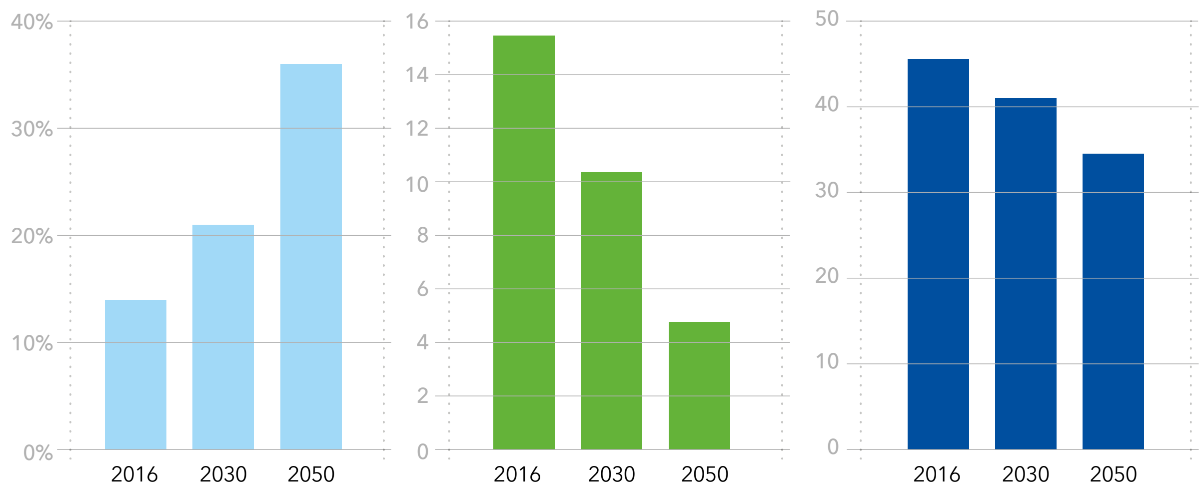


ENERGY TRANSITION INDICATORS - NORTH EAST EURASIA

FIGURE 5.6.4

Electrification | Energy intensity | Carbon intensity

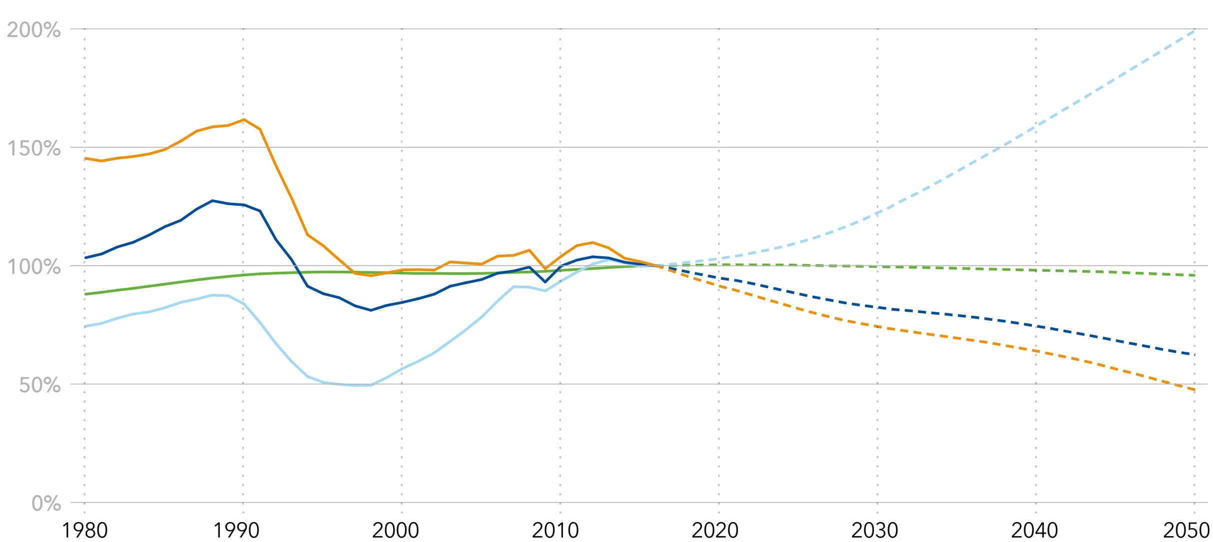
Electricity Share in Final Energy Demand | Units: MJ/USD | Units: tCO_2/TJ



Relationship between GDP, population, energy consumption and emissions

Units: Percentage of 2016 level

GDP | Population | Primary energy consumption | Emissions



China is an undisputed leader in the energy transition. It is transforming its energy mix to sustain rapid economic growth and protect local environments and the global climate. Electricity is the focus of the energy transition. The target is for renewables to account for 27% of power generation by 2020, taking advantage of the falling costs of technology.

As with its previous shifts from an agrarian to an industrial economy, and towards the tertiary sector, the government is actively steering urbanization (58.5% of population in 2017) and energy-system change.

China's five-year plans direct and influence the energy transition by stipulating targets for energy efficiency, peak emissions, and non-fossil shares, the latter targeting 15% of primary energy use in 2020. The overarching ambition is to secure supply while curbing environmental degradation and restoring the already-fragile environment. The 13th five-year plan (2016–2020) contains strategies for green development.

China combines energy, climate, and industrial policy objectives. It promotes manufacturing technologies with export potential (solar, wind, nuclear, EVs, batteries) and that have the benefit of large domestic markets.

The region is spearheading electrification of transport. It has a leading position in electric car manufacturing and is the world's largest market for electric light vehicles and buses.

LNG demand is soaring to curb local air pollution, with households switching from coal to gas.

GREATER CHINA (CHN)

AREA

9.6 MN KM^2

THE REGION CONSISTS OF MAINLAND CHINA, TAIWAN, HONG KONG, AND MACAU.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	1.43 BN	1.28 BN
GDP	16.3 TN USD	40.7 TN USD
GDP/PERSON	11,400 USD	31,800 USD
PRIMARY ENERGY USE	137 EJ	141 EJ
PRIMARY ENERGY USE/PERSON	96 GJ	111 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

GREATER CHINA

In 2010, Greater China overtook North America as the region with the highest primary energy consumption. As the result of both declining population and energy use per person, as well as a structural shift towards a service-based economy, energy demand peaks in 2033. The post-2030 decrease in energy demand will be in manufacturing and transport, while energy demand from buildings will continue to grow modestly.

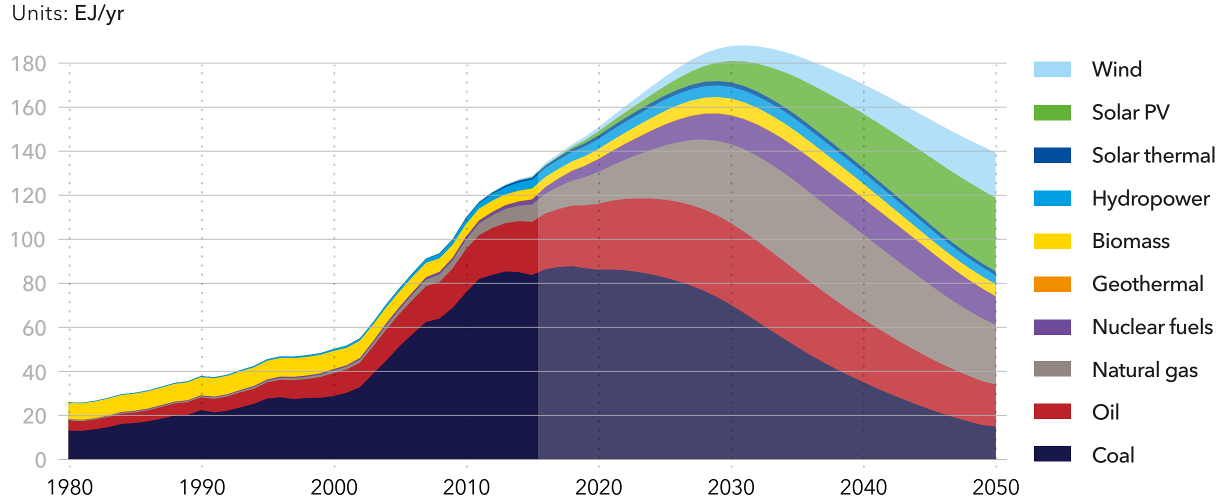
Greater China's energy mix will change dramatically, as shown in Figure 5.7.1. Currently, 82% of the region's energy demand is supplied by coal and oil. Coal is by far the largest source. From 2023, coal use will start to decline, first slowly and later more rapidly, and by 2050 it will supply only 11% of total energy. Oil use will continue to show solid growth and will peak in 2030 at a level 41% higher than today. Natural gas will grow its share in total energy use from 7% today to 19% in 2050. China is leading the world's wind and solar PV growth, and the two sources combined will have 39% of the region's energy use in 2050.

Electricity use in residential and commercial buildings, and later in transportation, increases rapidly, leading to electricity demand almost tripling by 2050, as illustrated in Figure 5.7.2. Power generation currently dominated by coal will soon diversify, with strong growth in gas-fired and nuclear power. Power production from onshore wind has been growing steadily since 2011 and will continue to do so: by 2050, it will be responsible for 26% of electricity production, with offshore wind contributing an additional 6%. The biggest winner will be solar PV, which will surpass coal as the major power generator by 2034. By 2050, it will supply 52% of the region's power needs, with a total of 7 TW installed.

FIGURE 5.7.1

Greater China primary energy consumption by source

Units: EJ/yr



POINTERS TO THE FUTURE

– Domestic renewable energy sources limits energy imports, which will remain high regardless. Securing long-term supplies of minerals and metals for clean energy technologies and infrastructure will sway geopolitics and investment in materials production.

– Local air pollution remains the key bottom-up driver of climate policy. It weighs heavily on health and welfare, and is a source of social discontent.

– Decoupling economic growth from increased energy use will continue, due also to game-changing shifts in business models. The region is a champion of ride-sharing models, and this will likely give impetus to the uptake of shared, electric autonomous vehicles in urban mobility. Circular economy initiatives will expand to slash the energy intensity of industrial districts.

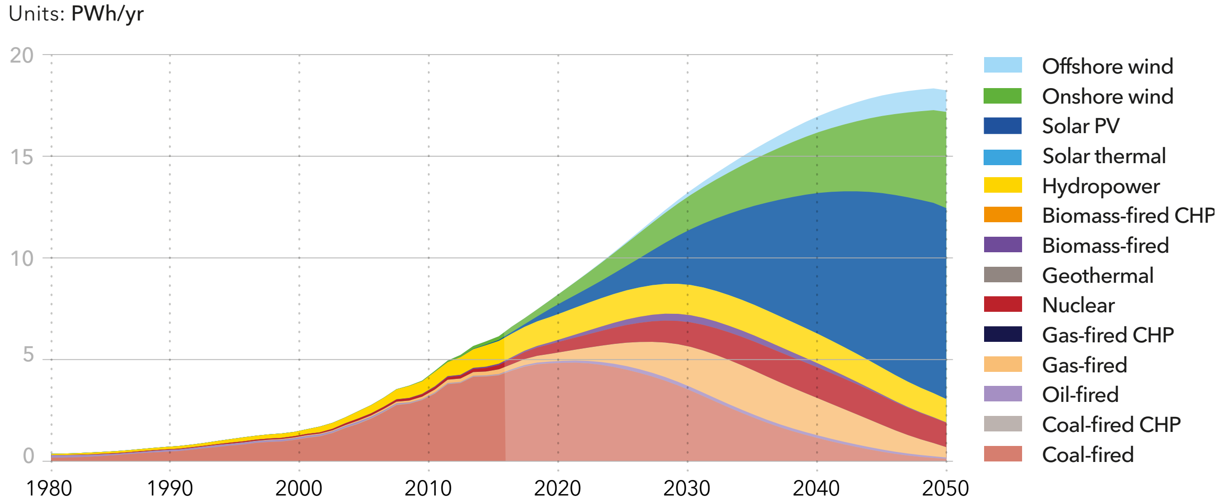
– In its Nationally Determined Contribution pledged under the Paris Agreement, China's aims for 2030 are to meet 20% of its energy needs with non-fossil energy; to reduce carbon intensity per unit of GDP by 60–65% from 2005; and for GHG emissions to peak around 2030.

– Around 1,700 power companies account for a third of China's GHG emissions. The country's national ETS starts with the power sector alone in a nationwide pilot phase. Auctions for permits are expected in about 2020. The initial seven pilot schemes will operate in parallel and be gradually moved to the national scheme, with trading eventually extending to all energy-intensive and high-emission sectors. There is speculation that China's ETS will link with world-wide systems.

FIGURE 5.7.2

Greater China electricity generation by power station type

Units: PWh/yr



GREATER CHINA

DECARBONIZATION OF THE ECONOMY

Greater China's energy use and emissions have grown significantly in recent decades, particularly in the period 2002–2012. The burden on the local and global environments caused by moving hundreds of millions of Chinese out of poverty via a coal-dependent energy sector has been severe.

Despite a continued high carbon intensity, the present situation is very different, with more-or-less flat emissions during the last few years, and Greater China becoming the undisputed leader in solar PV and wind installation and production.

We expect the energy mix to continue diversifying over the forecast period. Despite continued high emissions amid a collective global failure to reach the Paris Agreement goals, Greater China is on a track to decarbonize its economy faster than any other region over the coming decades.

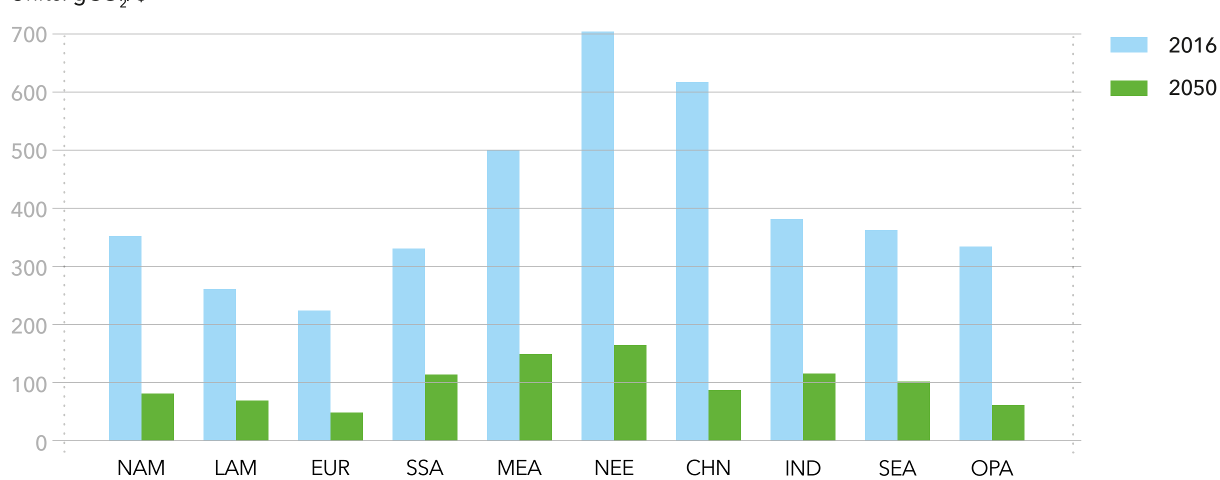
The remarkable shift in Chinese energy and climate policy is ultimately leading both China itself and the rest of the world onto a different and more promising emissions trajectory. The centralized nature of the Chinese state enables long-term strategies and effective implementation of actions.

The result is impressive from a GHG emissions perspective, as shown in Figure 5.7.3. Even though Greater China will still lag all OECD regions and Latin America in this regard in 2050, we foresee it reducing the carbon intensity of its economy six-fold from 2016 to 2050.

FIGURE 5.7.3

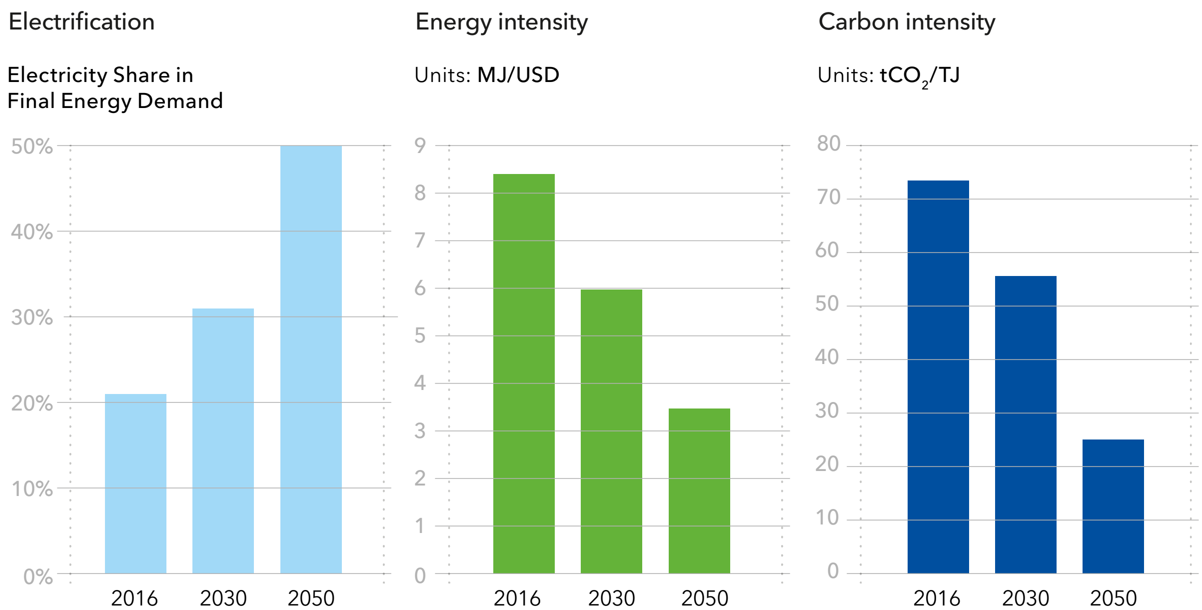
Carbon intensity of the economy by region

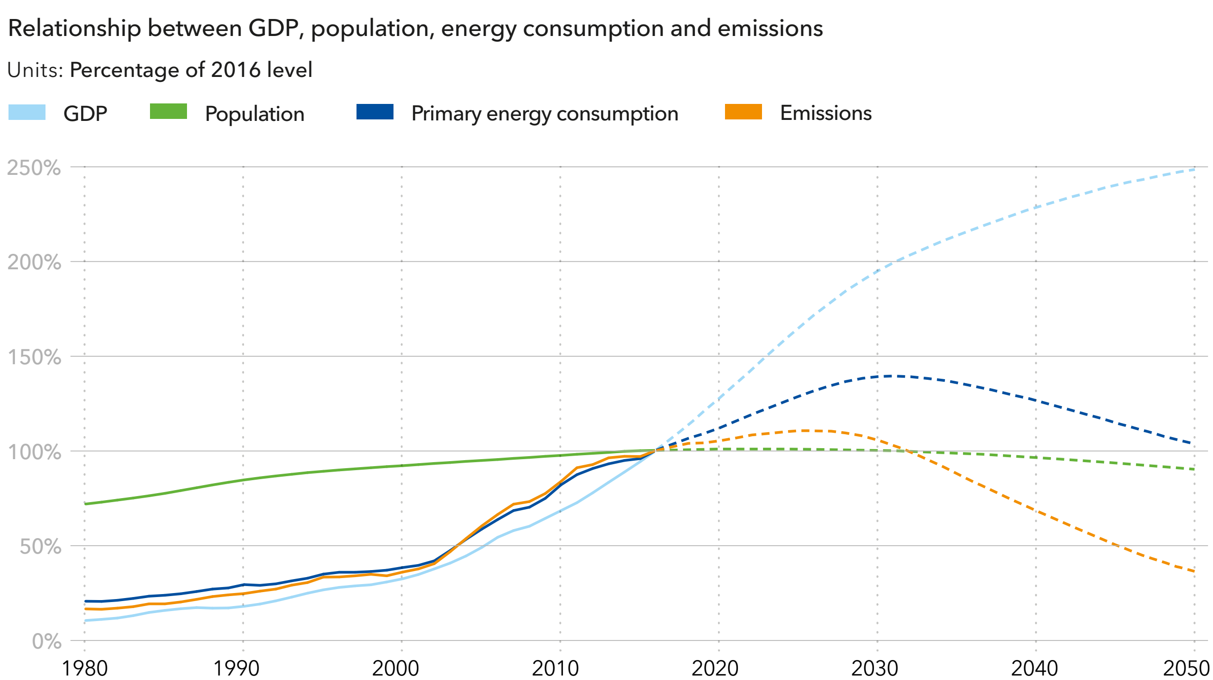
Units: $gCO_2/\$$



ENERGY TRANSITION INDICATORS - GREATER CHINA

FIGURE 5.7.4





Composed of diverse emerging economies. Energy demand is growing, fuelled by economic and population growth, although conflict-hit Afghanistan has suffered a five-year drop in GDP per person.

The energy landscape is affected most by energy-system developments in India and its choices for powering further economic growth, boosting per capita energy consumption, and expanding households' access to energy. India's own energy landscape varies by state in terms of demographics, income levels, and resource endowments.

Pakistan faces severe energy deficiency. Its energy mix is dominated by fossil fuels with reliance on imports, but it also has domestic coal reserves. It has abundant potential solar, wind and hydropower resources, which are largely unexploited.

Bangladesh faces high dependence on imported energy (LNG, coal, oil, power). It has successfully developed off-grid rooftop solar power for homes in remote areas; but utility-scale projects and renewable energy deployment have yet to take off. Fossil-fuel subsidies across gas, diesel, and electricity distribution drain budgets.

The region's high population density, especially on estuarine floodplains, renders it particularly prone to climate disruption and rising sea levels. Floods are a longstanding and major cause for concern.

INDIAN SUBCONTINENT (IND)

AREA

5.1 MN KM^2

THIS REGION CONSISTS OF INDIA, PAKISTAN, AFGHANISTAN, BANGLADESH, SRI LANKA, NEPAL, BHUTAN AND THE MALDIVES.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	1.76 BN	2.23 BN
GDP	6.6 TN USD	28.5 TN USD
GDP/PERSON	3,700 USD	12,800 USD
PRIMARY ENERGY USE	46 EJ	95 EJ
PRIMARY ENERGY USE/PERSON	26 GJ	43 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

INDIAN SUBCONTINENT

Driven by population and economic growth, the Indian Subcontinent's primary energy consumption will continue to grow. By 2035, it will overtake North America as the second largest energy user. Energy use in transport will double between now and 2050 in the region, while manufacturing will be on the way towards a threefold increase. Commercial and residential buildings' energy consumption is increasing rapidly as GDP per person grows and large groups of people are brought out of energy poverty. Some of this growth of energy consumption in buildings is offset by switching from biomass to more efficient natural gas and electricity.

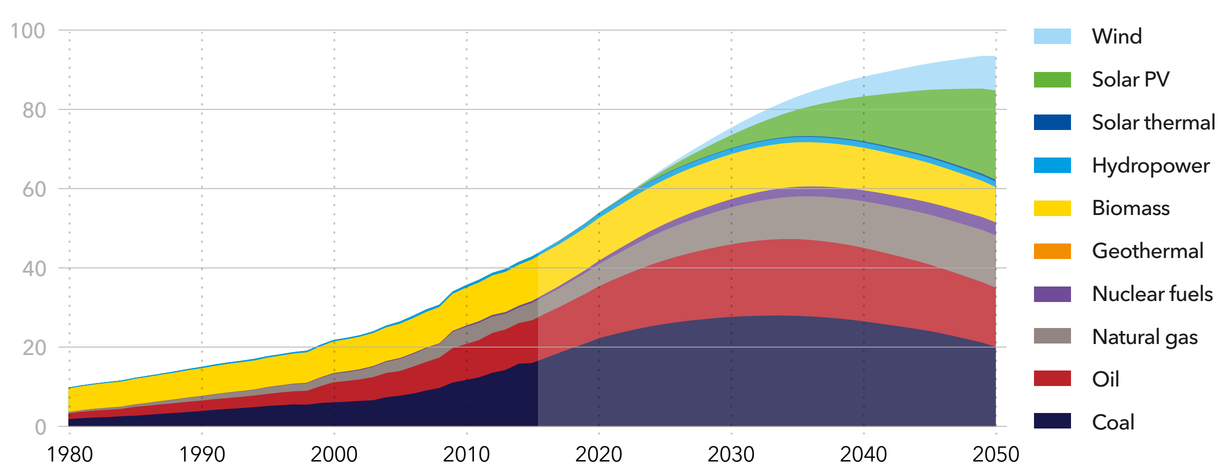
As can be seen in Figure 5.8.1, coal is the largest primary source of energy on the Indian Subcontinent and its use will grow by 51% between now and its peak in 2034. Oil consumption will increase 68% between now and its peak in 2035 as the number of cars more than triples in the next two decades. Natural gas consumption will grow, but it will not become a dominating energy source in this region, with its share of primary energy consumption increasing modestly from 10% to 14% between now and 2050. While present in the energy mix, nuclear will not play a major role, and biomass will maintain a more-or-less constant share of around 10% in primary energy consumption.

Electricity consumption will increase more than fivefold between now and 2050, as shown in Figure 5.8.2. Until 2025, most of the additional power demand will be supplied by coal-based generators. However, a fast uptake of renewables is underway, and the rapid growth is expected to continue. By 2037, solar PV will surpass coal as the largest supplier of power. By 2050, solar PV will supply 57% of the region's power needs, while onshore wind will be second with a share of 20%.

FIGURE 5.8.1

Indian Subcontinent primary energy consumption by source

Units: EJ/yr



POINTERS TO THE FUTURE

– India is targeting 175 GW of renewables by 2022, including 100 GW solar and 60 GW onshore wind. With its National Offshore Wind Energy Policy in place, the Indian government is also focused on this renewable resource.

– The Indian government is scaling up its rural electrification effort to provide more than 400 million people, including 47.5% of those living in India's rural areas, with access to electricity.

– Deteriorating air pollution in major cities is a prime concern. Under the Indian government's Smart Cities Mission initiative, 100 cities are being planned around concepts for clean and sustainable environments. The National Electric Mobility Mission Plan sets intermediate targets for vehicles and has electrification of the entire vehicle fleet by 2030 as a stated ambition.

– The region has low and limited application of explicit carbon pricing. Pakistan intends to study a possible carbon-pricing instrument. India's cap and trade system for enhancing energy efficiency in high-emission industries is expected to continue.

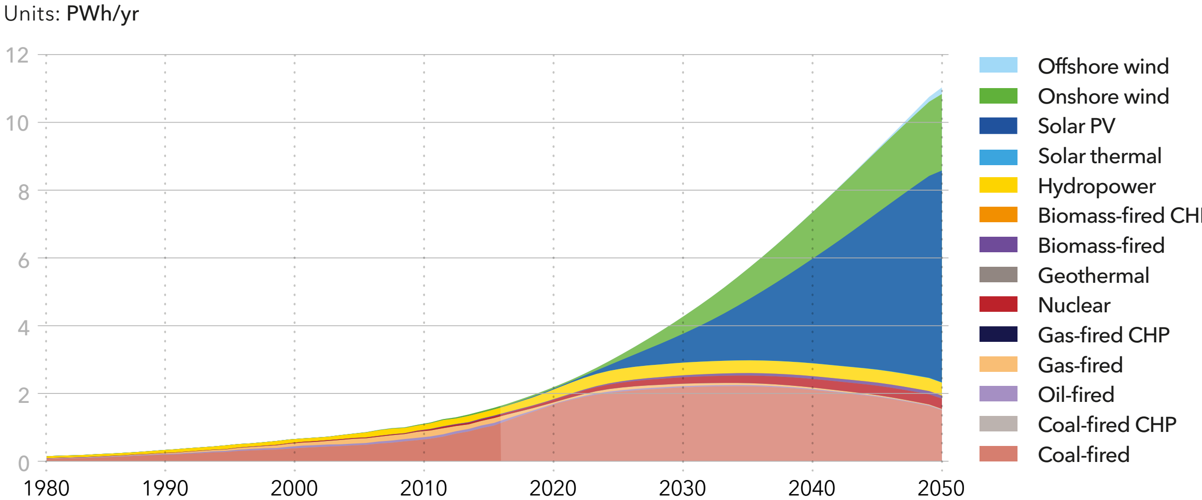
– For Pakistan, the China-Pakistan Economic Corridor projects will be instrumental in adding coal-fired power plants, renewable energy plants, and upgrades and extensions to infrastructure.

– Bangladesh is expected to strengthen renewable energy and energy-efficiency programmes to diversify and bridge its shortfall in energy supply. Inspired by India's success in cutting subsidies, Bangladesh will likely follow suit. Cross-border power cooperation will continue with India, and with Bhutan and Nepal through the development of hydropower and pumped storage.

FIGURE 5.8.2

Indian Subcontinent electricity generation by power station type

Units: PWh/yr



INDIAN SUBCONTINENT

THE POTENTIAL TO LEAPFROG COAL IS REALIZED THROUGH THE SURGE IN RENEWABLES

The Indian Subcontinent appears to be following Greater China's pattern of rapid growth in energy demand and an associated enormous expansion in the use of coal. But, is this really the case?

Over the three decades (1990–2020) of significant coal expansion in China, coal use will have seen a near-fourfold (280%) growth, as shown in Figure 5.8.3. By contrast, in India, three decades of significant coal expansion in the use of coal, between 2010 and 2040, will see a 130% rise in its use, according to our model. More interesting is coal's relative contribution to primary energy consumption. In China, the contribution of coal will be 57% by 2020; while in India, its share in primary energy consumption will reach about 30% by 2040.

Another contrast is the percentage share in the electricity mix at the time when coal peaks. In 2020, coal accounts for 58% of Chinese electricity generation. Whereas in India, coal will account for 41% of generation at the time of the expected peak around 2034. Therefore, India's 'Age of Coal' will never reach the heights of China's. While China's growth was coal-based, India takes a different route to a more diversified electricity mix. Our forecast predicts a 43% share of electricity generation for renewables by 2030 from a mix of hydropower, wind, solar and biomass; a share that grows to almost 67% by 2040.

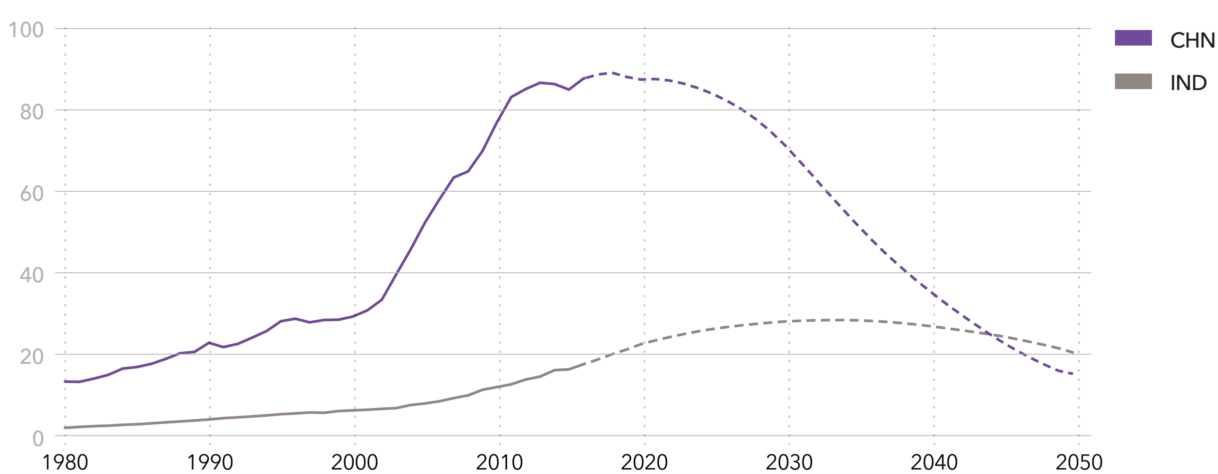
The main reason for these differences between India and China is the 20 year lag between the decades of growth in coal use in each region.

India is partly leapfrogging coal by benefitting from being a latecomer to electrification of its society. As electrification materializes much later than in OECD countries and in China, the Indian Subcontinent benefits from evolution, most notably in solar PV and wind, making renewables cheaper sources of energy than coal.

FIGURE 5.8.3

Primary energy consumption from coal

Units: EJ/yr

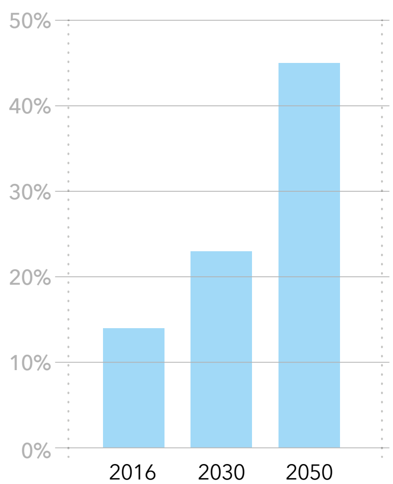


ENERGY TRANSITION INDICATORS - INDIAN SUBCONTINENT

FIGURE 5.8.4

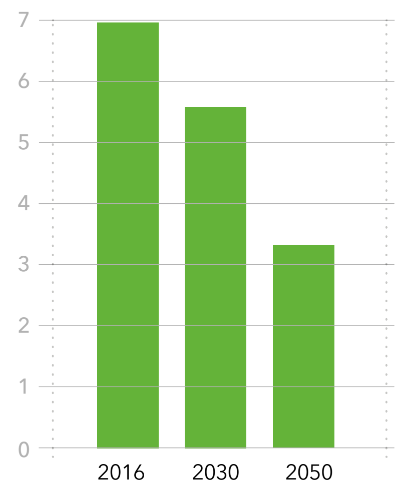
Electrification

Electricity Share in Final Energy Demand



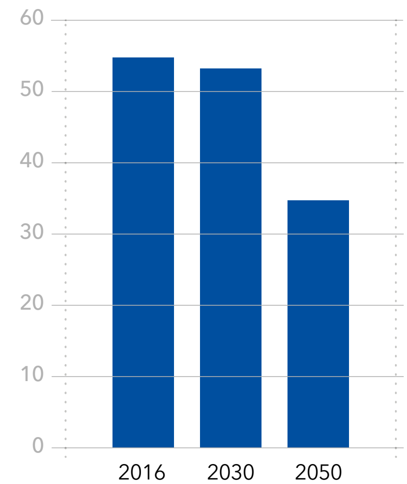
Energy intensity

Units: MJ/USD



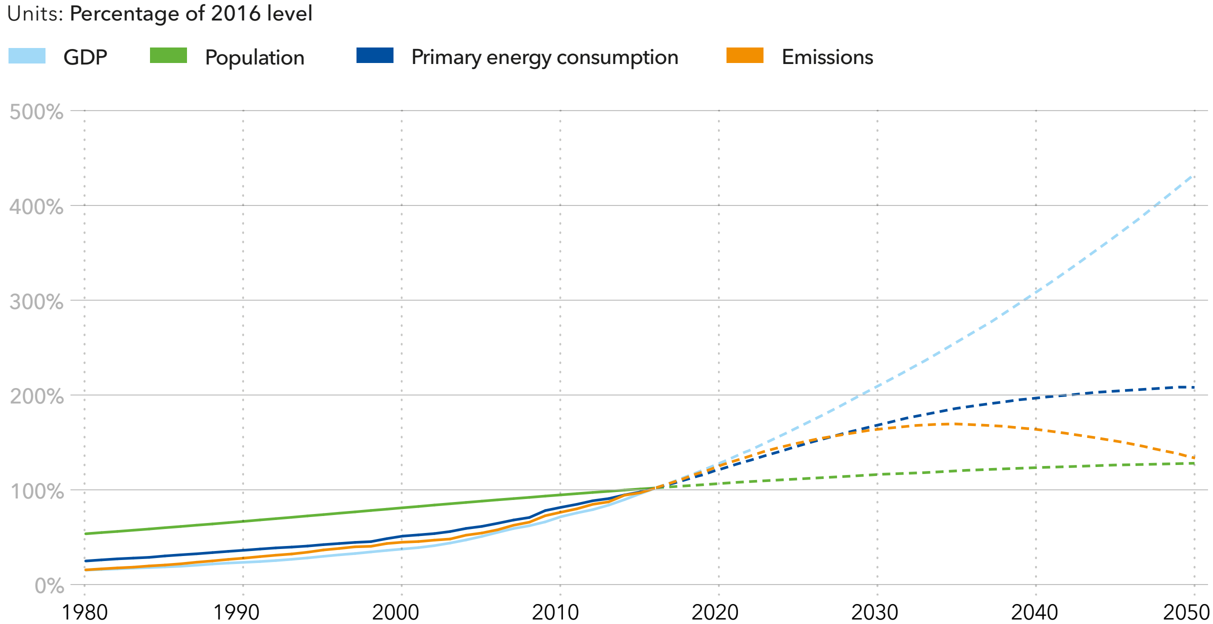
Carbon intensity

Units: tCO_2/TJ



Relationship between GDP, population, energy consumption and emissions

Units: Percentage of 2016 level



Indonesia, Thailand, and the Philippines are the largest economies. Singapore has the highest GDP per person. Although small in terms of energy use, it is a trendsetter within the region, including smart-grid technology and EV initiatives.

The pursuit of economic growth is the single most prominent unifying feature of national energy policies. Energy demand is growing with economic and population growth. A growing urban middle class is the main driver of electricity demand in residential and service sectors.

Dependence on fossil fuels is high in power generation; coal dominates, with natural gas close behind. Soaring demand and increasing reliance on energy imports mean energy security and 'clean' diversification of the mix are prime concerns in policy making to reconcile growth and sustainability.

Thailand leads the region in renewables, followed by Indonesia and the Philippines. Thailand is a regional role model for South East Asia nations gearing up renewables programmes and promotion policies.

Energy is highly politicized and remains subsidized by governments. This hinders transition towards new technologies in renewable generation and energy efficiency.

SOUTH EAST ASIA (SEA)

AREA

5.0 MN KM^2

SOUTH-EAST ASIA STRETCHES FROM MYANMAR TO PAPUA NEW GUINEA AND INCLUDES THE PACIFIC OCEAN STATES.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	650 MN	748 MN
GDP	3.8 TN USD	12.8 TN USD
GDP/PERSON	5,900 USD	17,100 USD
PRIMARY ENERGY USE	26 EJ	40 EJ
PRIMARY ENERGY USE/PERSON	40 GJ	53 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

SOUTH EAST ASIA

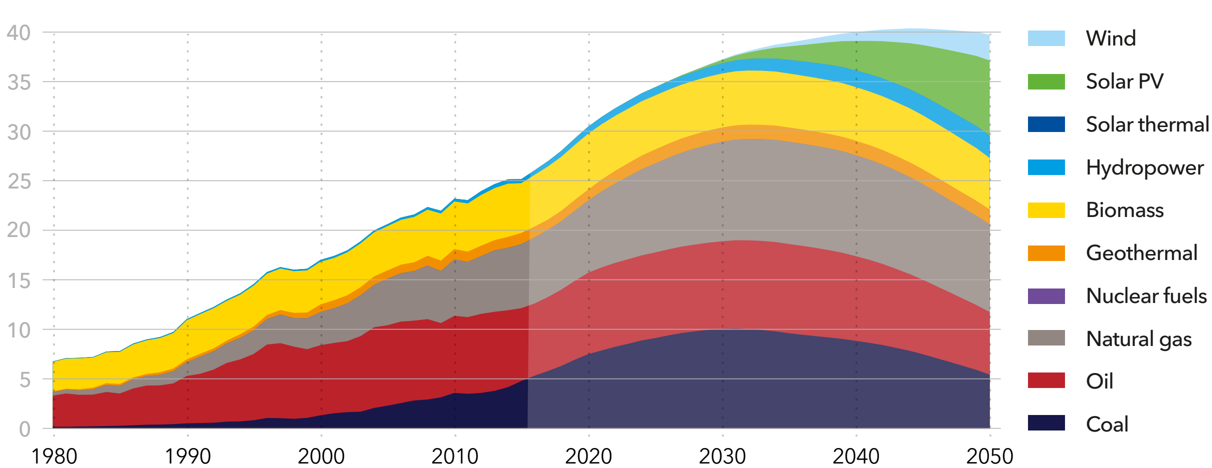
Figure 5.9.1 shows how primary energy consumption in South East Asia will continue to grow to be 47% higher than today by 2050. The projected growth is mainly the result of increased energy use in buildings and manufacturing sectors. Within buildings, energy use for cooking will decline dramatically beyond 2020 as households switch to electricity and natural gas. This efficiency gain partly offsets the large increase in energy consumption from space cooling, appliances and lighting.

Until 2030, energy use of fossil fuels will grow rapidly, with coal seeing the largest increase in absolute terms and relative to both oil and gas. Thereafter, all three fossil-energy sources peak within a period of five years, and their combined share of energy use is 52% in 2050. Biomass supply will grow modestly over the reference period. Solar PV and wind start from very low bases, but will make real contributions from 2030 onwards. Electricity consumption will increase more than threefold between now and 2050, as illustrated in Figure 5.9.2. Until 2030, most of the additional power demand will be supplied by coal and hydropower. Beyond 2030, there will be rapid growth of renewables, with solar PV taking the lead. By 2040, solar PV will have surpassed coal as the largest source of power and it will provide 49% of the region's electricity needs by mid-century. Renewables will provide 84% of total power generation by 2050.

FIGURE 5.9.1

South East Asia primary energy consumption by source

Units: EJ/yr



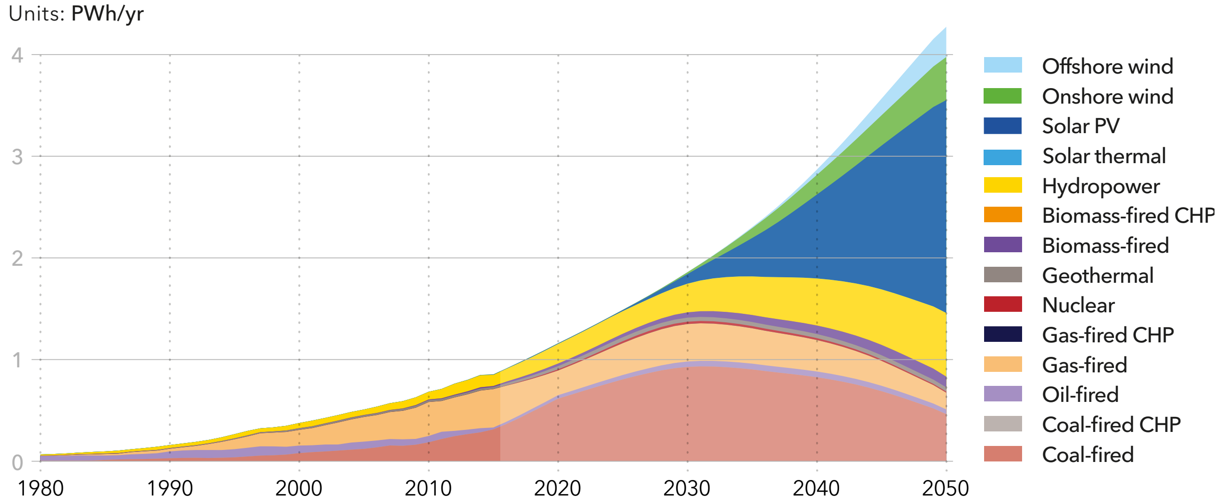
POINTERS TO THE FUTURE

- Meeting growing energy demand from rising populations in expanding economies is the key priority for South East Asian countries.
- The region is well placed for sustainable means of electrification. Soaring gas demand will drive new LNG projects. Governments will assist regional manufacturing industries to capture production of solar PV and electric vehicles.
- Lack of certainty about policy direction and investment frameworks are throttling renewable energy investments; for example, in Indonesia, Vietnam, and Malaysia. The region is considering carbon pricing amid expectation that it will be pulled along by China's carbon pricing efforts.
- Gas and power networks largely operate in isolation: stresses on grid infrastructure from integration of variable renewables need tackling. Grid initiatives will contribute to greater collective energy security and stability. One example is the Association of Southeast Asian Nations' Power Grid drive to develop a regional super grid.
- Cambodia, Indonesia, Myanmar, the Philippines and Vietnam are assessing least-cost, unsubsidized connection and fuel technologies for rapid electrification involving distributed generation and grid solutions.
- Cheap coal from Indonesia, Australia and, increasingly, from other countries shifting away from coal, will flood the regional energy market, putting pressure on transition mechanisms. Australia is predicting export growth in coal to Cambodia, Myanmar and the Philippines to replace potential lost exports to China.

FIGURE 5.9.2

South East Asia electricity generation by power station type

Units: PWh/yr



SOUTH EAST ASIA

MODERNIZATION DRIVES ENERGY DEMAND FOR BUILDINGS

South East Asia will see modernization of its building sector and increased energy use in both residential and commercial buildings. Most of the growth is based on increased use of electricity powering appliances and lighting as well as covering cooling needs.

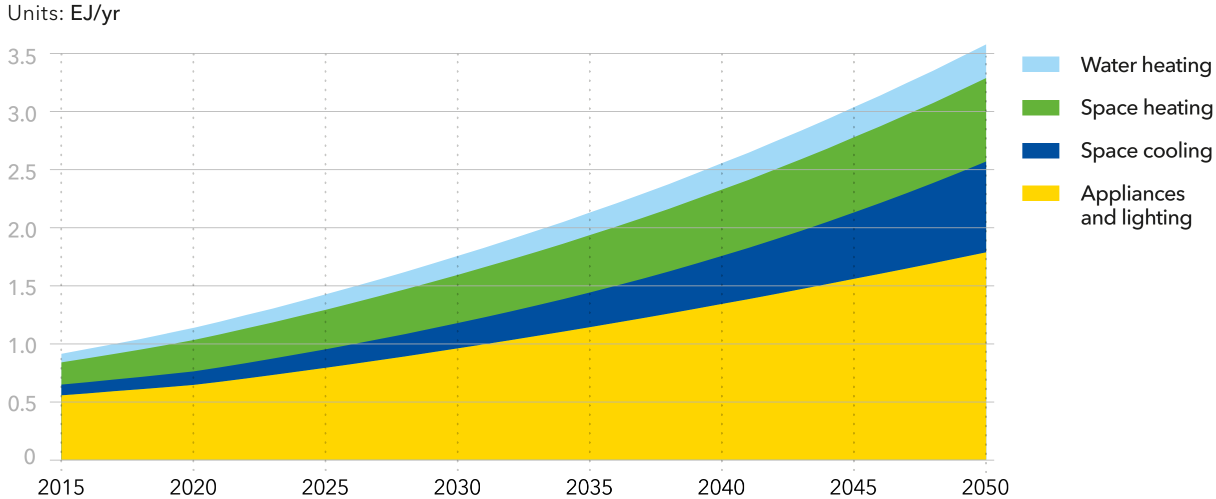
The residential sector will see a steady shift in cooking practices. Much of the expected growth will be offset by reduced energy demand related to a switch in cooking from biomass to more energy-efficient gas and electricity. While biomass use for water heating halves, there will be an overall doubling of demand for energy to heat water, with most of this consumption being met by electricity and natural gas. Overall energy demand in the residential buildings sector will grow by 18%, led by increased use of appliances and partly compensated for by switching to more efficient fuel sources for cooking.

In contrast to household efficiency gains from switching from biomass to more efficient energy sources for cooking, there is no such effect in commercial buildings. The region will see a quadrupling of energy demand for modern cooling, appliances and lighting in this sub-sector, as shown in Figure 5.9.3. Some efficiency gains will be found in space and water heating by switching from biomass and oil to electricity.

FIGURE 5.9.3

South East Asia commercial buildings energy demand by end use

Units: EJ/yr

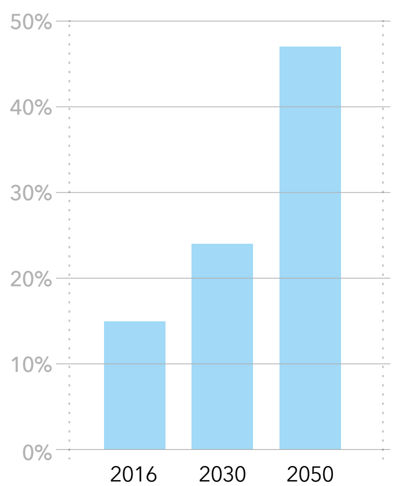


ENERGY TRANSITION INDICATORS - SOUTH EAST ASIA

FIGURE 5.9.4

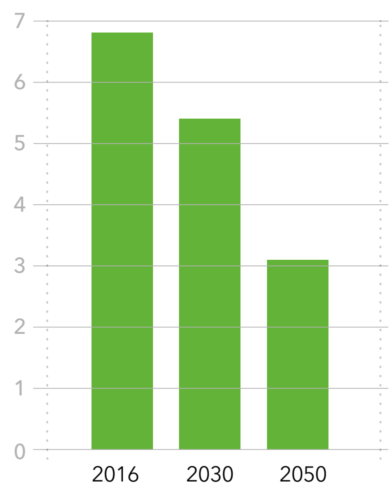
Electrification

Electricity Share in
Final Energy Demand



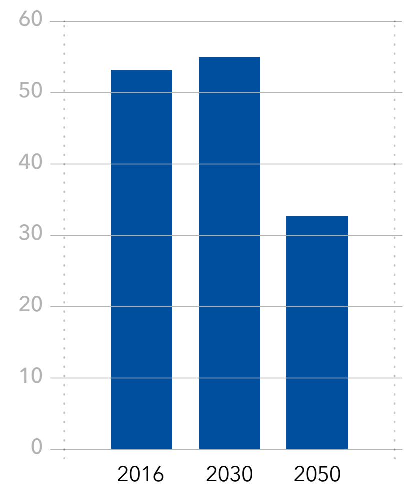
Energy intensity

Units: MJ/USD



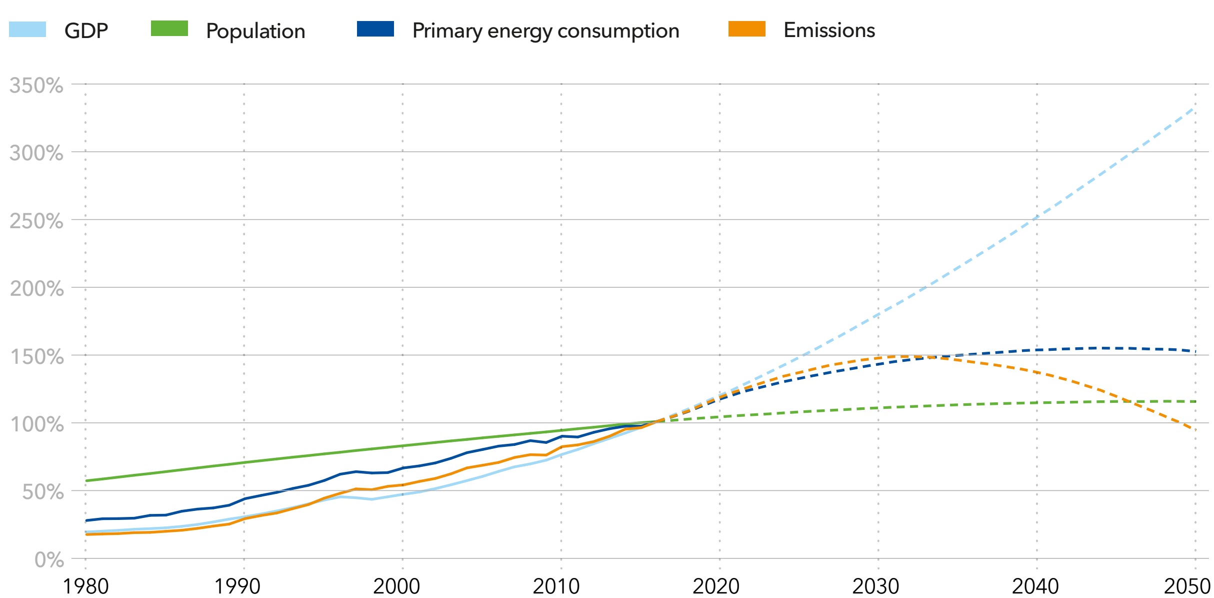
Carbon intensity

Units: tCO_2/TJ



Relationship between GDP, population, energy consumption and emissions

Units: Percentage of 2016 level



The region is diverse with respect to energy use and energy resources. Australia is a net exporter of energy; the others import energy for power generation or transportation fuel.

Energy security and sustainability are integrated into energy policies, but with varying levels of ambition. Japan, South Korea, and New Zealand have carbon pricing.

Australia exploits domestic coal and gas resources for its energy use and, increasingly, for export. Historic reliance on export revenues influences the country's future energy policies. Australia was an early leader in carbon capture and storage, but this has dropped off in recent years. With high-quality wind and solar potential, Australia is undergoing a boom in renewables and storage projects.

New Zealand has significant geothermal and hydropower generation but dwindling domestic gas supplies. For refined products, it relies on imports. It is strongly committed to renewables and is debating whether to rule out further fossil-fuel projects.

Japan imports considerable amounts of coal and LNG. Most of its geothermal and hydropower potential is deployed. Nuclear power remains contentious since the 2011 Fukushima reactor meltdown but is still a significant contributor.

South Korea is a major importer of fossil fuels and user of nuclear power. In line with its new president's election promise, it is implementing a transformation of energy policy from nuclear and coal to renewables, and to gas as a bridge energy carrier.

OECD PACIFIC (OPA)

AREA

8.5 MN KM²

THE REGION CONSISTS OF THE OECD COUNTRIES AUSTRALIA, NEW ZEALAND, JAPAN AND SOUTH KOREA.

	SNAPSHOT (2016)	FORECAST (2050)
POPULATION	207 MN	197 MN
GDP	6.5 TN USD	8.7 TN USD
GDP/PERSON	31,700 USD	44,200 USD
PRIMARY ENERGY USE	37 EJ	20 EJ
PRIMARY ENERGY USE/PERSON	178 GJ	102 GJ

All GDP figures in the report are based on purchasing power parity and in international USD 2005

OECD PACIFIC

Primary energy consumption in the OECD Pacific region will start declining within just a few years, as shown in Figure 5.10.1. By 2050, the region's final energy demand will be 45% lower than today. Population decline and rising energy efficiency are the main drivers, with energy use in both transport and manufacturing decreasing rapidly. The energy consumption of residential and commercial buildings will grow modestly, with demand from appliances and space cooling increasing while cooking and heating will become more energy efficient.

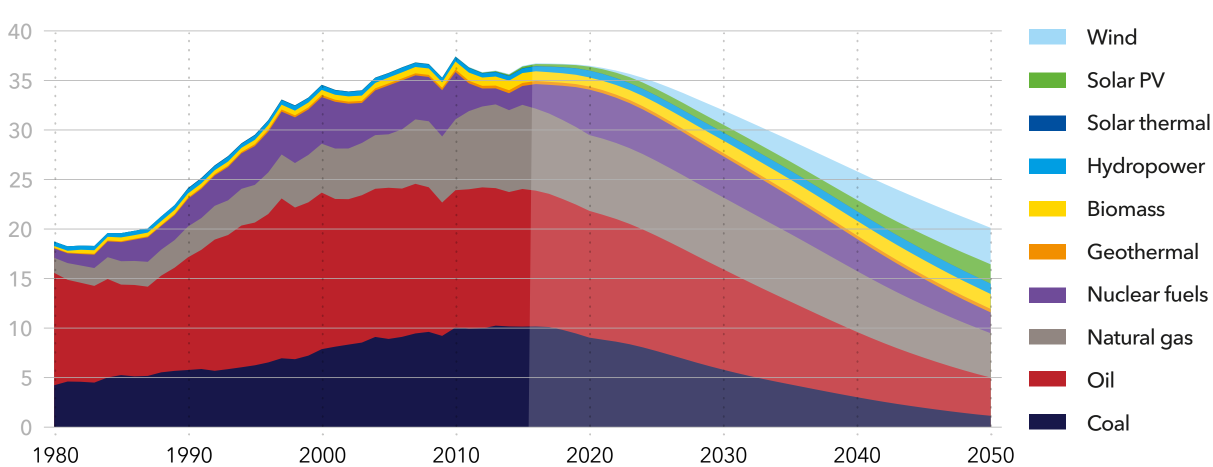
Oil and coal are currently the largest energy sources in the region but will decline rapidly. Between now and 2050, oil's share in total energy use will decline from 37% to 19% while coal's share falls from 28% to 6%. Natural gas consumption will decline, though more slowly than for the other fossil fuels, and it will overtake oil as the region's largest energy source in the 2040s.

The 30% forecast increase in electrification between now and 2050, as shown in Figure 5.10.2, is the lowest among all the regions in absolute terms, but electricity's share of final energy demand of 53% by mid-century is the highest. Nuclear power generation has been recovering after the Fukushima accident in 2011 and will continue to grow until 2020, after which it will level off and later decline slowly. Coal is currently the largest source of power in OECD Pacific but will decline rapidly. Initially this will be because of growth in nuclear and hydropower, and later because of the uptake of renewables. By 2032, onshore wind will overtake coal as the largest source of power. Late in the forecasting period, offshore wind will make a large contribution to power supply in the region. By 2040, solar PV will become the second largest power source. In 2050, OECD Pacific will have a low-carbon power mix, with renewables and nuclear having a combined share of 86%.

FIGURE 5.10.1

OECD Pacific primary energy consumption by source

Units: EJ/yr



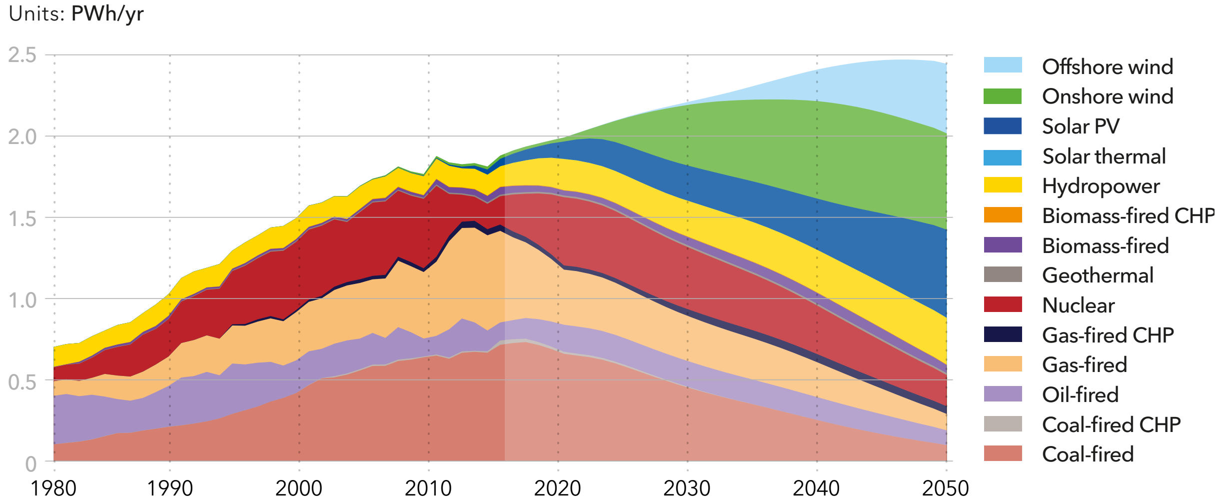
POINTERS TO THE FUTURE

- Australia lacks clear policies to achieve its commitment to reduce emissions in line with the Paris Agreement, and its emissions are growing. Emission reductions will likely be achieved by the booming renewables and storage sector rather than through government mandate or carbon pricing. Domestic coal generation is declining with no new generating plants planned, but thermal coal exports will continue to grow, primarily into South East Asia. Australia will soon be the world's largest exporter of LNG. It is starting to explore the domestic use and export of hydrogen.
- New Zealand continues to match policy with strategic energy actions. Leveraging the renewable electricity advantage is a priority in the transport sector, targeting a fleet of 64,000 EVs by the end of 2021. Energy-efficiency improvements, renewables, and efficient use of process heat in energy-intensive industries will also be priorities.
- Japan's dependence on imported fossil fuels has risen since the Fukushima nuclear plant disaster; the government plans to keep re-opening nuclear plants that can demonstrate improved safety; public finance is going to new coal-fired power plants; and the search for alternatives to energy imports continues. Japan is piloting liquid hydrogen for decarbonizing heat and transport and targeting offshore wind and rooftop solar PV growth for power generation.
- South Korea aims to increase renewables' share in its energy mix from around 7% now to 20% by 2030 under its 'Renewable Energy 3020' plan, with solar and wind as key growth areas. Domestic energy policies will continue to favour LNG and renewable energy. Hydrogen utilization is being researched and planned for transport.

FIGURE 5.10.2

OECD Pacific electricity generation by power station type

Units: PWh/yr



OECD PACIFIC

HYDROGEN ENTERING THE ENERGY MIX

Globally, electricity will be the dominant energy carrier by 2050, meeting 45% of energy demand, almost equalling the combined share of the four next-largest sources: gas, oil, biomass, and coal. The last tier of carriers, geothermal, direct heat, solar thermal, off-grid PV and hydrogen, will each account for less than 1% of energy demand. Of these, hydrogen will see the fastest increase after 2030 and this region will account for the entire growth of these so-called 'four little sisters' to electricity, as illustrated in Figure 5.10.3.

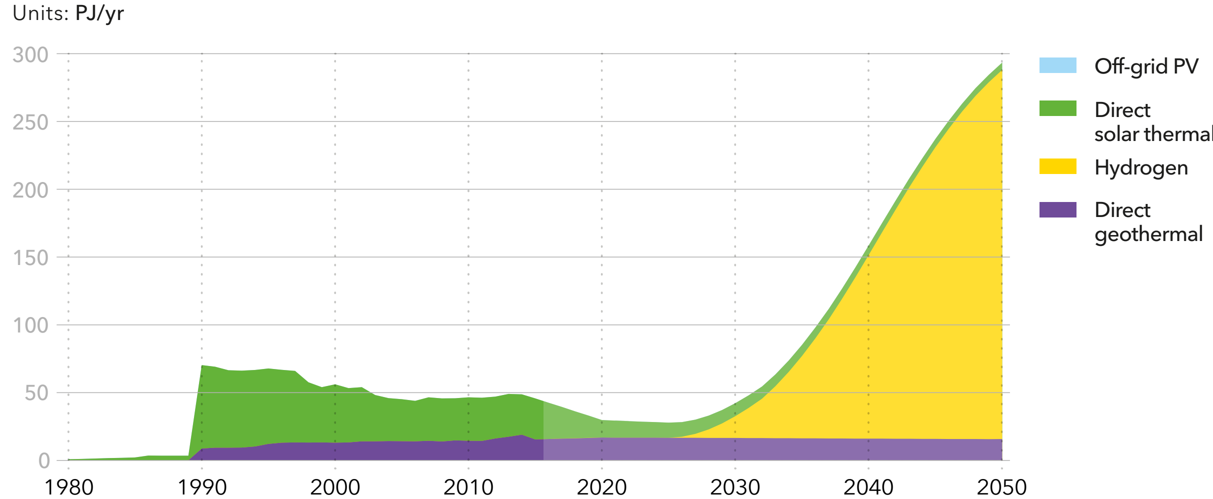
As noted in Chapter 4, hydrogen is likely only to take root in those regions where it benefits from an existing gas distribution system coinciding with a strong decarbonization public policy. High variable renewables penetration, with corresponding and substantial periods of surplus electricity being available at low cost, is also a part of the picture: it enables electrolysis-based manufacture of hydrogen.

These forces come into play notably in OECD Pacific, where Japan is the dominant energy consumer. Here, energy security in a post-nuclear energy system adds to the preference for hydrogen, as shown in Figure 5.10.3. Though it must be noted that even in this region, hydrogen will cover only 3.4% of electricity production in 2050. However, its growth curve is extremely steep. By simple extrapolation, it is possible to imagine a fully-fledged hydrogen economy by the century's end, as proposed by several, including Shell (2018). In our estimate, we see only heat and heavy road transport as hydrogen users by 2050. But players who see the steep rise after 2030 might conceivably be willing to invest more than we have assumed. Thus, replacement of fossil sources for industrial feedstock and light vehicles are alternatives that will be considered as targets by proponents of hydrogen (WindEurope 2018).

FIGURE 5.10.3

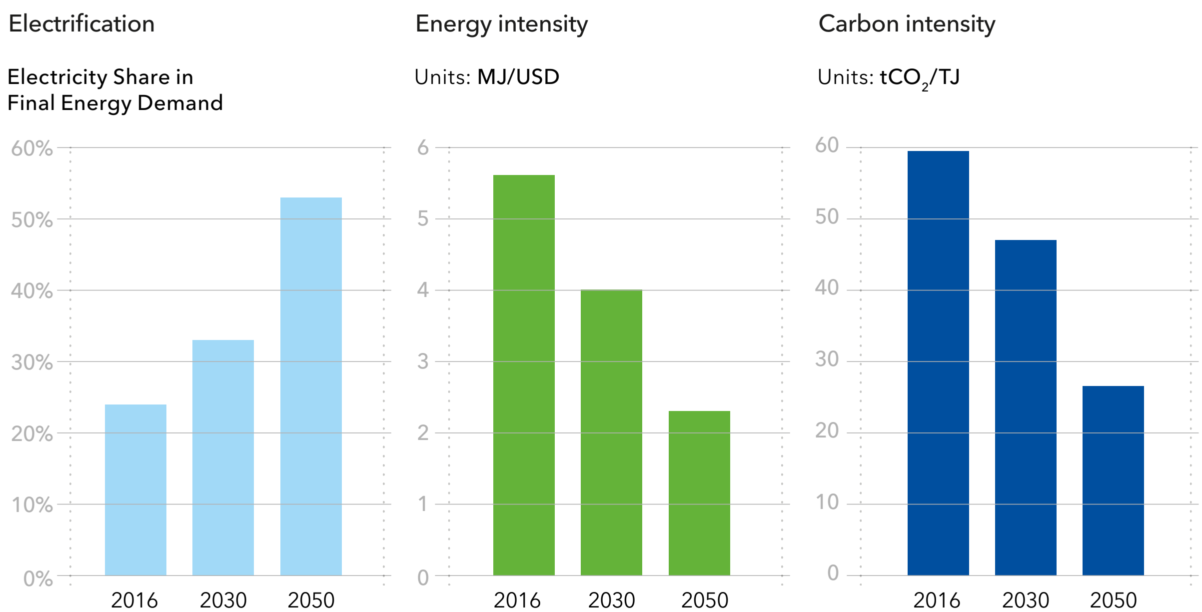
OECD Pacific use of the 'four sisters'

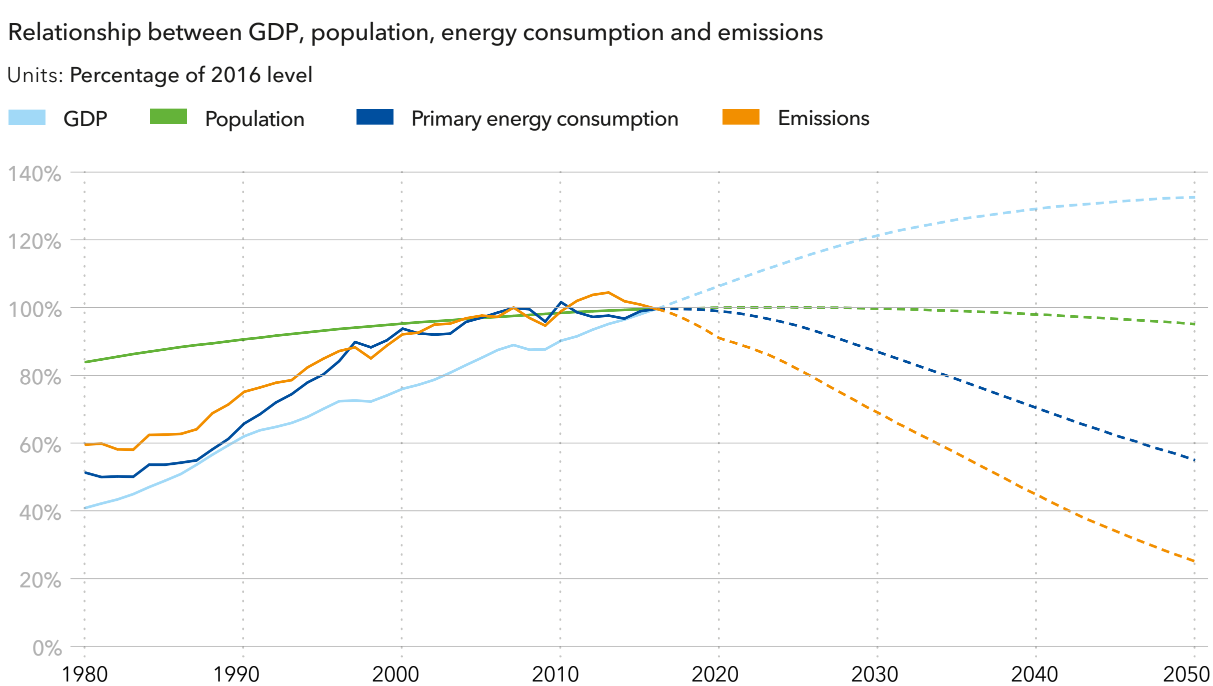
Units: PJ/yr



ENERGY TRANSITION INDICATORS - OECD PACIFIC

FIGURE 5.10.4





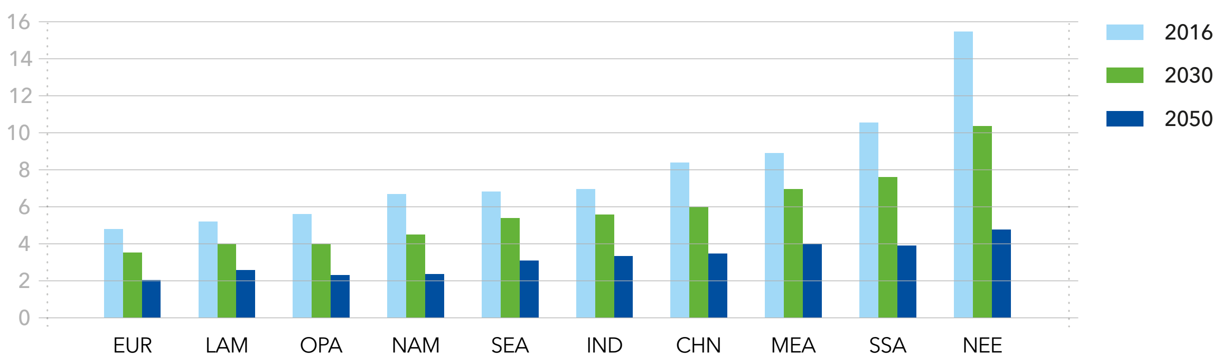
COMPARISON OF REGIONS

We present here a comparison of the regions based on key energy transition indicators.

FIGURE 5.11.1

Energy intensity of GDP

Units: MJ/USD

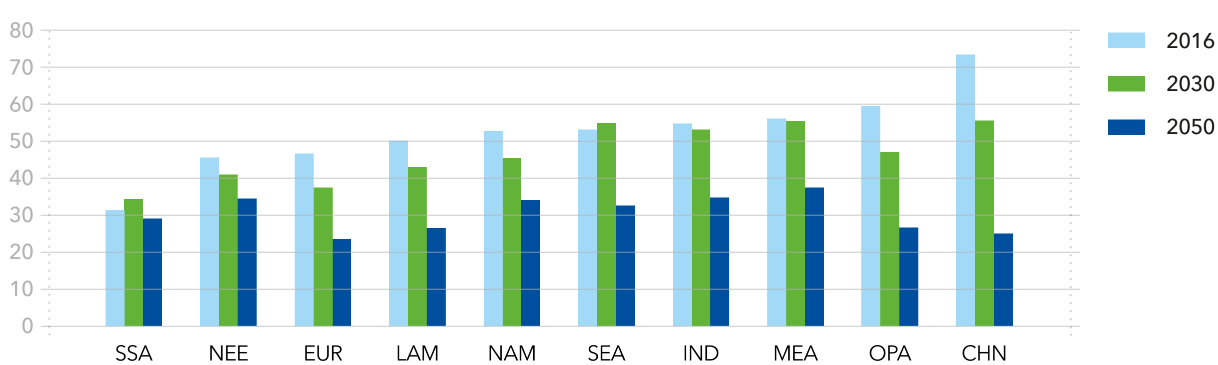


Energy intensity is measured as primary energy consumption per unit of GDP. All regions experience a decline in this measure. This is explained by efficiency gains, partly due to steady electrification of energy end use. It is also because of the increasing share of renewables in electricity generation, through which electricity becomes more efficient as losses (to heat) are much lower. Consequently, the decline in overall energy intensity accelerates. North East Eurasia sees the fastest relative decline, 69% between 2016 and 2050, followed by North America with a 64% reduction.

FIGURE 5.11.2

Carbon intensity of primary energy consumption

Units: tCO_2/TJ

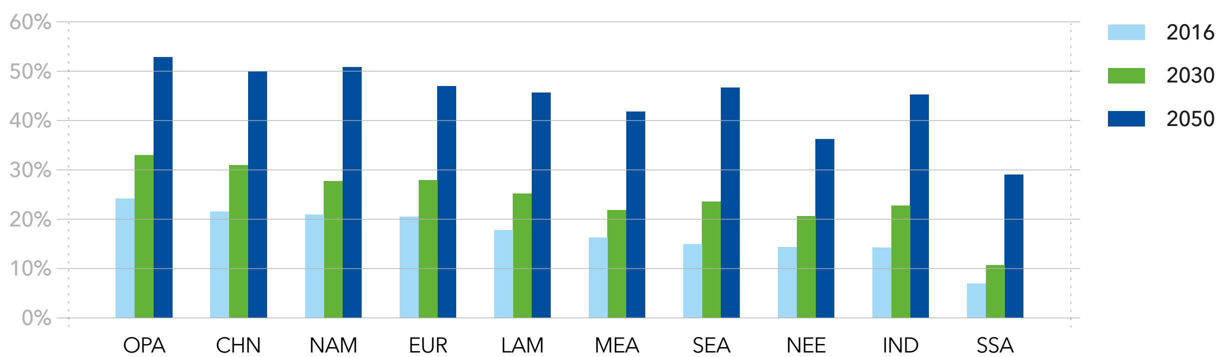


Carbon intensity is measured as tonnes of carbon dioxide per terajoule of primary energy consumption. Greater China has the most rapid decarbonization, with its carbon intensity declining by 66%, followed by OECD Pacific (55%), and Europe (49%). Sub-Saharan Africa will see the smallest relative change (7%) as the region already has a relatively low-carbon energy supply, with a large role for traditional biomass.

FIGURE 5.11.3

Share of electricity in final energy demand

Units: Percentages

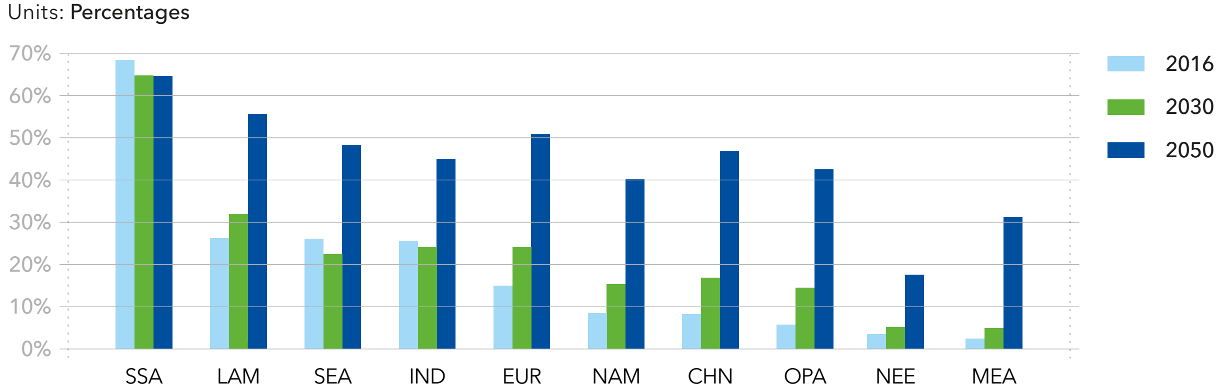


Electrification is measured as the share of electricity in the final energy demand mix. It is clearly seen that electrification is taking place everywhere. The pace will be fastest in Sub-Saharan Africa, where the share of electricity will quadruple from 7% in 2016 to 29% in 2050. The Indian Subcontinent will move into second place, as electricity's share rises from 14% to 35%.

FIGURE 5.11.4

Share of renewables in primary energy consumption

Units: Percentages



Renewables are measured on the basis of their shares in primary energy consumption. The Middle East and North Africa will see the fastest relative growth rate on this measure, from 2% in 2016 to 31% in 2050. OECD Pacific will see the second largest relative increase, with renewables' share growing from 6% to 42%.

CHAPTER 6
THE NEXT FIVE YEARS

6. THE NEXT FIVE YEARS

In this chapter, we focus on the next five years and highlight key areas that provide an indication of the direction and pace of the energy transition. These are areas in rapid flux or at a decision crossroads. Observing their development over the shorter term gives insight as to whether adjustments to our long-term forecast are required.

ELECTRIFICATION OF TRANSPORT

We see electrification of transport – buses, cars, trucks etc. – accelerating greatly over the next two decades. As battery costs tumble and EV technology matures, the road ahead is clearing for this revolution. Compared with our 2017 Outlook, our present position is much more bullish on the uptake of electric buses and other heavy vehicles. This follows very rapid development of these markets over the past year, notably in China, but also important signals from cities around the world.

> “Compared to our 2017 Outlook, our present position is much more bullish on the uptake of electric buses and other heavy vehicles.

Electrification of aviation was unheard of until just a few of years ago. Since then, several players, e.g. Norwegian Avinor and Widerøe, have begun to talk about commercial electric flights within a decade. However, for the time being our Outlook regards the uptake of electric aircraft as negligible in the coming decades.

The short-term barriers to the proliferation of EVs are well known, and include higher upfront vehicle costs, possible resource limitations on supplies of cobalt for batteries, the number of EV-charging points in cities, and range anxiety. That being said, national and local authorities have ambitious scale-up plans for EVs in their territories, and are backing this through supportive incentives and regulations. Car manufacturers are moving at great speed on R&D, and are promising a widening range of EV technology choices, models, and capabilities.

Over the next few years we will see whether battery costs continue to fall, moving EVs towards cost parity with combustion engine vehicles by 2024, as we predict. We will also see how manufacturers deliver on their promises of extended range and vehicle diversity, and how cities and communities progress on the development of charging infrastructure. A particularly interesting sub-sector to monitor is the electrification of freight vehicle fleets, as well as the general electrification of last mile parcel delivery through e-scooters, e-bikes, and, conceivably, drones (Joerss et al. 2016).

USE OF PLASTICS

Oil producers commonly point to expectations of increased use of oil as feedstock for petrochemicals when asked how electrification will affect future oil demand. DNV GL is forecasting only a temporary increase in the use of oil as a feedstock, and sees a reduction in overall use from 2030 onwards. About 30% of feedstock is used to produce plastics.

Significant and increasing global attention is focused on the use and re-use of plastics. As reported in *National Geographic (2017),* the world has produced 8.3 billion tonnes of plastics in the last 60 years, and less than 9% of that has been recycled. However, a paradigm shift – the so-called 'war on plastic' – is now underway (Hodges 2018). There is widespread concern about a massive concentration of plastic waste in the oceans, and about the potential effects of plastic microbeads in aquatic environments. Initiatives to gather, recycle or use plastics are ubiquitous. If successful, these trends will heavily influence not only the state of our oceans and nature in general, but also the future demand for oil.

> "Developments to watch over the next few years include: policies across the EU and elsewhere setting plastic recycling targets, initiatives to eliminate single-use plastics (e.g. drinking straws) and developments in the chemical recycling of plastics.

Developments to watch over the next few years include: policies across the EU and elsewhere setting plastic recycling targets, initiatives to eliminate single-use plastics (e.g. drinking straws) and developments in the chemical recycling of plastics. Primary and mechanical recycling of plastics have clear limitations, targeting mainly high-density polyethylene (HDPE) and polyethylene terephthalate (PET), and enabling the true recycling of only a small fraction of plastic waste. Even the most recyclable plastic materials tolerate only a limited number of processing cycles. For example, approximately 18% of PET in the form of plastic bottles (900 000 tonnes) is recycled worldwide, but of this, the majority is in fact downcycled to fibre production with less than a fifth reused for bottles (Garcia 2016).

Commercial pilots of chemical recycling applications – pyrolysis and solvolysis – are showing some promise. Examples include the CreaSolv® process developed by the Fraunhofer Institute and Unilever, as well as the modular pyrolysis approach being developed by Recycling Technologies in the UK for the recycling of end-of-life plastics into virgin resin, waxes and oils. If these, and related applications scale rapidly, we will need to revisit our estimates on the impact of plastic recycling on crude oil demand.

SHALE REVOLUTION

The rapid rise of unconventionals in the form of shale hydrocarbons has changed the oil and gas market dramatically over the last decade. The shale revolution has driven the emergence of the US, the dominant player in shale, as a swing producer in oil and gas markets. This has reduced the market influence of OPEC.

The longer-term impact of unconventionals is interesting. The DNV GL ETO model is not built for forecasting shorter-term price fluctuations. It does, however, indicate a longer-term downward trend in oil and gas production costs. Our Outlook uses a faster cost reduction for shale than for other oil and gas types. Observing whether the increased competitiveness of shale will continue, is key for shale to deliver to our forecast.

Methane emissions in the US gas value chain are attracting growing adverse attention because of recent assessments claiming much higher values than earlier estimated (Alvarez et al., 2018). The entire oil and gas industry can address this inefficiency by best practices and technical means to improve production and reduce overall greenhouse gas emissions. If gas is to preserve its reputation as a lower-carbon fossil fuel alternative during the energy transition, such measures will need urgent attention. If the industry fails, renewables could gain even more impetus, and, rather counter-intuitively, the relative reputation and competitiveness of coal versus gas may improve.

We forecast that the shale revolution will spread to other regions. Latin America is set to start larger-scale production of unconventionals within the next five years, for example. If this does not happen, it is an indication that the shale revolution may not extend beyond the US, though the impact of unconventional hydrocarbon production there will continue to be felt internationally in global markets.

GEOPOLITICS AND ENERGY SECURITY

The rise of mostly right-leaning populism in the Western Hemisphere is the most important political trend of this century. Although populism mainly has its roots in public opposition to immigration, cultural liberalization and perceived loss of sovereignty to unresponsive international bodies (Galston 2018), there has been a spillover effect towards economic protectionism. This has been particularly marked over the last two years, affecting global free trade and international relations. The unilateral imposition of tariffs on goods and services is growing, and some commentators fear that all-out trade wars are imminent.

The momentum of the energy transition relies on the rapid spread of new technologies, including renewables and EVs. Investors in pilot projects, technology start-ups, and uptake of technology in one region generally anticipate the subsequent development of global markets. Recent examples include the growth of international markets in energy-storage batteries, solar PV panels, and wind turbines. Increased international tension threatens our forecast rapid ramp-up of such technologies, and we will continue to track political and regulatory developments closely.

Energy security is a driver of the energy transition and international trade. Strained international relations may slow the momentum of both the transition and trade. However, it may also drive a scaling-up of domestic energy production in the form of renewables or nuclear, for example. It could also boost investment in LNG terminals, aimed at securing a greater diversity of supply in global markets.

Continued international rivalry is a threat to world growth and demand for consumer goods, energy, and raw materials. If a longer period of geo-political unrest ensues, it will likely slow world GDP growth and reduce world energy demand.

"Methane emissions in the US gas value chain are attracting growing adverse attention because of recent assessments claiming much higher values than earlier estimated.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CHINA AND INDIA POLICIES AND PACE OF IMPLEMENTATION

Only a few years ago, member countries of the OECD dominated policies to advance the energy transition. China and India are now the most important countries to watch in this regard. They are superpowers in both population and energy use, and the speed at which they shift from coal-based to renewable energy systems is a decisive factor for the world's future energy system.

Both countries have recently updated targets for technology areas and the deadlines for policy goals to be achieved. In doing so, they have shifted the goalposts for their own energy transitions and the pace of global change.

Our model results show both countries are likely to do even better than their current COP21 Paris Agreement pledges on climate change mitigation. This is not to say that we expect undeviating growth in renewables and decline in fossil fuels in either or both nations. For example, China saw an increase in coal demand in 2017 and recently introduced measures which have had the effect of dampening short-term growth of solar PV.

It is important to watch whether rapid and ambitious policy developments continue in China and India, and to track the rate of implementation and whether policy goals and quantified targets are met. There are many indicators to watch. Solar PV and wind installations are definitively important, as will be trends in coal demand over the next few years.

The Chinese and Indian heads of state are increasingly influential on the world stage at a time when the US appears to be more insular. It will be important to see whether the leadership role of the two countries will step up global cooperation and inspire other developing nations to follow suit, and, indeed, whether it will spur large developed economies, for example the US, to greater action in investing in the long-term competitiveness of their energy systems.

> "The speed at which China and India shift ... is the decisive factor for the world's future energy system.

INVESTOR MOVEMENTS

Financial investors seeking to maximize future returns on their capital are early movers on technology and resource trends. They can also rebalance their portfolios much faster than owners of physical assets. In recent years, the divestment movement targeting fossils fuels, particularly coal, has reportedly grown to more than USD 6 trillion under management (Gard 2018).

The pressure for the assessment of climate-related financial risks and disclosure has intensified with the work of the FSB Task Force on Climate-related Financial Disclosures, and attention to trustee duties and litigation is rising. This year in January, New York City announced it will sell off USD 5 billion in fossil-fuel investments from its pension fund; and in July, the Irish Parliament passed a bill requiring its Strategic Investment Fund to divest the country fully from fossil fuels (Guardian 2018).

Our Outlook demonstrates that fossil fuels have a key role to play in the energy system for many decades. Although new investment, particularly in coal and oil, will decrease over time, fresh capital is still needed to meet our forecast for required production capacity additions.

If the divestment movement continues to strengthen it will raise capital costs for fossil fuel companies trying to ensure that their mines, oil and gas fields, and plants are financed and built. The investment community also acts as a trendsetter for public and official perceptions and, later, policies. We will watch whether the divestment movement and shifts in investor preferences remain largely a facet of developed countries. If they spread worldwide, it would indicate an increase in the speed of the energy transition.

PROGRESS ON THE COP21 PARIS AGREEMENT

Following an initial burst of enthusiasm after the 2015 COP21 Paris Agreement, reality is setting in among policy makers and industry.

The sum of COP21 nationally determined contributions (NDCs) to climate change mitigation falls short of delivering on the Agreement's targets, and pressure is mounting on countries to step up their ambitions. This has been seen recently in the European Union, for example. The US's announcement that it intends to withdraw from the Agreement has shifted the balance within continuing COP negotiations. Leaders of the remaining countries have shown their continuous commitment and willingness to move forward in the absence of the US.

We recognize that while final agreement on the Paris rule book may take longer than the current agreed timeline – during COP24 in December 2018 – non-state actors are expected to continue to show leadership. They will do this by maintaining pressure on their governments and demonstrating their ability to raise the climate mitigation ambitions of their own organizations as well as those of countries. Yet it remains to be seen if the requisite political will for ambitious decarbonization can be mustered. We expect increased tension as each country will seek to best position itself within the changing geopolitical environment described earlier in this chapter.

The Paris Agreement was made possible by continuous rapid technical development, advances in energy efficiency and cost reductions in renewable energy, which, coupled with an increased local government and industry focus on decarbonization, gave countries the confidence to agree on the deal. Continued clean tech innovation should make possible stronger NDCs (Stern 2018), also making the ratcheting up of emission reduction targets less costly.

An important indicator of the likely pace of change will be the availability of international financing to encourage least-developed countries to support and implement the Agreement. One example of such financing is the USD 100 billion per year Green Climate Fund established within the framework of the UN Framework Convention on Climate Change. Action rather than promises from private business and developed world governments will be important to what is attempted and achieved in least-developed nations.

> "Pressure is mounting on countries to step up their [climate action] ambitions... Yet it remains to be seen if the requisite political will for ambitious decarbonization can be mustered.


The glacier was here in
Le glacier était ici en
1908

CHAPTER

7

CLIMATE IMPLICATIONS

7. CLIMATE IMPLICATIONS

The energy sector is the dominant source of anthropogenic greenhouse gas (GHG) emissions. In this chapter, we describe the temperature increase associated with the energy future we forecast. We begin by describing the estimated energy-related CO_2 emissions derived from our model, and then outline some assumptions on other anthropogenic CO_2 emissions.

With that information at hand, together with estimates of remaining carbon budgets, we estimate the possible global average temperature increase, remaining cognizant of the uncertainties related to carbon budgets and their related climate response.

Global energy-related CO_2 emissions have been virtually flat at around 32 Gt (gigatonnes)/yr over the last three years (IEA 2017a), however 2017 is projected to have an increase of 2% (Le Quéré et al. 2018). Our Outlook projects energy-related emissions to stay virtually flat over the next decade, reaching their highest level in 2025, some 3% higher than today. Thereafter, they will decline steadily over the remainder of our forecast period to the point where they are reduced by almost 50% to around 18 Gt by 2050, as illustrated in Figure 7.1.

Energy-related emissions primarily originate from burning fossil fuels. Based on our forecast of primary energy use, by 2050 emissions from coal will have declined by almost 65%, emissions from oil by 52%, but gas-related emissions will have increased by 6%, as indicated in Figure 7.1. By 2050, we predict that only a small fraction of fossil-related emissions, 0.3 Gt or 1.7%, are captured by carbon capture and storage (CCS).

The 10 different regions do not perform alike in the forecast period. Sub-Saharan Africa is the only region that continuously increases its emissions, but from a very low base. Greater China, currently the largest emitter, will have peak emissions in the mid-20s, which will subsequently reduce by more than two thirds. The share of global emissions from North America, Europe and OECD Pacific will decline, but it will increase for the Indian Subcontinent, Sub-Saharan Africa, the Middle East and North Africa and South East Asia. Greater China and the Indian Subcontinent will be the biggest emitters by 2050 (Figure 7. 2).

When comparing emissions per person, North America will have the highest per person rate in 2050, followed by North East Eurasia and the Middle East and North Africa. Emissions per person will remain lowest in Sub-Saharan Africa.

> “We project energy-related emissions to stay virtually flat over the next decade, reaching their highest level in 2025, some 3% higher than today.

FIGURE 7.1

World energy-related CO_2 emissions from fossil fuels

Units: $GtCO_2/yr$

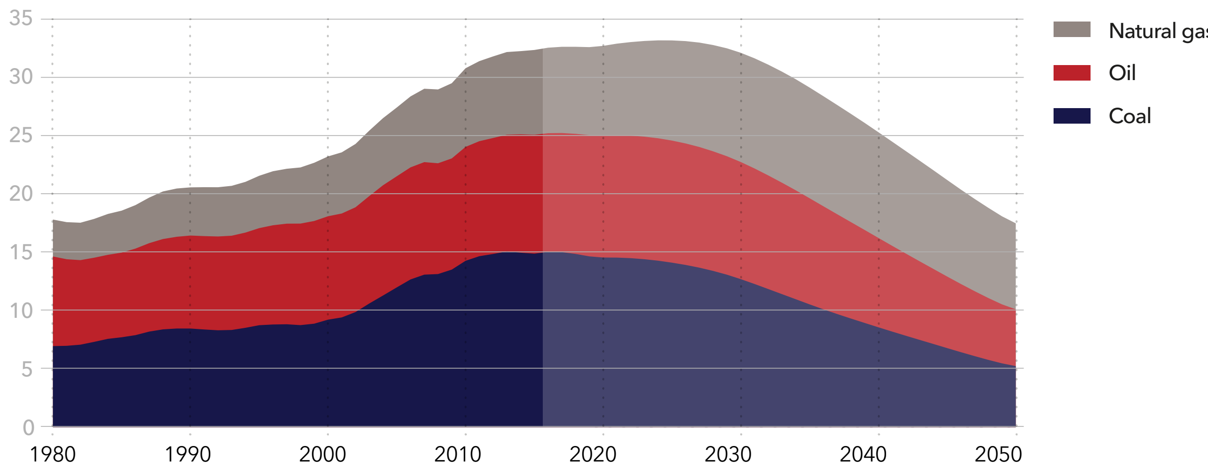
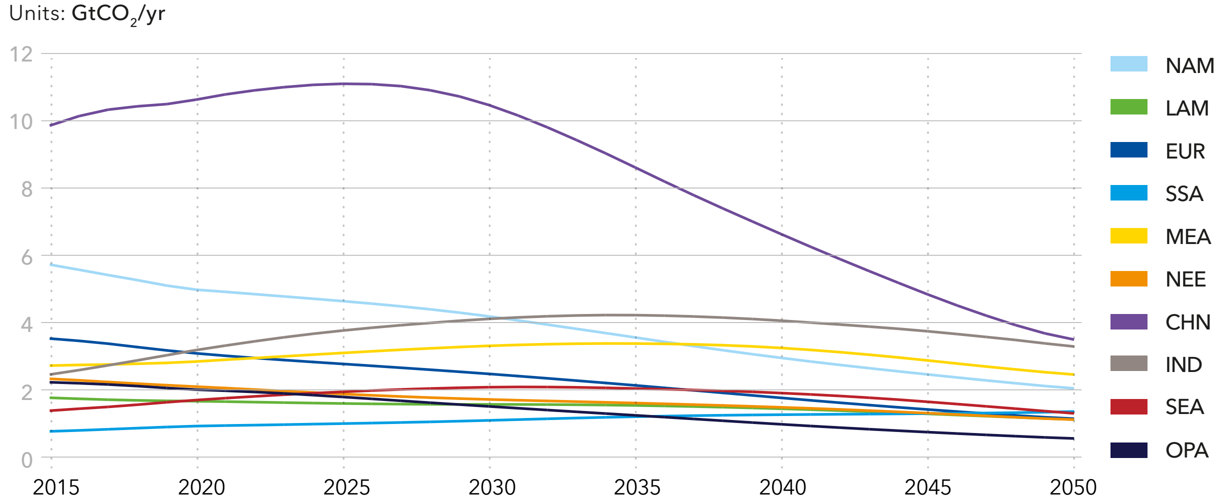


FIGURE 7.2

Energy-related CO_2 emissions by region

Units: $GtCO_2/yr$



NON-ENERGY RELATED EMISSIONS

In addition to emissions from the energy sector, our Energy Transition Outlook model includes emissions from industrial processes that consume fossil fuels as raw material in the different sectors, without using the fuel or transforming it into another energy carrier.

Our model does not include emissions from industrial processes not associated with fossil fuel combustion (e.g. calcination in the cement process). Emissions from these sources are by definition not linked to the amount of fuel that is burned. Estimates for industrial emissions are 2.7 Gt CO_2/yr as of 2015 (Olivier et al. 2016). About 50% of these emissions come from cement production. The remainder is split between coke ovens and the production and use of chemicals, lime, metals, and CO_2 venting. Based on recent trends (Olivier et al. 2016), we estimate a 10% increase in industrial emissions stabilizing at 3.0 Gt CO_2/yr in 2016. Although we forecast that output of global base materials will increase by 68% by 2050, we expect that these industrial emissions will stay flat, on average, because of process improvements (e.g., switching to more efficient kilns in cement production and other technical improvements). These developments will decrease emission per tonne of industrial output. However, we acknowledge the uncertainty in this.

Emissions from AFOLU (agriculture, forestry and other land use) are not included in our model. Historically AFOLU emissions have contributed around 5 Gt CO_2/yr to global emissions, with the most recent reading for 2017 at 4.8 Gt (Le Quéré et al. 2018). There is some uncertainty regarding new increases looming as some countries reverse their progress. Mitigation steps include measures on both the demand side and the supply side, and their effects can have a large impact, including negative carbon emissions (IPCC 2014b). In our Outlook, we assume a future mainly in line with SSP2, and, as described in Chapter 2, we expect climate and sustainability concerns result in policy decisions that place pressure on controlling AFOLU and other emissions in the future. Thus, in our model, CO_2 emissions are reduced linearly by 50% from land use changes, falling from 4.8 Gt in 2015 to 2.4 Gt in 2050. Although continued decline is uncertain in the short term, this is likely to be a conservative assumption in the longer term, as a much more aggressive reduction to zero or even carbon-negative emissions is possible.

DECARBONIZATION OF THE ENERGY SYSTEM

Decarbonizing is occuring in multiple areas of the energy system. This includes gas-for-coal switching, for example in North American power production – and, more fundamentally, the decarbonization that follows the growth of renewables and their replacement of fossil-based energy, primarily in the electricity sector.

> "Due to the increasing use of electric power in all three key energy demand sectors there will be a significant decarbonization effect.

The rate at which the entire energy system is decarbonizing (with carbon intensity measured as tonnes of CO_2per terajoule – tCO_2/TJ) is shown in Figure 7.3.

Owing to the increasing use of electric power in all three key energy demand sectors – transport, buildings, and manufacturing – there will be a

FIGURE 7.3

Carbon intensity by sector

Units: tCO_2/TJ

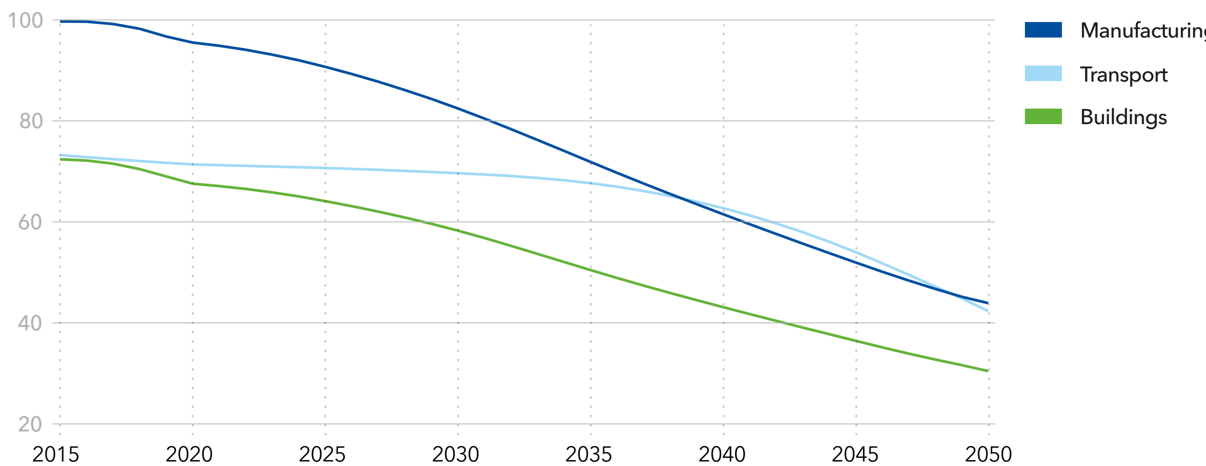
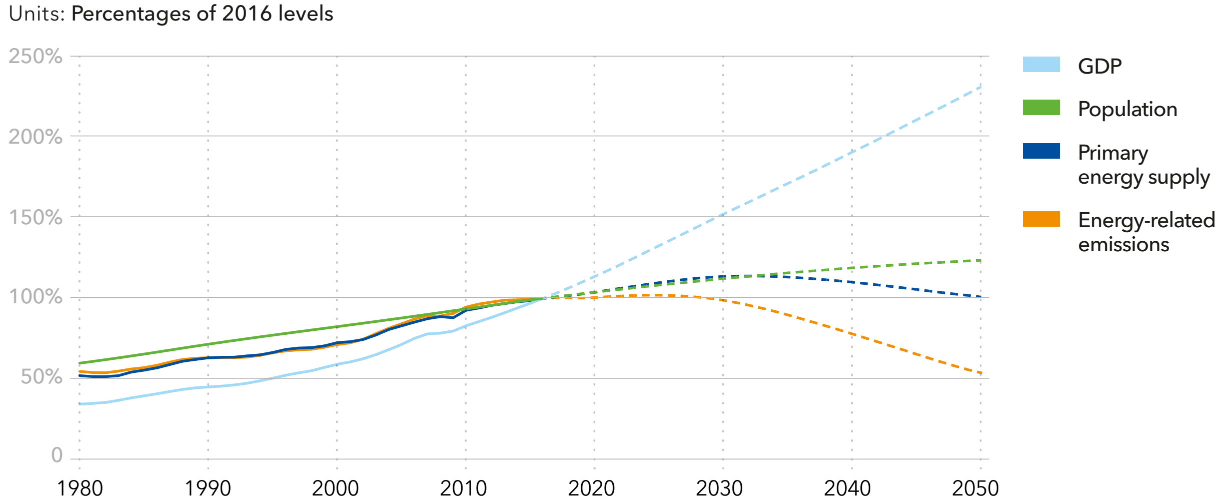


FIGURE 7.4

The decoupling of economic growth from other key parameters

Units: Percentages of 2016 levels



significant decarbonization effect, since the electricity will be produced increasingly by renewables. The energy mix beyond electricity is also changing, often through the replacement of coal by less carbon-intensive energy sources. The decarbonization rate is steady within buildings and manufacturing, but will remain slow in transport until 2040, when electrification of the sector increases significantly, with the widespread adoption of electric vehicles (EVs). Towards 2050, there will also be decreasing use of oil due to its replacement by less carbon-intensive energy sources, including biofuel, in both aviation and shipping.

All regions will decarbonize, starting from different levels, and proceeding at varying rates, as shown in Section 5.11.

> "Carbon intensity of economic growth will decrease in all regions, and most rapidly in China.

Decarbonization appears to be even stronger when viewed against economic activity, where improvements in energy intensity measured as joules per US dollar (J/USD) are multiplied by improvements in emission intensity (tCO_2/J). Carbon intensity of economic growth will decrease in all regions, and most rapidly in China.

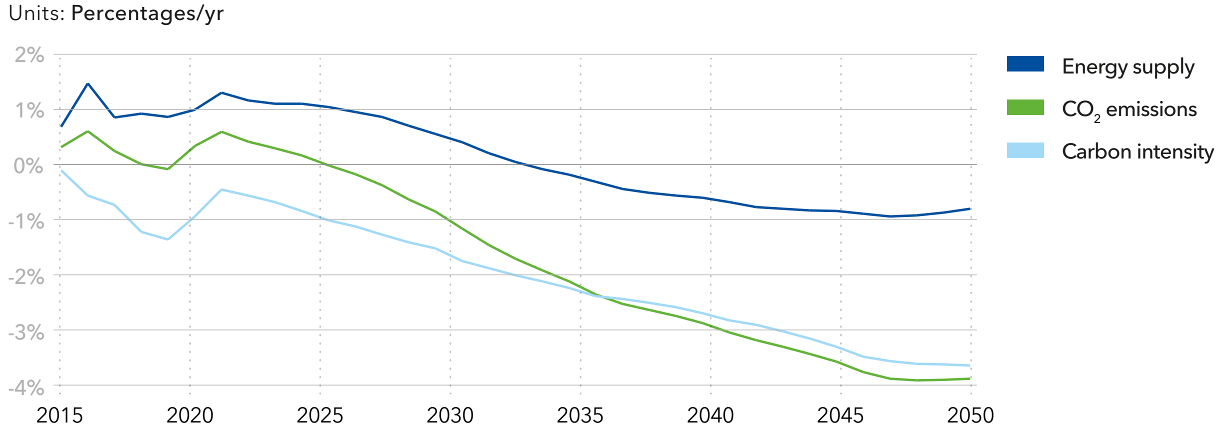
For a clearer understanding of how the energy system is changing: growth in population, GDP, energy supply and energy related CO_2 emissions are compared in Figure 7.4, assigning a base value of 100% to all parameters in 2016.

As can be seen from Figure 7.4, economic growth will continue much more quickly than population growth, which will continue to rise, but only slowly. Energy use will first increase and then essentially flatten as described in detail in Chapter 4, and energy-related CO_2 emissions will almost halve by 2050. The annual rate of reduction for carbon intensity will initially start at 1% and accelerate to over 3% by 2050, whereas both global energy supply and emissions initially increase their annual growth. Emissions will start declining in 2025, while energy supply will start to decline in 2032. Emissions will continuously decline until late 2040s, when they will level off at -4% per year, as illustrated in Figure 7.5.

FIGURE 7.5

Carbon intensity, energy supply and emissions rate of change

Units: Percentages/yr



CARBON BUDGET

The carbon budget is an estimate of the cumulative amount of CO_2 that can be emitted to the atmosphere over a defined time-period while staying within a certain temperature threshold.

The well-researched linkage between global warming and carbon emissions means that it is possible to convert the amount of CO_2 emissions into an expected range of temperature increase. However, carbon budgets are affected by several factors in addition to the energy related emissions. These include: accuracy of historical emission levels, inclusion of other GHG in addition to CO_2, the use and inclusion of negative-emission technologies, and, finally, climate sensitivity.

Recent progress in collaborative research, collected by IPCC in the *Special Report Global Warming of 1.5 °C* scheduled for publication in October 2018, suggests that updates to the carbon budgets and climate sensitivity should be expected. However, as this report is not yet formally issued, in this Outlook we use the Threshold Avoidance Budget described by Rogelj et al. (2016), using budget figures for cumulative emissions from a specified date until global mean temperature peaks at 1.5 or 2.0°C.

At COP21 in Paris, the Parties agreed to keep the global average temperature increase to "well below" 2°C and to strive to limit the increase to 1.5°C above pre-industrial levels. Starting with 2°C, the CO_2 budget for 2°C is 2900 Gt CO_2, using the 66% ('likely') probability threshold reported by the IPCC (2014a). In this CO_2 budget of 2900 Gt, 800 Gt CO_2-eq is already deducted from the total budget of 3700 Gt CO_2-eq, to allow for the non-CO_2 emissions, such as methane (CH_4).

Our ETO model (ETOM) does not cover CH_4 emissions from fossil fuels or other non-CO_2 emissions (e.g. nitrous oxide (N_2O), from land-use

changes, agriculture, or waste. Large changes in these non-CO_2 emissions, including in agriculture, land fill and use of fertilizer, will influence the size of the carbon budget.

> "With anthropogenic emissions calculated from the global energy use and energy mix predicted by our forecast, the 2°C carbon budget will be exhausted in 2037.

Deducting the historical emissions up to 2015, based on IPCC (2014a), we estimate a remaining 2°C carbon budget of 850 Gt CO_2 (Rogelj et al. 2016) in 2015. However, 850 Gt CO_2 is only a median value; there are large uncertainties and scenario dependencies on the non-CO_2 emissions, that influence the remaining carbon budget. Rogelj et al. (2016) provide a range for the 2°C carbon budget of 590-1240 Gt and while we acknowledge this uncertainty, we use the median value in our calculations.

With a temperature threshold set at 1.5°C the remaining carbon budget is estimated to be only 200 Gt of CO_2, even when using a 50% probability threshold (IPCC 2014a). With the estimated emissions, this budget will be exhausted by 2021.

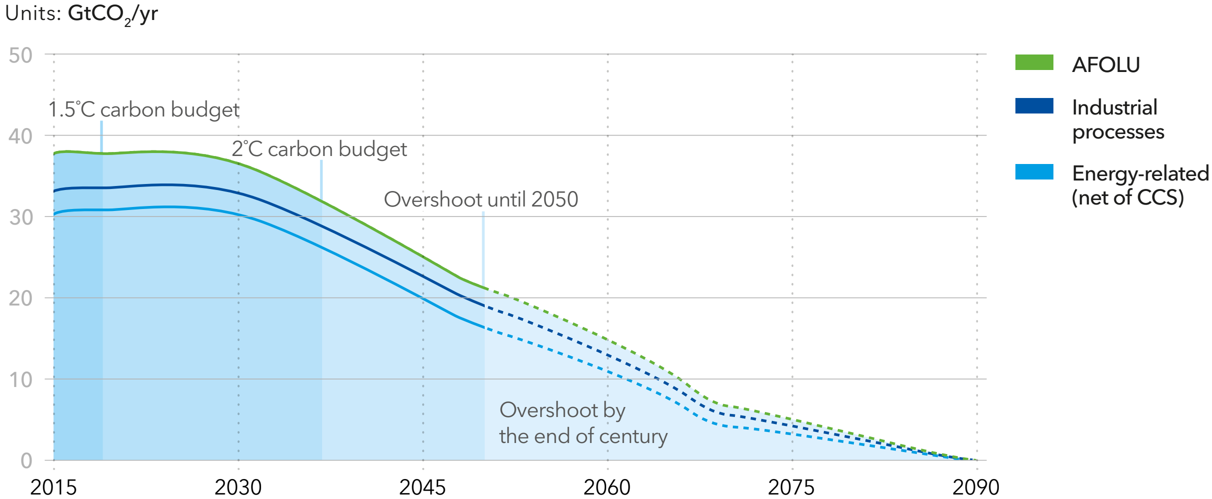
However, there are large uncertainties in this budget due to lack of studies, a situation that the upcoming *IPCC Special Report on 1.5°C*, seeks to address.

With anthropogenic emissions calculated from the global energy use and energy mix predicted by our forecast, the 2°C carbon budget will be exhausted in 2037, and by 2050, emissions will have exceeded the 2°C carbon budget by 390 Gt CO_2, as can be seen in Figure 7.6.

FIGURE 7.6

Carbon emissions and budget

Units: $GtCO_2/yr$



TEMPERATURE RISE

In our Outlook, we stop the forecast at 2050 and thus emission levels and captured emissions are not modelled for the latter part of this century. However, it is clear from the data in Table 7.1 that we will overshoot both 1.5 and 2.0 degrees Celsius. In order to make an estimate of future temperature increases, we extract current trends of energy and emissions. As discussed above, there are also large uncertainties in the carbon budget itself as well as the levels of emissions in the latter half of the century.

Nevertheless, we have sufficient information to provide a rough estimate. After 2050, humans will continue to emit considerable amounts of CO_2, but on a downward trend. For the sake of expedience, we extrapolated the emission trend we have in 2050 until it reached net zero emissions in 2090. Thereafter we expect the world to continue on a net zero-emissions path. Using this approach, cumulative emissions between 2050 to 2090 are 380 Gt CO_2.

To this we must add the 2°C carbon budget overshoot amount prior to 2050 of 390 Gt CO_2, arriving at a total 2°C carbon budget overshoot through to 2100 of 770 Gt CO_2.

This calculation does not include any large-scale carbon negative emissions from e.g. bio-energy with carbon capture and storage (BECCS) or extensive afforestation, towards the end of the century.

> “The figures suggest that the world is heading towards a level of warming of 2.6°C above pre-industrial global average levels in the second half of this century.

Comparing the 770 Gt CO_2 overshoot with the carbon budget in (IPCC, 2014a), directly interpolating between the 2°C and 3°C, using 66% likely carbon budgets, the figures suggest that the world is heading towards a level of warming of

TABLE 7.1
Overview of anthropogenic CO_2 emissions measured in Gt/yr

	2016	2020	2030	2040	2050
Energy related emissions	33	33	32	25	18
Captured and stored	0.020	0.034	0.041	0.064	0.30
Industrial processes	3.0	3.0	3.0	3.0	3.0
AFLOU	4.7	4.5	3.8	3.1	2.4
Total anthropogenic CO_2 emissions	**40**	**40**	**39**	**32**	**23**
Remaining carbon budget	810	650	250	-110	-390

Note: It is likely that the upcoming IPCC *Special Report Global Warming of 1.5 °C* will present new carbon budget figures, and recent research papers indicate a higher budget than previously estimated. If the carbon budget figures are updated, DNV GL will also revise its calculations. However, there are no indications that the updated figures will change the carbon budget to such an extentthat there will be no overshoot by the end of the century.

2.6°C above pre-industrial global average levels in the second half of this century.

There are considerable uncertainties associated with this estimate, not only in energy-related emissions, but also in areas like future BECCS, in future AFOLU emissions, in climate tipping points and other non-linear earth system reactions, (e.g. on methane stored in permafrost), which are beyond the scope of this Outlook.

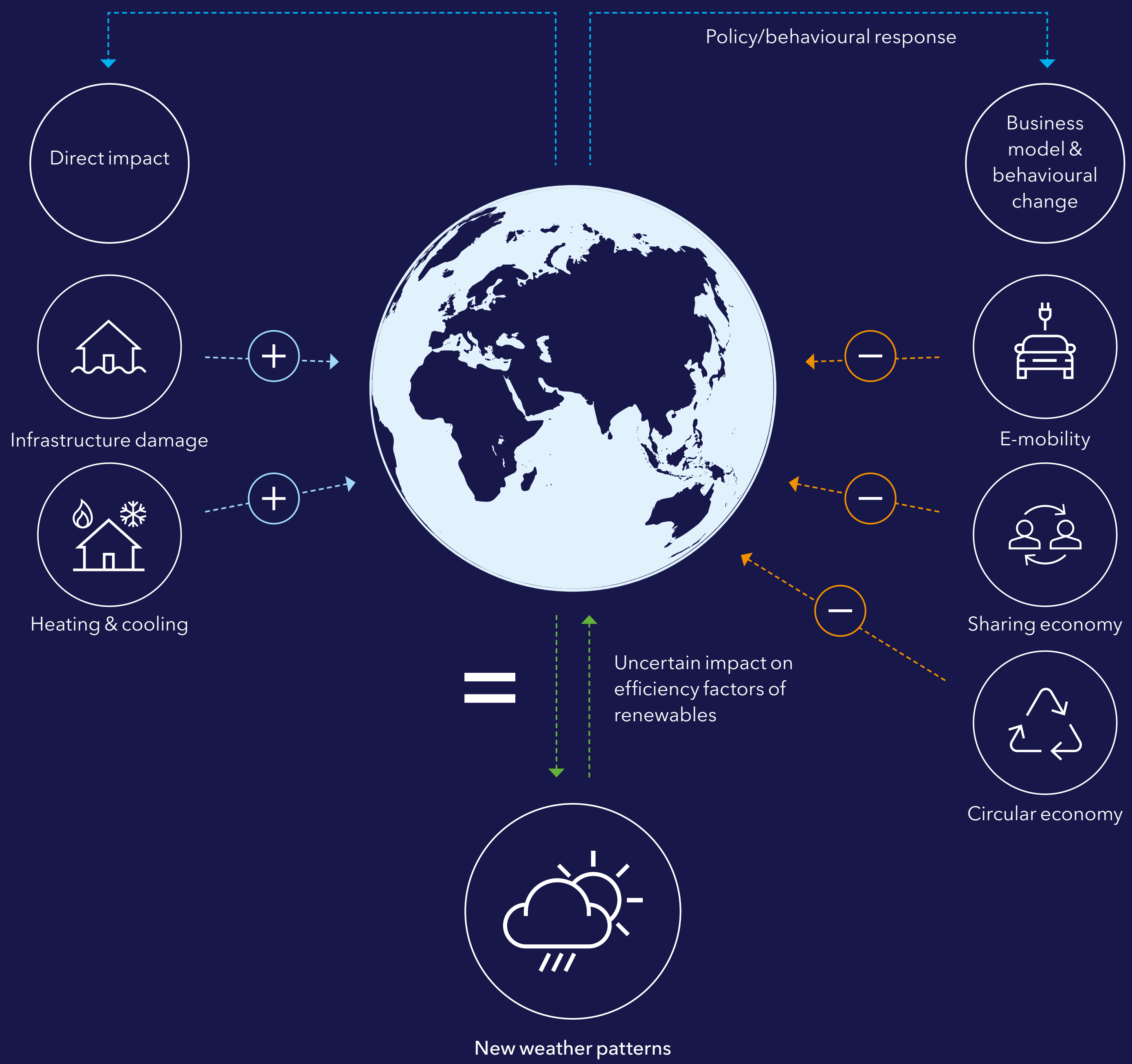
WATER CONSTRAINTS

- The future of energy is connected to that of other resources, e.g. forests and water. Climate change impacts water availability which, in turn, affects the energy transition.
- The world's energy systems are inextricably linked with water systems: the energy sector is the second largest user of freshwater after agriculture, and water is a considerable source of cost for many energy companies. Water scarcity is intensifying in large parts of the world, and there is a mismatch between escalating demands for water and a finite supply that varies by location. This situation, often referred to as the water-energy nexus, will influence the energy transition.
- The World Energy Council estimates that 98% of power currently produced needs water (WEC 2016). Water scarcity can limit sufficient cooling for coal and nuclear plants, forcing shutdowns – as has happened in India, Europe and the United States in recent years. In addition to cooling in coal power plants, large amounts of water are used for washing produced coal to remove excess ash, as a measure towards improving air quality. In regions with limited water supply, water resources may be insufficient to continue with wide-scale coal washing.
- Hydraulic fracturing, used in unconventional oil and gas production, increasingly employs trucking, desalination, and pipeline installations to secure the water supply necessary for operation.
- For hydropower production, water scarcity can be catastrophic: a low river flow can cut hydropower dramatically, as happened for months in southern Africa following the 2015–16 El Niño drought. Supply shortage due to dry weather is similarly affecting hydroelectric output across Latin America.
- Water constraints will intensify in several regions due to global warming. For energy systems developments, the additional cost of accessing water is likely to give a further push towards renewable energy, e.g., solar PV and wind, where water is not a major input or cost component. This is likely to be another driver of the proliferation of these technologies in the energy mix.

> "For energy systems developments, the additional cost of accessing water is likely to give a further push towards renewable energy.

FIGURE 7.7

Selected feedback loops illustrating the impact of global warming on the energy system



CLIMATE CHANGE IMPACT ON THE ENERGY SYSTEM

- The key driver of the energy transition is the avoidance of climate change and its implications. However, anthropogenic climate change is happening and will continue to happen in the coming decades, despite an ongoing, rapid and comprehensive energy transition.
- Climate change will in turn impact the energy transition. This will take many forms, such as new patterns of demand for cooling and heating; alterations in efficiency factors for hydropower, PV or wind; but also resulting from business model changes, new travel patterns and modes of transport; and changes in behavioural patterns that will emerge as society and business seek to mitigate climate change.
- In this 2018 version of our Outlook, we include the impact of climate change on heating and cooling degree days, which in turn determine heating and cooling needs in the buildings sector. In later versions of the model and future editions of this Outlook, we plan to include more quantitative changes based on such climate change-driven effects.

CHAPTER 8

CLOSING THE GAP TO 2°C

8. CLOSING THE GAP TO 2°C

Climate change resulting from anthropogenic carbon emissions is already interfering with the climate system in a visible way, and any further small temperature increase will worsen the effects. What can be done to prevent humanity from careening over a limit, beyond which, scientists caution, lies "dangerous climate change territory"?

Starting with the Stockholm Environmental Institute and continuing with the IPCC, 2°C above pre-industrial levels has become a long-established threshold. The 2010 Cancun Agreement emphasized the threshold status of 2°C. The 2015 COP21 Paris Agreement repeated the reference to a 2°C target but went further.

The Agreement's signatories committed their countries to a much more ambitious threshold by agreeing to hold the increase in the global average temperature "to well below 2°C above pre-industrial levels" and to pursue "efforts to limit the temperature increase to 1.5°C" (UNFCCC 2015). The contrast between a 1.5°C and a 2°C temperature rise is dramatic for many nations and individuals.

CLOSING THE GAP BETWEEN CLIMATE CHANGE GOALS AND OUR FORECAST

The modelling of 1.5°C or 2°C 'futures' typically involves back-casting, not forecasting. It starts with desired goals, then formulates a way to get there. Recent examples include the Energy Transitions Commission (ETC 2017) and '2-degree' scenarios from IEA and several oil and gas companies.

This year, DNV GL's Outlook points towards global warming reaching 2.6°C by 2100, and raises urgent questions about how the world can close the gap between this future and the 'well below 2°C' goal of the Paris Agreement.

With knowledge of the size of the gap, our energy transition model enables us to discuss the additional efforts needed to close the gap between a 1.5°C or 2°C outcome, and what our model actually projects as our best estimate of the future.

We forecast a rapid, some would say dramatic, energy transition. Despite this, our predicted future exceeds the 2°C carbon budget by 390 gigatonnes of carbon dioxide (Gt CO_2) by 2050, and the 1.5°C carbon budget by 990 Gt CO_2. Emissions will continue beyond 2050, and simple extrapolation of trends from that point results in another 380 Gt CO_2 emitted during 2050–2090.

> "Closing the gap means reducing emissions from now until the end of the century by around 770 Gt CO_2 to stay below the 2°C threshold.

Thus, closing the gap means reducing emissions from now until the end of the century by around 770 Gt CO_2 to stay below the 2°C threshold, and by about 1,420 Gt CO_2 to limit the temperature increase to 1.5°C. We have already acknowledged the uncertainties in these figures.

LIMITING THE TEMPERATURE INCREASE TO 2°C

It is beyond the scope of this Outlook to propose measures such as limiting population increase or productivity gains. However, in order to reduce energy-related emissions, there are three options:

- Reduce energy use by improving energy efficiency.
- Boost decarbonization; for example, by increasing the share of renewables in the energy mix and/or replacing carbon-intensive fuels with less carbon-intensive ones.
- Capture the carbon emissions.

Our sensitivity tests (Section 4.9) demonstrate that none of these individual measures, on its own, is capable of delivering a future where the 2°C carbon budget is not exhausted prior to 2050. Consequently, we need to look at more drastic measures.

ENERGY EFFICIENCY

In our Outlook, the energy intensity of the world's energy system reduces by 2.3%/yr on average until 2050. Holding everything else equal, not even a 5% annual reduction in energy intensity would result in sufficiently low global energy use to meet the 2°C target.

Based on this, and even though improved energy efficiency is essential to reducing energy use and emissions, we do not regard meeting the 2°C target with energy efficiency improvements alone as a viable solution.

INCREASE THE SHARE OF RENEWABLES

It might be tempting to think that the 2°C budget can be met by producing electricity exclusively from renewables. However, the fact is that the 770 Gt overshoot estimated to 2100 is higher than the combined emissions from all power plants from today until 2090. Thus, even if all electricity produced from today onwards was carbon free, it still would not suffice to eliminate the overshoot. Only when combined with an extraordinarily high rate of electrification could we achieve the necessary emission reductions with renewables alone.

> “Even if all electricity produced from today onwards was carbon free, it still would not suffice to eliminate the overshoot.

Furthermore, sensitivity tests on faster learning rates leading to cheaper renewables, on increased electric vehicle uptake, and on higher carbon prices reveal that none of these solutions by itself can close the gap to limit warming to 2°C. It is essential to continue with decarbonizing the various sectors; a lot can be done within the buildings, manufacturing, and transport energy demand sectors. But all of those emissions savings won't, in aggregate, be sufficient.

We are forced to conclude that closing the gap to 2°C by increasing the share of renewables alone is not a viable solution.

CARBON CAPTURE AND STORAGE

Carbon capture is normally considered economically viable from large emission sources, such as power plants and industry emissions. Most emissions from combusting coal and gas come from these sources. Most emissions from oil are from small transport sources. Carbon capture for these continues to be viewed as expensive and unrealistic despite extensive research into using the technology for these purposes.

The capture element of carbon capture and storage (CCS) should therefore target emissions from coal and gas, together with industrial emissions. By extrapolating our model's energy use results towards 2100, as explained in Chapter 7, we predict cumulative carbon emissions for the period 2016–2090 to be 430 Gt CO_2 for coal and 470 Gt CO_2 for gas. Even if all coal and gas emissions could be captured, which is unrealistic, we would need to capture 100% of them from 2024 onwards to capture 770Gt of CO_2.

Doubling the carbon price from our current estimates leads in our model to capturing 7.6 Gt CO_2 in 2050, instead of 0.3 Gt CO_2. But even if effective, a high carbon price and resultant CCS uptake will not in itself close the gap to a 2°C future.

We conclude that closing the gap to 2°C by CCS alone is not a viable solution.

A COMBINATION OF MEASURES

Although our best estimate of the energy future indicates a 2.6°C increase in global warming by 2100, staying below the 2°C threshold is not impossible. Certainly, no single solution that we have discussed will close the gap entirely; but combining various measures can achieve it. The Energy Transitions Commission (ETC 2017) also recommends this strategy.

> “No single solution that we have discussed will close the gap entirely; but combining various measures can.

In our analysis of energy expenditure in Chapter 4, we discussed how the future that our model predicts requires a lower share of GDP spent on the energy system than today. If a lower proportion of GDP is needed, governments may instead choose to maintain the current share of GDP devoted to energy expenditures and spend the difference on accelerating the energy transition. Trillions of extra dollars could thus be made available.

A high carbon price will help significantly, not least by stimulating CCS uptake. A combination of faster energy efficiency improvements and a higher CO_2 price would probably be sufficient to stay within the 2°C carbon budget. CCS can be mandated through regulatory measures as well, not only through carbon pricing and cost incentives.

Other strategies that could be combined in various ways to secure a 2°C future include: higher energy efficiency improvements or higher carbon prices coupled, for example, with various combinations of behavioural changes in the circular and sharing economy, higher electrification rates, increased uptake of renewables, fuel substitution with biofuel or hydrogen, and sustainable materials. Governmental pull or push policies, including financing new research and establishing new standards, are likely to contribute positively to all such measures. However, we do not attempt to quantify these paths as part of this Outlook.

Reducing emissions from agriculture, forestry and other land use is frequently included in lists of this kind. We do not include this in our model, but any combination of cost-effective measures to reduce emissions needs to include policies to reduce deforestation, ensure afforestation and promote more efficient land use.

In this analysis, we have avoided pushing reductions in emissions into the future and claiming that future net-negative emissions will solve the problem. To curb temperature increase, net-negative emissions will be needed at some stage, but the preferred solution to meet Paris ambitions is to act swiftly. Pushing all solutions into the future – expecting that negative emission technologies will compensate for inadequate near-term mitigation measures – is a high-cost, high-risk approach.

Whichever solutions we choose, closing the gap between the future that we forecast and a 2°C future is challenging. Only extraordinary steps combining the efforts of governments and the private sector will get us there. However, it is essential to reiterate that it is indeed possible through combinations of carbon pricing, greater energy-efficiency improvements, and the other measures mentioned here. As we explain in Section 4.7 of this Outlook, there should, in theory at least, be funds available for actions of this kind as the world's expenditure on energy reduces as a share of its growing GDP.

LIMITING THE TEMPERATURE INCREASE TO 1.5°C

As stated in Chapter 7, the 1.5°C carbon budget is likely to be exhausted as early as 2021. No single measure, and no realistic combination that DNV GL can see, will keep us within this budget.

If we are indeed to stay within the 1.5°C threshold, we need to allow for a temporary overshoot of the budget, and then achieve net-negative emissions later in the century, probably well before 2050. The options for mitigation outlined in this chapter must be implemented at massive scale and speed. The temporary overshoot is a high-risk approach, but we cannot envisage other ways to manage a 1.5°C scenario.

As this is an Energy Transition Outlook, we do not discuss here what it takes to close the gap to achieve the UN's sustainable development goals (SDGs). However, as we have previously noted (DNV GL 2016), succeeding with a rapid energy transition that closes the gap to a 2°C future is the most effective step that humanity can take to achieve the SDGs.

> "The preferred solution to meet Paris ambitions is to act swiftly. Pushing all solutions into the future is a high-cost, high-risk approach.

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HISTORICAL DATA

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

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

THE PROJECT TEAM

This report has been prepared by DNV GL as a cross-disciplinary exercise between the DNV GL Group and our business areas of Oil & Gas, Energy, and Maritime across 15 countries. In addition, we have been greatly assisted by the external Energy Transition Outlook Collaboration Network, with some 40 experts listed in the opening pages of this report.

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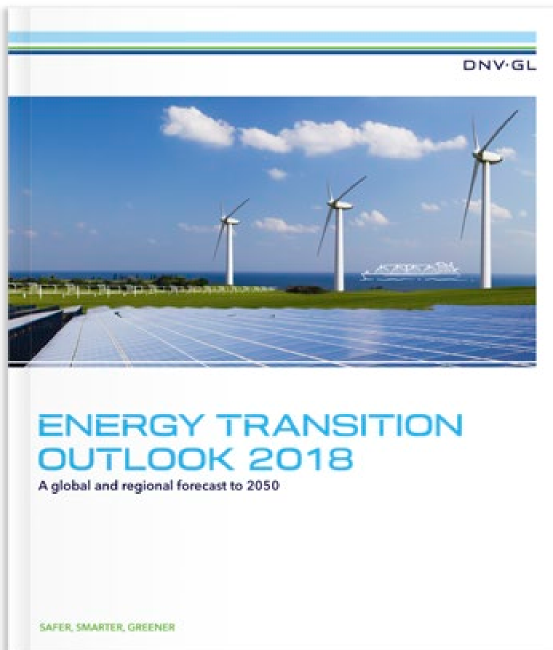
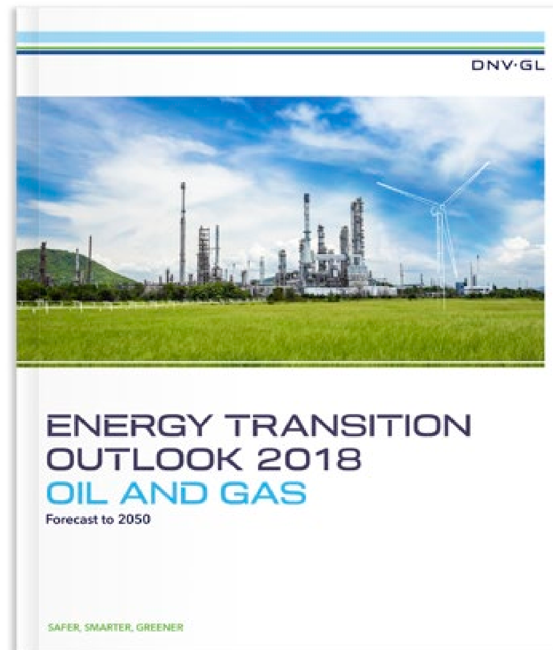
ENERGY TRANSITION OUTLOOK 2018 REPORTS OVERVIEW





ENERGY TRANSITION OUTLOOK

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

– The DNV GL Model and our main assumptions on population, productivity, technology, costs and the role of policy and governments

– Our outlook for global energy demand for transport, buildings and manufacturing, energy supply for each energy carrier, energy efficiency and expenditures

– Regional energy outlooks for each of our 10 regions

– The climate implications of our outlook and an assessment of how to close the gap to 2°C.

OIL AND GAS

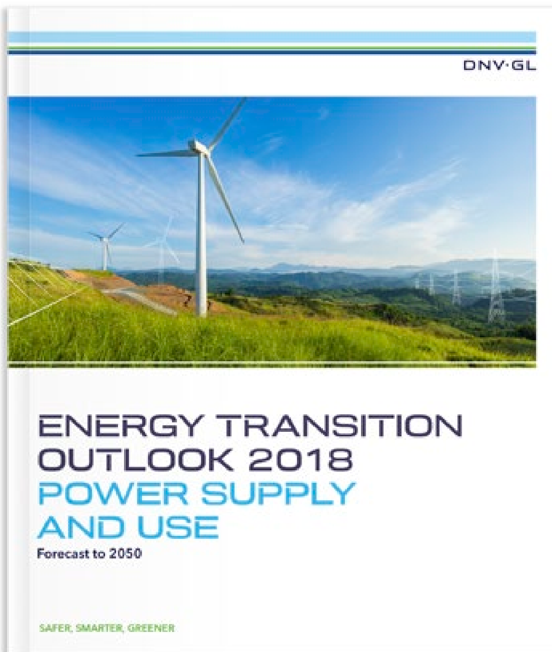
Our Oil and Gas report underlines the continued importance of these hydrocarbons for the world's energy future. It forecasts several trends:

– Gas will overtake oil to become the largest energy source in 2026, and industry efforts will be directed accordingly

– Production is likely to come from a greater number of smaller, more technically-challenging reservoirs, with shorter lifespans

– Investment in pipeline and LNG infrastructure will increase to connect new sources of supply with changing demand centres

– New gases will enter distribution networks, and lifecycle performance will come under increasing focus for the refining and petrochemical industries.



POWER SUPPLY AND USE

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

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

MARITIME

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

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

The report concludes with a presentation of the important concept of the 'carbon robust ship': a structured, knowledge-based approach to handling uncertainty – supported by modelling tools – which helps stakeholders to stay ahead of industry developments and remain competitive towards 2050.

Design SDG//Drive Oslo. **Print** ETN Grafisk. **Paper** Arctic Volume White 115/200 gr. **Images** AAroads p.29; Alain Baars/DNV GL p.211; Alamy p.108; Arajan Zoomers/DNV GL p.148; Dreamstime p.174, 182; Getty Images: p.9, 10, 29, 160, 285; Globalgoals.org p.45, 64; Holger Martens/DNV GL p.14, 49; iStock p.137, 285; Jaap Bunschoten/DNV GL p.185; Magne Røe/DNV GL p.311; Markus Krüger/DNV GL p.281; Nina Rangøy/DNV GL p.4, 297; Courtesy Oxford PV p.198; Patrick Butler/SolarAid p.139; Courtesy Ruter p.193; Shutterstock (cover) p.19; 24, 27, 37, 46, 70, 77, 86, 89, 53, 65, 99, 147, 186, 212, 216, 222, 228, 234, 240, 246, 252, 258, 264, 270, 278, 283, 285, 286, 289, 290, 298, 303, 204, 307; Courtesy Siemens AG p.127; Steen Donsby/Eidesvik p.66; Thinkstock p.39, 43; Courtesy Volvo Buses p.24.

Updated: 6 Sept 2018.

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DNV GL is a global 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. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries.

Combining technical, digital and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide customers and society with operational and technological foresight. With origins stretching back to 1864 and operations in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.

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