DNV·GL

ENERGY TRANSITION OUTLOOK 2020

A global and regional forecast to 2050

SAFER, SMARTER, GREENER

ENERGY TRANSITION OUTLOOK 2020

A GLOBAL AND REGIONAL FORECAST TO 2050

FOREWORD

At a time when we are trying to recover from the ongoing pandemic as individuals and as communities, we cannot afford to make costly mistakes. That is why I believe that the 2020 edition of our Outlook is needed now more than ever: to shine a light on a transition that represents the greatest source of risk, and opportunity, in our business environment.

For most of the current energy system we forecast a rapid energy transition between now and 2050 – effectively, within a generation. By mid-century we expect to see an energy mix split roughly equally between fossil and non-fossil sources, taking into account expected developments in policies, technologies and associated costs.

Our predictions are rooted in real-world experience with energy customers across the world spanning the full energy mix. Nevertheless, some of our readers may find our conclusions startling.

There is a massive, ongoing electrification of the global energy system; where electricity is less than 20% of the energy mix today, it will more than double its share by 2050. During that period, solar PV will grow 25-fold and wind 10-fold, and in roughly equal shares will together be responsible for over 60% of the electricity generated by 2050. The plunging costs and technological advances in renewables are remarkable, and nowhere more so than in fixed and floating offshore wind. Electricity powered by renewables is the main driver of accelerating efficiency gains in our global energy system that will outpace both population and GDP growth, such that the world will reach peak primary energy supply in just over a decade from now.

The COVID-19 pandemic continues to exact a tragic toll on lives and livelihoods and will greatly impact global energy use in the near term. Energy demand will fall 8% this year, and with a slow recovery, our whole energy demand forecast is rebased downwards by 8% relative to our previous forecast through to 2050. The pandemic has also brought forward peak emissions and will lead to an earlier plateauing of oil use.

But that is not doing much, unfortunately, to advance the pace of decarbonization. Solutions exist to meet the Paris Agreement, including hydrogen, CCS and further energy-efficiency improvements, but these need a *significant* policy push to scale.

The world will need to achieve the same percentage of emissions reduction seen in 2020 every year through to 2050 to succeed in reaching the ambitions of the Paris Agreement. So, we urgently need to find more sustainable and lasting ways to reduce emissions. Some subsectors are well underway, like wind, solar PV and EVs; but we must also urgently tackle those areas, like heavy industry and long-distance transport, where emissions are hard to abate.

Tough business and policy choices lie ahead, but also plentiful opportunities for those who master the wave of the energy transition. As ever, I welcome your feedback on our Outlook, and encourage you to access our forecast data which we make available on our open industry platform, Veracity.

REMI ERIKSEN

GROUP PRESIDENT
AND CEO, DNV GL

HIGHLIGHTS

SHORTER TERM

1. **COVID-19 will reduce global energy demand by 8% this year**
   - Although energy demand will pick up again from 2021, it will be from a lower base, and for the remaining years to 2050, annual global energy demand will fluctuate some 6 to 8% lower than our pre-pandemic forecast
   - Pandemic-linked behavioural shifts, like remote working and reduced commuting, will have a lasting effect lowering energy use
2. **Energy-related CO_2 emissions have peaked, brought forward five years by the pandemic**
   - Transport energy use peaked in 2019
   - COVID-19 has brought peak oil demand forward; oil use may never again exceed 2019 levels
3. **Technology can deliver a Paris-compliant future, if scaled properly**
   - Encouraging progress has been made and is expected to continue for solar PV, wind and battery storage
4. **Market forces alone will not fix hard-to-abate sectors; stronger policies and regulations are needed**
   - Decarbonization of high-heat processes in industry, the heating of buildings, and heavy transport is proceeding too slowly
   - Solutions exist, including hydrogen, CCS, and further energy-efficiency improvements, but these need a policy push to scale

LONGER TERM

1. **Rapid electrification will transform the energy mix by 2050**
   - The share of electricity in the final demand mix will more than double from today's level by 2050
   - Half of the passenger vehicles sold worldwide will be EVs by 2032
2. **Solar PV and wind – in equal shares – will dominate power generation**
   - Electrification, powered by renewables, drives decelerating energy intensity, which will see energy use peak worldwide in 2032
   - Significant investment in connectivity and flexibility will enable a 62% variable renewable share by 2050
3. **Natural gas will take over as the largest energy source this decade, and remain so until 2050**
   - However, only 13% of natural gas used in 2050 will be decarbonized
4. **Despite flat energy demand and a growing renewable share, the energy transition is nowhere near fast enough to deliver on the Paris Agreement**
   - Most likely we are heading towards 2.3°C warming by the end of the century
   - A lot more renewable power, decarbonization, energy-efficiency improvement, and carbon capture is needed
   - The world will spend an ever-smaller share of GDP on energy, allowing for additional investment to further speed up the transition

HIGHLIGHTS – SHORT TERM OBERVATIONS

Impact of COVID-19 reduces global energy demand by 8%

We follow IMF's Longer Outbreak case, which predicts a 6% reduction in world GDP due to COVID-19 in 2020 and a small 7% rebound in 2021. Growth will be impaired by the pandemic for a further half-decade, resulting in world GDP 9% lower in 2025 than it would have been without COVID-19.

Some pandemic-induced changes are likely to endure. Demand for aviation in 2025 will be 5% lower than previously forecast, while commuting is conservatively estimated to decline by 2% and office-space requirements by 1%.

Delayed growth and behavioural changes will see global energy demand reduce by 8% in 2020. It will pick up in 2021, but then fluctuates annually some 6-8% below our pre-pandemic forecast to 2050. With the drop-off in demand, oil and coal are most severely impacted, followed by gas, with renewables least affected. Transport energy use will never again reach 2019 levels, and the demand for steel and construction materials for office buildings will be significantly reduced.

Energy-related emissions have peaked, brought forward five years by COVID-19

Global energy demand will only see a modest growth post COVID-19, owing to continuous improvements in energy intensity. By contrast, renewables will continue to grow rapidly, permanently altering the energy mix. Coal use peaked in 2014, crude oil use likely peaked in 2019, and natural gas will peak in 2035. Energy-related emissions are therefore not likely to return to 2019 levels.

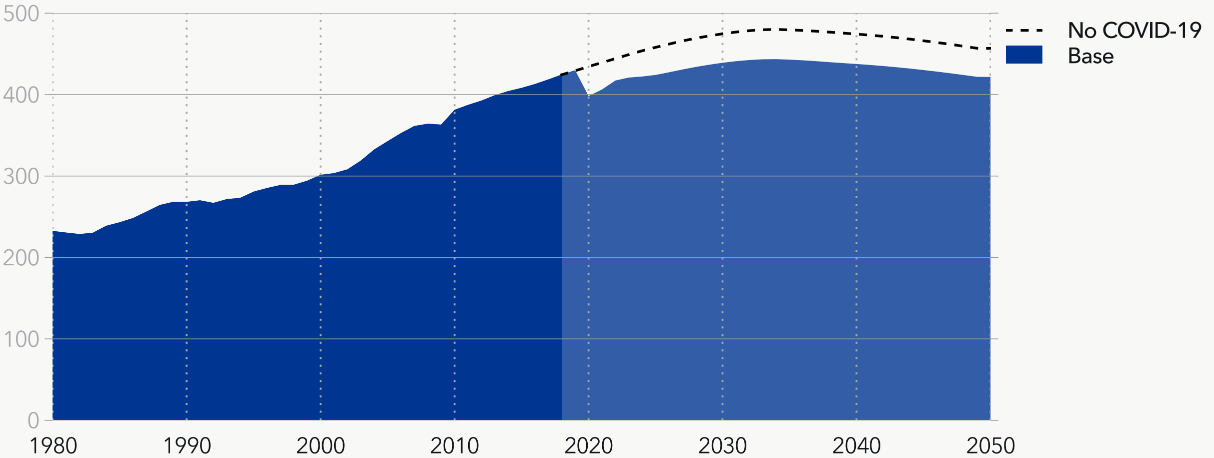
Lower emissions in 2020 come at the expense of a pandemic which is exacting a tragic toll on lives and livelihoods. We see a small rebound in global emissions as economies recover, but peak emissions will remain behind us. In 2030, emissions are 10% lower than our pre-pandemic forecast, and in 2050, energy-related emissions will be at 17 Gt CO_2, about half of the present level. But that is not enough: if we want to be on track towards 1.5°C, we need to repeat this year's 8% emission reduction *every year* through to 2050.

The post-COVID-19 stimulus packages hold the potential to alter the speed of the transition, but at present they appear to be falling with equal weight on both the fossil and non-fossil sides of the energy mix.

FIGURE 1

World final energy demand - with and without COVID-19

Units: EJ/yr



Historical data source: IEA WEB (2019)

With sufficient scale, technology can deliver a Paris compliant future

In recent years, we have seen encouraging technology improvements, cost declines and market implementations in many easy-to-abate sectors. Cost reductions in solar PV have surprised many forecasters, and we expect costs to continue to decline. Battery costs have also been plunging dramatically, increasing the competitiveness of passenger EVs and spurring further rapid scaling of EV manufacturing.

We recently investigated Europe's lower emissions scenarios (DNV GL, 2020f,g) and found that zero emissions in Europe is possible and affordable – if the current fraction of GDP devoted to energy expenditures is maintained. Paris compliant scenarios require significant technology scale-ups that must be weighed against 'real world' settings.

The physical and market designs of power systems will change rapidly, including a considerable buildout of the grid to cater for an ever-higher renewables share. The roll out of charging infrastructure and economic incentives for EV owners for a few more years will accelerate further scaling and electrification.

The market alone will not fix harder-to-abate sectors; stronger policies and regulations are needed

In many harder-to-abate sectors, like heating of buildings, high-heat processes in industry and heavy transport, progress with decarbonization, including efficiency gains, has been slow and has fallen well short of what is required by the Paris Agreement. The technology and solutions to decarbonize these sectors exist (e.g. hydrogen and CCS), but implementation has been patchy, with only a handful of solutions applied at scale.

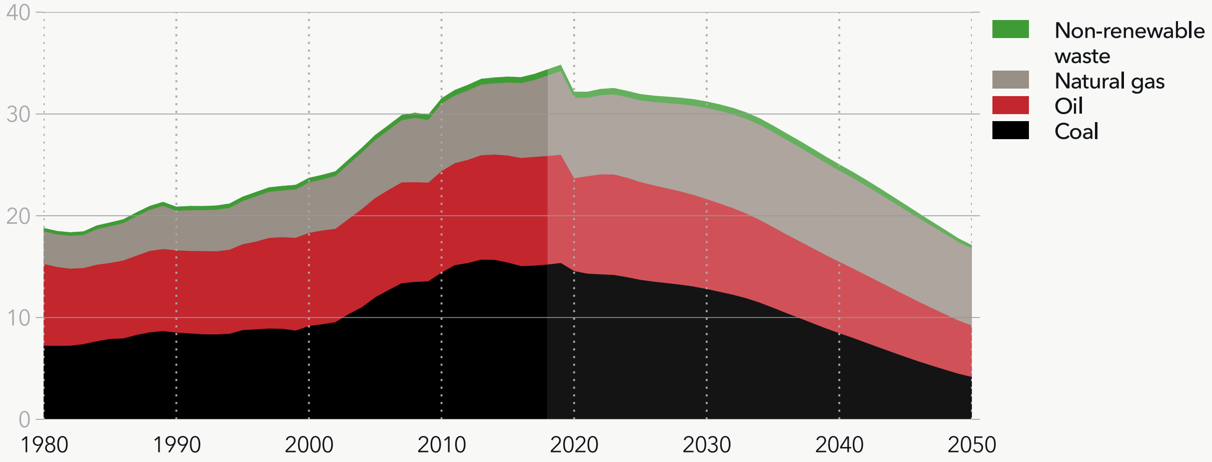
For hard-to-abate sectors, near-term policy mechanisms in the form of e.g. R&D funding, economic incentives for piloting and implementation, performance standards and mandates, are urgently needed to mature solutions and bring these to commercial readiness. Nationally Determined Contributions (NDCs), now due for renewal, should significantly strengthen these areas.

Energy efficiency can greatly reduce energy demand in most sectors, but split incentives and lack of regulations prevents progress which, from a societal perspective, can come at low or even negative costs.

FIGURE 2

World energy-related CO_2 emissions by fuel

Units: $GtCO_2/yr$



HIGHLIGHTS – LONG TERM FORECAST

The electrification rate of the energy system is strong; half of all passenger vehicles being sold will be electric in 2032

In 2018 only 19% of final energy demand was delivered in the form of electricity. By 2050, that will more than double to 41% and 60 PWh.

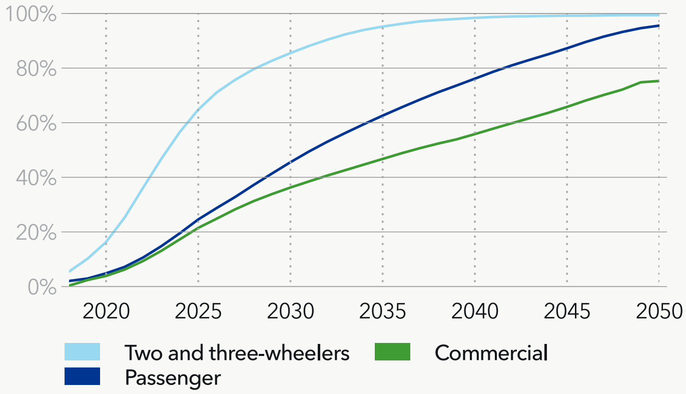
Looking at the various demand sectors, electrification is strong in both buildings and manufacturing, but most of all in transport, where the share of electricity in final demand grows from 1% to 27% over the forecast period. Since the efficiency of the electric system is far higher than the efficiency of combustion systems, the resulting emissions reduction is much higher. Indeed, transport sector oil use declines 58%, and transport sector CO_2 emissions almost halve.

Plunging battery costs will spur the rapid electrification of the passenger vehicle fleet, and by 2032, half of all new passenger vehicles sold globally will be electric. Already in 2024 this will happen for 2&3-wheelers, while the more diverse commercial vehicles take longer, reaching the 50% mark in 2037.

FIGURE 3

World market share of electric vehicle sales by vehicle type

Units: Percentages



Variable renewable energy will deliver over 60% of global power mix in 2050, half from wind and half from solar PV

The present fossil-heavy power mix will undergo a dramatic change and be dominated by renewables by 2050. While hydropower also contributes, the biggest change, and the largest producers of power, will be solar PV and wind, with solar PV equalling the sum of onshore, offshore fixed and offshore floating wind. Floating offshore wind will be an exciting new market with 250 GW installed producing 2% of global power in 2050.

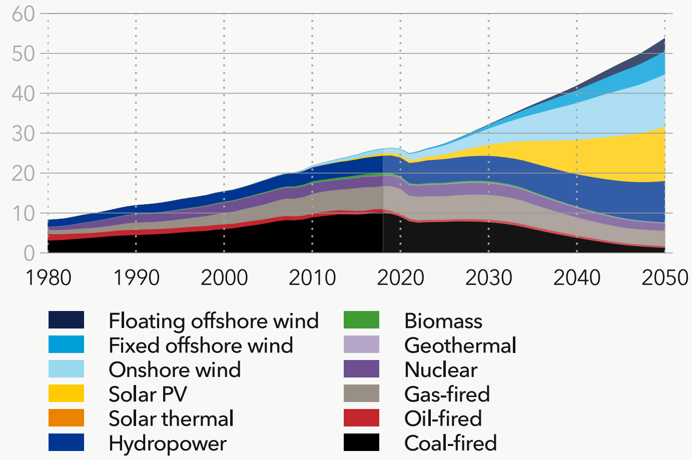
Already today, new solar PV and wind are the cheapest forms of new power many places, and within a decade will start to outcompete existing coal and gas power. This will happen despite solar and wind receiving lower average prices than hydropower and fossil power that can produce power on demand.

Such a large share of renewables will need increased connectivity, storage and demand-response, all of which will increase grid investments. Over the next 30 years, USD 20trn will be invested in grids globally.

FIGURE 4

World electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2019), IRENA (2019)

Gas will take over as the largest energy source this decade; towards 2050 the share of decarbonized natural gas will increase to 13%.

Natural gas currently has a smaller share of the global energy mix than oil and coal, but it will grow to become the largest energy source in 2026. Gas demand peaks in 2035 and it remains the largest energy source through to 2050, at that time representing 29% of global energy use. Power (34%), buildings (21%) and manufacturing (18%) are the biggest consumers of natural gas.

After a slow start, the decarbonization of gas picks up towards the end of the forecast period, when we see rapid growth of blue hydrogen from methane reforming, and of gas with CCS in power and industry – together representing 22 EJ or 13% of natural gas use in 2050.

The EU's Green Deal, with higher carbon prices, and similar policies following in other regions are important policy levers – but do not boost significant gas decarbonization until after 2035.

Despite flat energy demand and a growing renewable share, the energy transition is nowhere near fast enough to deliver on the Paris Agreement.

Even with the rapid changes in energy intensity and renewables penetration we forecast, CO_2 emissions are still at half of today's level in 2050. This is dramatically different from the 50% reduction needed by 2030 and close to net-zero in 2050 required to reach a 1.5°C future.

We forecast that the 1.5°C carbon budget is exhausted in 2028 and the 2°C budget in 2051, and extrapolating the emission trends, our Outlook points towards a 2.3°C warming of the planet by end of this century, a level considered dangerous by the world's scientific community.

In order to close the gap and achieve a future where global warming is limited to safer levels, we need to further reduce energy use, electrify all sectors possible via renewable electricity, decarbonize harder-to-abate sectors through e.g. decarbonized gas, and succeed with carbon capture and storage on an industrial scale.

FIGURE 5

World primary natural gas supply

Units: EJ/yr

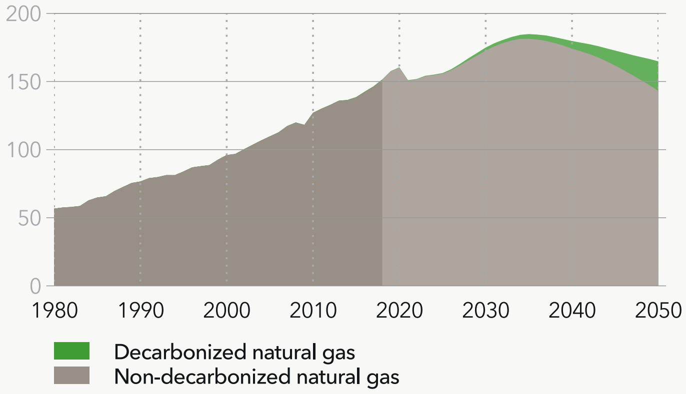
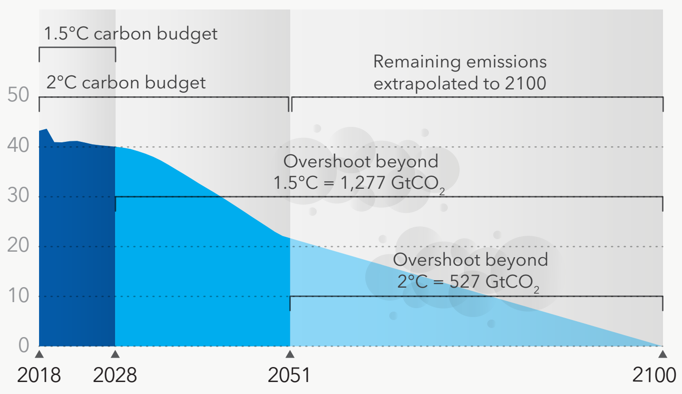
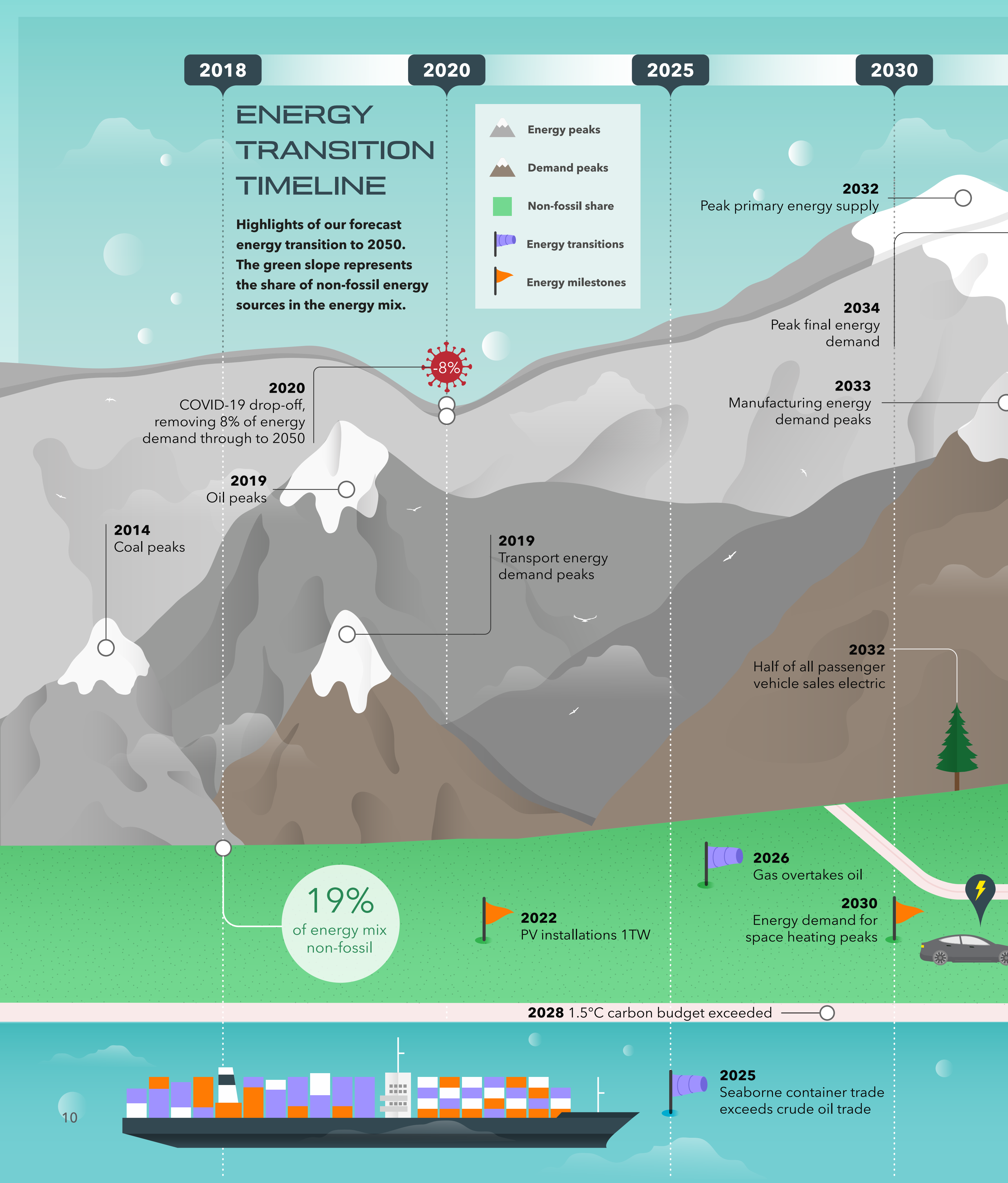


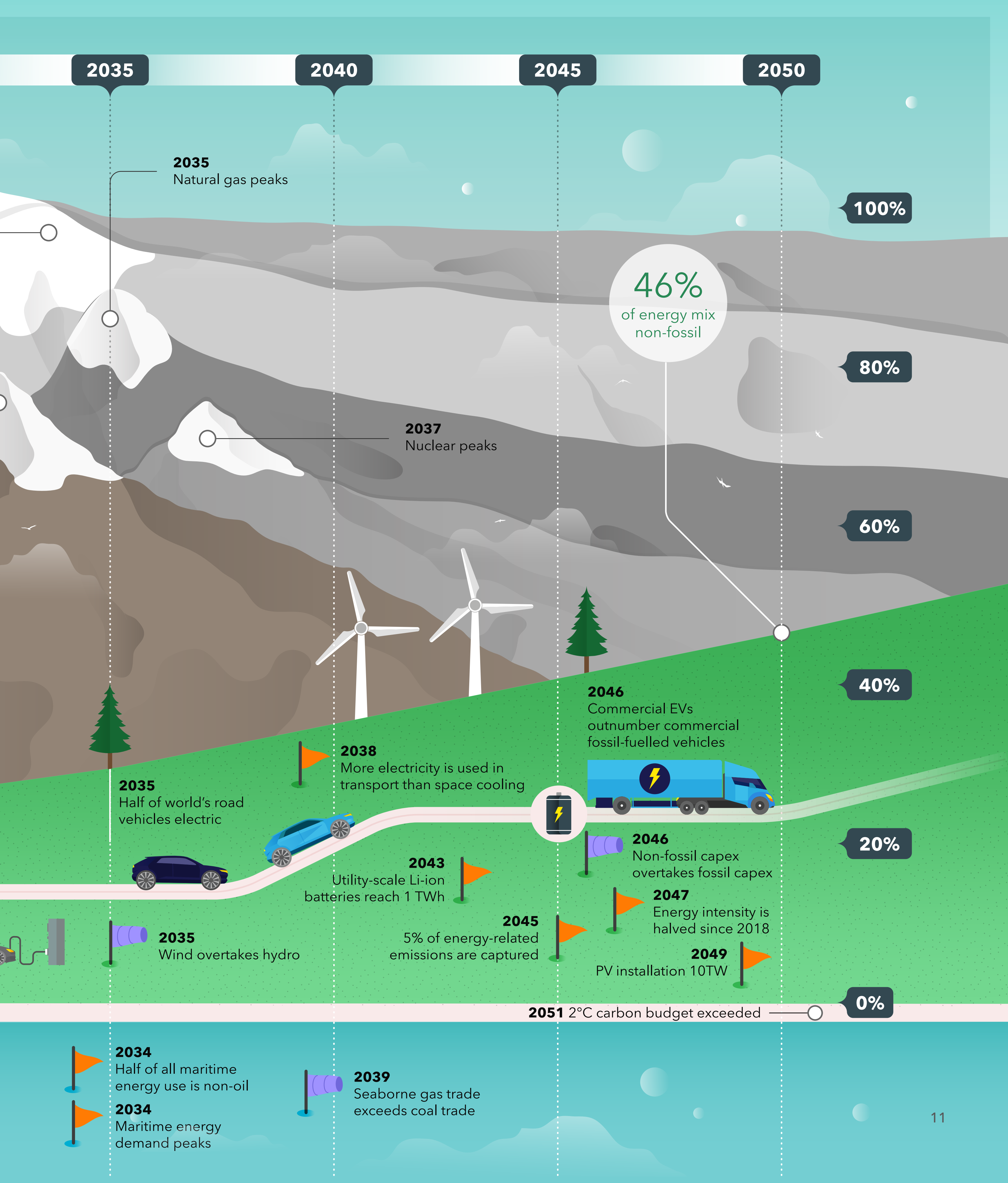
FIGURE 6

Carbon emissions and carbon budgets

Units: $GtCO_2$/yr




2018
2020
2025
2030
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.
Energy peaks
Demand peaks
Non-fossil share
Energy transitions
Energy milestones
2032 Peak primary energy supply
2034 Peak final energy demand
2033 Manufacturing energy demand peaks
-8%
2020 COVID-19 drop-off, removing 8% of energy demand through to 2050
2019 Oil peaks
2014 Coal peaks
2019 Transport energy demand peaks
2032 Half of all passenger vehicle sales electric
2026 Gas overtakes oil
2030 Energy demand for space heating peaks
19% of energy mix non-fossil
2022 PV installations 1TW
2028 1.5°C carbon budget exceeded
2025 Seaborne container trade exceeds crude oil trade



2035
2040
2045
2050
2035
Natural gas peaks
100%
46%
of energy mix
non-fossil
80%
2037
Nuclear peaks
60%
40%
2046
Commercial EVs
outnumber commercial
fossil-fuelled vehicles
2038
More electricity is used in
transport than space cooling
2035
Half of world's road
vehicles electric
2046
Non-fossil capex
overtakes fossil capex
20%
2043
Utility-scale Li-ion
batteries reach 1 TWh
2047
Energy intensity is
halved since 2018
2045
5% of energy-related
emissions are captured
2035
Wind overtakes hydro
2049
PV installation 10TW
0%
2051 2°C carbon budget exceeded
2034
Half of all maritime
energy use is non-oil
2034
Maritime energy
demand peaks
2039
Seaborne gas trade
exceeds coal trade

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Image: AAroads

INTRODUCTION

ABOUT THIS OUTLOOK

This annual Outlook, now in its fourth edition, presents the results from our independent model of the world's energy system. It covers the period through to 2050 and forecasts the energy transition globally and in 10 world regions (see page 18). This report is intended as a strategy-forming tool for analysts and decision makers within the industry and other stakeholders. Our forecast data may be accessed at eto.dnvgl.com/data. The changes we forecast hold significant risks and opportunities for investment strategies, operating models, safety, fuel choice and so on. Some of these are detailed in our 'industry implication' supplements:

- Oil and Gas
- Maritime
- Power Supply & Use

OUR APPROACH

In contrast to scenario-based outlooks, we present a single 'best estimate' forecast of the energy future, with sensitivities discussed in relation to our key conclusions.

Our model simulates the interactions over time of the consumers of energy (transport, buildings, manufacturing and so on) and all sources of supply. It encompasses demand and supply of energy globally, and the use and exchange of energy between and within world regions. The selection of energy sources is driven algorithmically based on modelled costs, and in some cases, prices.

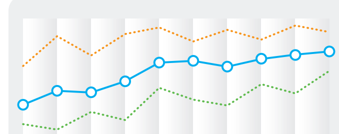
The analysis covers the period 1980–2050, with changes unfolding on a multi-year scale, that in some areas is fine-tuned to reflect hourly dynamics. We include policy factors in our forecast like subsidies, carbon pricing, pollution interventions and energy-efficiency standards. Some behavioural change is also accounted for, largely in relation to a changing environment.

INDEPENDENT VIEW

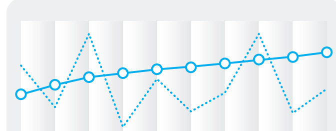
DNV GL was founded 156 years ago to safeguard life, property and the environment. We are owned by a foundation and are trusted by a wide range of customers to advance the safety and sustainability of their businesses. More than 70% of our business is related to energy. Two of our main business areas focus, respectively, on oil and gas, and on power and renewables. This gives us a deep and balanced perspective on the relationship between fossil and non-fossil sources of energy.

Developing an independent understanding of, and forecasting, the energy transition is therefore of strategic importance to both us and our customers.

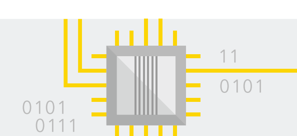
Our **best estimate**, not the future we want



A single forecast, not scenarios



Long term dynamics, not short-term imbalances



Continued development of proven **technology**, not uncertain breakthroughs

Main **policy** trends included; caution on untested commitments, e.g. NDCs, etc.

Behavioural changes: some assumptions made, e.g. linked to a changing environment

OUR EXTERNAL COLLABORATION NETWORK FOR OUR 2020 OUTLOOK INCLUDES:

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HIGHLIGHTS

Our forecast for energy **demand through** to 2050 shows the dramatic effect of efficiency gains, largely enabled by accelerated electrification, that will start to outpace economic growth in the coming years. Despite the rapidly growing consumption of energy services by a burgeoning global middle class, we forecast that final-energy demand will, in fact, peak in 2034, and at a level only 4% higher than that of today. Thereafter, energy demand will gradually drift downwards to 2050, returning to the same level as it is today.

In the near term, we show how energy demand is impacted by **COVID-19**. Demand will fall by 8% this year, and then fluctuate annually between 6-8% lower than would have been the case without the pandemic. Some pandemic-related changes will have lasting effects – for example in commuting, office space and aviation.

Electrification strongly impacts end use in all three main demand sectors – transport, manufacturing and buildings. However, it is in transport that the electron gains most over molecules of fossil fuel: we show how passenger **electric vehicles (EVs)** are likely to outsell their fossil-fuel counterparts worldwide by the mid-2030s. The maritime and aviation industries cannot easily electrify, but both subsectors will make substantial progress towards low- and zero-emission fuels by 2050.

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ENERGY DEMAND

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1 ENERGY DEMAND

Energy consumption is dependent on the supply and demand balance, but, in reality, it starts with demand, as there is enough energy in the world to meet our demands. This chapter describes the energy requirements within the various sectors: transport, buildings, manufacturing, and feedstock.

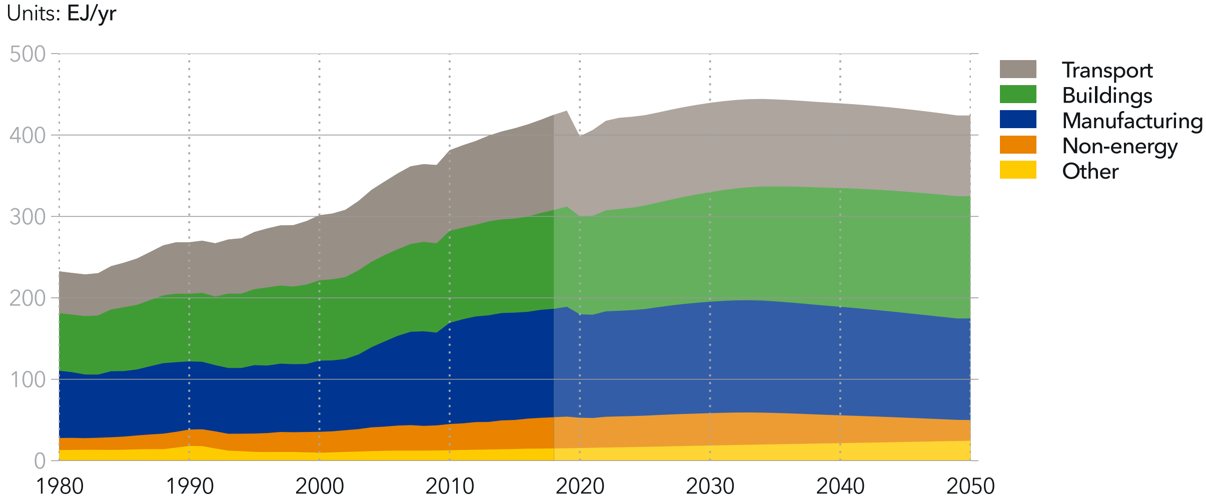
Historically, energy demand has grown in lockstep with population growth and improvements in standards of living. Global population growth will slow down, although it will still be increasing, reaching 9.4 billion people in 2050. Economic growth will also continue, and the size of the global economy in 2050 will be 270 trillion USD, with an average growth rate of 2.3% from 2020 to 2050. Further details on our forecast for population and economic growth are included in the annex of this Outlook.

In the absence of an energy transition, more people requiring ever-more energy services – be it transportation, heating, lighting, or consumer goods – would simply lead to increased energy demand, as has occurred historically. Indeed, energy demand has grown in recent years despite impressive end-use efficiencies achieved by means of, for example, advances in lighting and heat-pump technologies.

FIGURE 1.1

World final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2019)

The coming three decades are likely to be different: we forecast that efficiency gains, largely enabled by accelerated electrification, will start to outpace economic growth. Despite the rapidly growing consumption of energy services by a burgeoning global middle class, we forecast that final-energy demand will, in fact, peak in 2034, and at a level only 4% higher than that of today. Thereafter, energy demand will gradually drift downwards to 2050, returning to the same level as it is today. This is illustrated in Figure 1.1, where the COVID-19 effect can also be clearly seen, strongest in transport and least in buildings energy use.

Peak final-energy demand will occur at different times in the various world regions; indeed, for the regions with lowest GDP per capita, demand will not peak during our forecast period.

Furthermore, demand will not peak uniformly across the various demand sectors. The strongest growth will occur in the buildings sector, where significantly more residential and commercial floor area will be available to serve more prosperous populations. Consequently, buildings will collectively consume 24% more energy in 2050 than in 2018, its share in global energy use growing from 29% to 35%.

In the manufacturing sector, substantial energy-efficiency gains, including increased recycling, will outpace the growth in demand for goods, such that manufacturing energy use will peak in the 2030s.

Although transport services will typically double (or more) over the forecast period, energy use will reduce. The most important reason is the significant efficiency improvement associated with the switch from internal combustion engine to battery-electric propulsion. Roughly half of the world’s fleet of passenger vehicles will be electric by 2040. Efficiency gains in the road-transport subsector will more than counterbalance the increases in energy demand in aviation and rail. This trend will also be helped by the maritime sector experiencing dramatic efficiency gains that will strongly reduce energy use, despite a substantial growth in the world fleet.

“We forecast that energy efficiency gains will start to outpace economic growth, with final energy demand peaking in 2034

MEASURING ENERGY; JOULES, WATTS AND TOES

EJ, TWh, or Mtoe? The oil and gas industry normally presents energy figures in tonnes of oil equivalents (toe), based on m³ of gas and barrels of oil, while the power industry uses kilowatt hours (kWh). The main unit for energy, according to the International System of Units (SI), is, however, joules, or rather exajoules (EJ) when it comes to the very large quantities associated with national or global production. EJ is therefore the primary unit that we use in this Outlook.

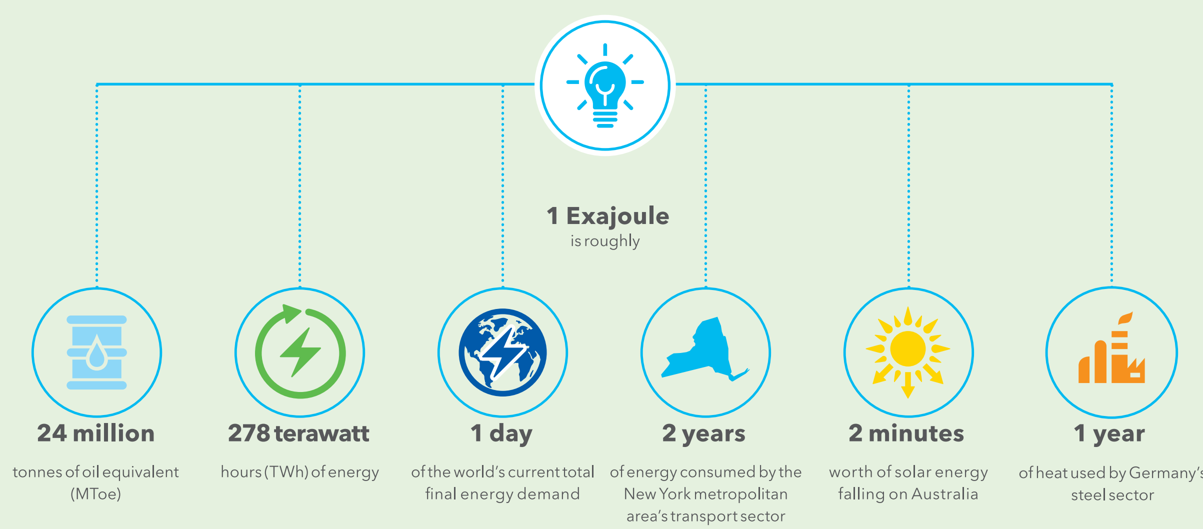
So, what is a joule? In practical terms, a joule can be thought of as the energy needed to lift a 100 g smartphone 1 metre up; or the amount of electricity needed to power a 1-watt LED bulb for 1 second (1 Ws). In other words, a joule is a very small unit of energy, and, when talking about global energy,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

Although we use J or EJ as the main unit of energy, in a few places we use Wh. For measurements of quantities of energy production, we use tonnes, m³, and barrels.

For ease of comparison, conversions are:

1 EJ = 277.8 TWh
1 EJ = 23.88 Mtoe

MEASURING ENERGY IN OUR OUTLOOK



THE EFFECT OF COVID-19

At the time of the last model run for this Outlook, July 1, 2020, the impact of COVID-19 on the energy landscape already appeared massive, and many of the impacts seen over the last half year are likely to persist for the next 2 years. A key question is the extent to which these changes are temporary or whether they will leave a permanent imprint on energy demand and/or supply.

We have looked at the Great Depression of the 1930s, the 2008-2010 financial crisis, and the oil price fall in 2014-2017 as analogies for the economic and energy-related impacts of the present pandemic.

In line with the IMF (2020a) and its "longer outbreak scenario", the least severe of its three corona-impact scenarios provided in April 2020, we see economic growth set back by almost 10% before the world returns to a "pre-COVID" growth path in 2025. As noted below, however, some impacts will change energy-consumption patterns permanently.

A CAUSAL MODEL

Most forecasting models are linear econometric models. They are well suited for shorter-term forecasting, provided that base statistical relationships can be assumed not to change. However, as noted by several analysts, that assumption is not currently valid. Our ETO model (ETOM) differs from econometric approaches in that, in line with the system dynamics tradition (Sterman, 2000), our model is causal. Although the ETOM validation is necessarily limited to the experienced past, its focus on long-term and causal relationships means that it is more robust to the current turmoil within the energy system.

We focus here on possible effects of potential pandemic-linked changes on workplace patterns, leisure travel, supply chains, job creation, and (possibly) greener public policy.

WORKING FROM HOME

The extent to which people work from home impacts both daily commutes and business trips, and also influences the need for office and residential space. Depending on the region, up to half the workforce can work from home (Dingel and Neiman, 2020), with more developed regions having the higher share. The COVID-19 pandemic has created a jump in home-office use, with remote-working platforms taking off thereby forcing greater familiarity with new tools, as well as improving the quality of digital tools and work processes. Similarly, travel restrictions have boosted acceptance and skills in using virtual communication with colleagues and clients across the world. In addition, new ways of engagement and digital communication technologies have boosted use of remote technical surveys.

The consolidation of using remote communication and digital tools will permanently impact ways of working and service provision, reducing transport needs in all sectors. This will affect the demand for workspace (i.e., office buildings) by 2% and reduce private passenger-vehicle use by 1% as commuting becomes unnecessary for many. Similarly, work-related flights will decline by even more, with 10% of that air-transport segment permanently disappearing.

Nevertheless, we see little reason why the present severe impact of the pandemic on international leisure travel will become permanent. It could be argued that vacationers who, in 2020, explore their home country might develop a taste for that and stay closer to home in the future too. However, that option has always been available, and, in contrast to working from home, leisure activities have not developed new ways of operating. As leisure travel is expected to rebound fully from the pandemic effects, the decrease in air travel will be only 5%.

RE-DESIGN OF SUPPLY CHAINS

Travel restrictions and national social-distancing regulations have strained international supply chains and exposed vulnerabilities in security of supplies, magnified by lack of transportation capacity. This effect is compounded by nationalistic ideas — that it is in each country's best self-interest to produce as much food, medical supplies, and industrial output at home. The pandemic has bolstered "make-at-home" arguments. On the other hand, international cooperation to coordinate research and financial efforts to combat the crisis, in both health and science areas, is also strengthened. The former trend would lead to less transport, the latter to more. The former might, however, also show up as building new facilities at home, and by changing the energy mix and use – not necessarily in the direction of higher efficiency. Even as the pre-pandemic trend inched towards "national arguments" growing in importance, we see the net result of these two competing narratives of more and less international trade and cooperation as a marginal move, tending towards slower growth in cross-border collaboration and supply chains.

Shipping will be affected in the corona period to 2025. Even after that, however, the permanent effect of less vehicle use and reduced demand for office space will lead to less steel being needed and a consequent downward nudge in international trade.

THE ECONOMIC IMPACT

In order to address the economic crisis following the pandemic, governments are establishing financial stimulus packages with the main intention of regaining and maintaining activity and jobs. The specific content of the economic stimulus packages will affect whether and how COVID-19 will speed up or slow down the energy transition. Some countries will use this opportunity to ensure a greener transition, supporting, for example, production and purchase of EVs, whereas others may inject large tax reliefs into vulnerable oil and gas industries. At the time of writing, August 2020, we see both directions, but with relatively few countries specifically aiming for green packages. This means that the net result is only a neutral impulse to the transition.

COVID-19 responses also facilitate discussions on behavioural changes, which have previously received less attention in the energy-transition debate than technological changes. Behaviours can and do change with the perception of crisis. The climate crisis has, to date, not evoked such reactions, but the COVID-19 response demonstrates that it is possible. If so, it would be a transition accelerator.

It appears likely that the COVID-19 impact will still be massive in Q3 and Q4 of 2020, thereafter returning to normality within another 5 years. However, we anticipate the pandemic's main long-term (beyond 2025) impacts to be minor — other than the transition being stalled for 2-3 years. This standstill has a dual effect. On the side of accelerating the transition, public money and policy will be needed – in a Keynesian framework – to keep productivity afloat. This favours future green investments. On the other hand, activity-enhancing time delays are shorter in fossil-related activities, so these are

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likely to be favoured. The pandemic job-boosting activities are thus expected to fall evenly on both sides, thus having marginal net long-term accelerating effect on the transition speed.

Using the IMF (2020a) 'longer outbreak' scenario, but also in line with a consensus view (OECD, 2020), we expect the relative global GDP reduction to differ across regions. Instead of the originally projected growth of 3% in 2020 and 2.9% in 2021, we see a decline of 10% (mostly in Q2-Q3) to 7% in 2020, easing to a decline of 5% in 2021. Thereafter, there will be a gradual return to "normal" GDP growth by 2025. The short-term downturn in activities are partly those that will result in later upswings, such as delayed housing construction and new vehicle sales, and those that are lost forever, such as restaurant meals and holiday travels.

In Table 1.1, we show how GDP projects differently in the regions, on a cumulative basis, from the no-COVID-19 situation. By 2025, the world economy has suffered a full 9.4% effect of the pandemic, with double-digit effects in Middle East and North Africa, North America and Europe.

Table 1.2 shows that there will be lingering effects on final-energy demand for a full five-year period until 2025. The keen reader will also note that although the effects are region specific until 2023, thereafter, as our IMF source notes, there are no regional differences in the COVID-19 effects.

Table 1.3 shows the impact on the global final-energy demand sectors. Although energy demand declines at twice the rate of GDP in 2020, by 2021 the decline in energy demand is in line with GDP. Thereafter, energy demand is less impacted than GDP. This is due to the reduction in the energy intensity of the economy, as GDP growth and energy-demand growth are slightly and increasingly decoupled.

The economic lockdown has strongly affected, and will continue to affect, transport demand. In 2020, aviation demand is reduced by 45%. However, after 2023, the decline in transport-energy demand can be explained by GDP effects. Note, however, that aviation demand remains permanently reduced by 5% due to increased use of digital technologies for communication and, consequently, less business travel. Buildings are affected much less than the other demand sectors, as people need somewhere to live regardless. Use of appliances will be marginally affected, as will the need to heat and cool homes. The main effect on buildings is a long-term impact from increased use of home offices, and thus less need for office space. Manufacturing volumes, and consequently energy-use decline, will be twice the GDP impact in 2020, mainly due to a 27% dip in vehicle manufacturing, but also resulting from less steel use in buildings construction.

Vehicle sales will be strongly impacted by the pandemic. In less affluent regions especially, vehicle ownership is growing faster than GDP. Conversely, GDP decline has an outsized effect on ownership reduction. In addition, in wealthier regions, vehicle sales are mostly replacement sales. With vehicle lifetimes at around 10-20 years, depending on vehicle type and region, a 7% reduction in new vehicle ownership will wipe out all vehicle production for a year. We have capped the annual reduction in production to 25%, resulting in the contraction in vehicle manufacture being extended to several years.

Battery electric vehicle (BEV) production will be marginally more affected than manufacture of internal combustion vehicles (ICEVs).

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TABLE 1.1

Cumulative impact of COVID-19 on regional GDP compared with a non-COVID-19 case

	2020	2021	2022	2023	2024	2025	2030	2050
NAM	-5.4%	-9.0%	-8.1%	-9.3%	-10.3%	-10.7%	-10.7%	-10.7%
LAM	-4.0%	-6.0%	-4.8%	-6.1%	-7.1%	-7.6%	-7.6%	-7.6%
EUR	-5.9%	-10.1%	-9.2%	-10.4%	-11.3%	-11.8%	-11.8%	-11.8%
SSA	-3.6%	-6.4%	-6.2%	-7.4%	-8.4%	-8.9%	-8.9%	-8.9%
MEA	-4.8%	-8.2%	-7.6%	-8.8%	-9.8%	-10.2%	-10.2%	-10.2%
NEE	-4.3%	-7.0%	-6.1%	-7.3%	-8.3%	-8.8%	-8.8%	-8.8%
CHN	-4.0%	-6.2%	-5.3%	-6.5%	-7.4%	-7.9%	-7.9%	-7.9%
IND	-3.9%	-7.1%	-7.2%	-8.4%	-9.4%	-9.8%	-9.8%	-9.8%
SEA	-4.1%	-6.6%	-5.8%	-7.0%	-8.0%	-8.4%	-8.4%	-8.4%
OPA	-4.3%	-7.2%	-6.4%	-7.6%	-8.6%	-9.0%	-9.0%	-9.0%
World	**-4.6%**	**-7.6%**	**-6.9%**	**-8.0%**	**-9.0%**	**-9.4%**	**-9.4%**	**-9.4%**

TABLE 1.2

Global cumulative impact of COVID-19 on the final-energy demand

	2020	2021	2022	2023	2024	2025	2030	2050
World	**-8.3%**	**-7.5%**	**-6.0%**	**-6.3%**	**-7.0%**	**-7.4%**	**-7.5%**	**-7.6%**

TABLE 1.3

Global cumulative COVID-19 impact on final energy demand sectors

	2020	2021	2022	2023	2024	2025	2030	2050
Buildings	-2.8%	-3.2%	-2.6%	-3.1%	-3.8%	-4.0%	-5.0%	-5.8%
Manufacturing	-7.2%	-8.2%	-7.1%	-7.8%	-8.4%	-8.7%	-7.8%	-7.9%
Transport	-17.2%	-11.6%	-8.5%	-7.5%	-8.1%	-9.0%	-9.8%	-9.7%
Non-Energy	-6.0%	-9.4%	-8.4%	-9.8%	-10.9%	-11.3%	-10.8%	-10.4%

This is caused by a delay in uptake, thus putting a brake on the decline in battery cost. However, this additional BEV effect fades out over time, as shown in Table 1.4.

The non-energy (Table 1.3) demand sector – where coal, oil and natural gas are consumed as feedstock – use will mimic the dynamics of manufacturing volumes, but will be slightly stronger after the first year.

The pandemic stimulus packages afford a unique opportunity for governments to hasten the energy transition. The short-term effect is notable, as the energy-supply mix is greening. Nevertheless, long-term effects on primary-energy supply are muted, as shown in Table 1.5 – with differences visible from a no-COVID (growth in all supply categories) situation.

Nuclear, hydro, and biomass are quite robust to the COVID-19 impact and are in the 2.4% to 3.2% range in 2050, while all other primary sources are in the 8.8% to 10.2% range. By mid-century, fossil-energy sources are affected 50% more by the COVID-19 pandemic than non-fossil energy sources.

Europe is the region with the strongest transition pressure. With the impact of the pandemic reflected in our forecast, 60.4% of primary energy is supplied by non-fossil sources.

Without the COVID-19 effect, it would have been marginally higher – at 60.7%. This contrasts with the global situation, where COVID-19 tips the non-fossil share to 46%, whereas it would have been 45% without the pandemic.

At the time of the final writing, late August 2020, it appears that our COVID-19 modelling assumptions – reflecting the IMF (2020a) 'Longer Outbreak Scenario - LBS' – still holds overall. In particular, the IMF itself has changed its base case in line with its earlier LBS; thus the global GDP base forecast in April of a contraction of 3% globally, was then adjusted downward in June to a 4.9% contraction (IMF 2020b). The April LBS we have reflected is a 5.8% contraction. OECD (2020) used a 6% decline in its June publication (for its 'single hit' case), and the World Bank in June forecast a decline of 5.2%. The world therefore definitely finds itself in a longer outbreak case. ■

> "The world definitely finds itself in a longer outbreak case as outlined by the IMF

TABLE 1.4

Vehicle sales (cumulative) as affected by COVID-19

	2020	2021	2022	2023	2024	2025	2030	2050
BEV sales	-29%	-23%	-12%	-16%	-16%	-13%	-9%	-6%
ICE sales	-27%	-22%	-10%	-16%	-16%	-13%	-2%	1%

TABLE 1.5

Global COVID-19 impact on primary-energy supply, by source

	2020	2021	2022	2023	2024	2025	2030	2050
Biomass	-1.8%	-1.7%	-1.0%	-0.9%	-1.2%	-1.4%	-1.1%	-2.4%
Hydropower	-5.6%	-1.8%	0.3%	-0.5%	-1.3%	-1.8%	-3.5%	-3.2%
Solar PV	-4.6%	-3.1%	-5.8%	-8.2%	-10.0%	-11.2%	-12.6%	-8.8%
Wind	-4.6%	-1.9%	-3.3%	-5.1%	-6.9%	-8.5%	-14.4%	-10.2%
Nuclear	-4.3%	-0.5%	-0.5%	-0.5%	-0.5%	-0.6%	-0.5%	-2.4%
Total non-fossil	**-3.3%**	**-1.4%**	**-1.0%**	**-1.4%**	**-2.0%**	**-2.4%**	**-4.1%**	**-6.2%**
Coal	-6.1%	-8.3%	-7.5%	-7.4%	-7.9%	-8.2%	-6.3%	-9.0%
Oil	-13.2%	-9.9%	-7.6%	-7.1%	-7.7%	-8.5%	-9.3%	-9.6%
Gas	-6.3%	-9.5%	-8.7%	-8.8%	-9.6%	-10.1%	-9.4%	-9.3%
Total Fossil	**-8.6%**	**-9.2%**	**-7.9%**	**-7.8%**	**-8.4%**	**-9.0%**	**-8.5%**	**-9.4%**

1.1 TRANSPORT

Despite a large growth in all transport subsectors, efficiency gains – mainly due to electrification – will result in transport energy demand falling from 117 EJ in 2018 to 99 EJ in 2050.

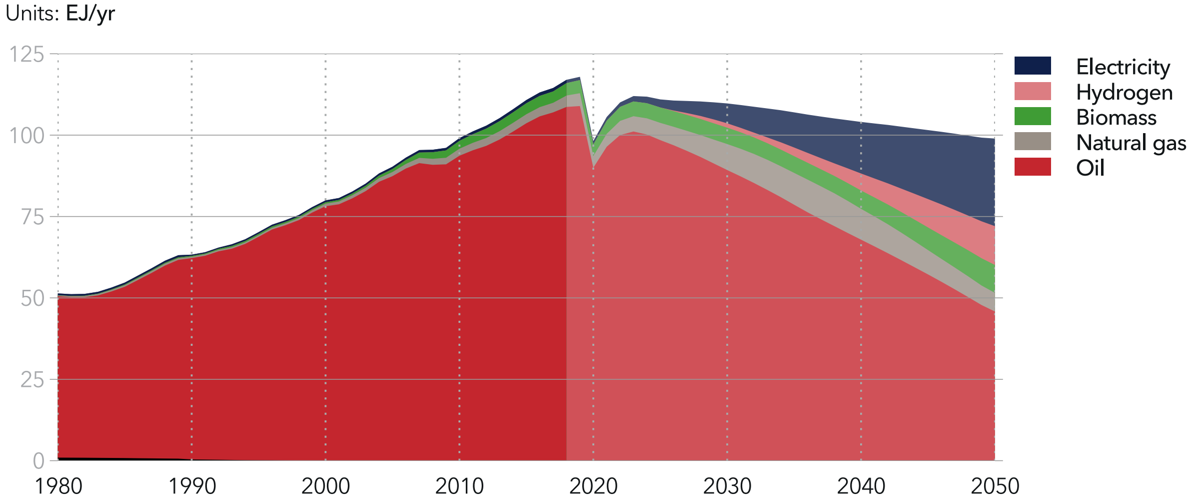
The transport sector has seen significant pandemic-associated reductions in energy demand in all subsectors, from road transport, through shipping, to air transport.

Transport was responsible for 27% of global final energy demand in 2018, almost entirely in the form of fossil fuels (Figure 1.2). In some countries and subsectors, gas is used to reduce local pollution, whereas in others there is significant use of electric propulsion in passenger vehicles. For instance, half of new sales of passenger vehicles in Norway are EVs. Of the 10 world regions analysed, nine (excluding Middle East and North Africa) have biofuel-blend mandates or give biofuels preferential treatment. Nevertheless, globally, 92.4% of road-sector current energy use is refined oil, with biofuels and natural gas each taking a 3.2% share. The road transport energy mix is mirrored by aviation and maritime; in the rail subsector, 42% of energy use is electric. Biofuel mandates are a prime example of the role of public policy in transport fuels. Decarbonization and fuel efficiency are interlinked, and some regions, notably China and OECD countries, use a mixture of push and pull strategies to achieve their decarbonization ambitions. Moreover, UN bodies, such as the International Maritime Organization (IMO), have opted for firm targets. The IMO's 2020 target for reducing sulfur emissions will, however, result in an

FIGURE 1.2

World transport sector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2019)

increase – rather than a decrease – in carbon emissions. On the other hand, the IMO is aiming for a 50% reduction in GHG by 2050, and we expect that this will be achieved through a combination of fuel switches and efficiency gains.

We envisage public policy targeting and banning emissions, with significant industrial and consumer support, continuing for at least another decade. However, over time, battery cost-learning rates will render such policies superfluous – at least in the road sector, which accounts for almost 80% of transport-energy use. Vehicle manufacturers are increasingly overhauling their strategies to cope with the looming market dominance of BEVs. For most uses, BEVs will soon become more cost effective than ICEVs; they typically have less than a third of the energy consumption, and, additionally, have much lower maintenance costs. However, BEV uptake does hinge upon policy support in the near term, and removing such support could reverse BEV-uptake dynamics (Testa and Bakken, 2018). Hence, our Outlook includes significant near-term policy support – for example, the recent EU vehicle carbon emissions-reduction legislation, which is strongly influencing vehicle manufacturers; for example, the Volkswagen AG ambition of achieving a share of at least 40% of EVs in the Group Fleet by 2030 (Volkswagen AG, 2019).

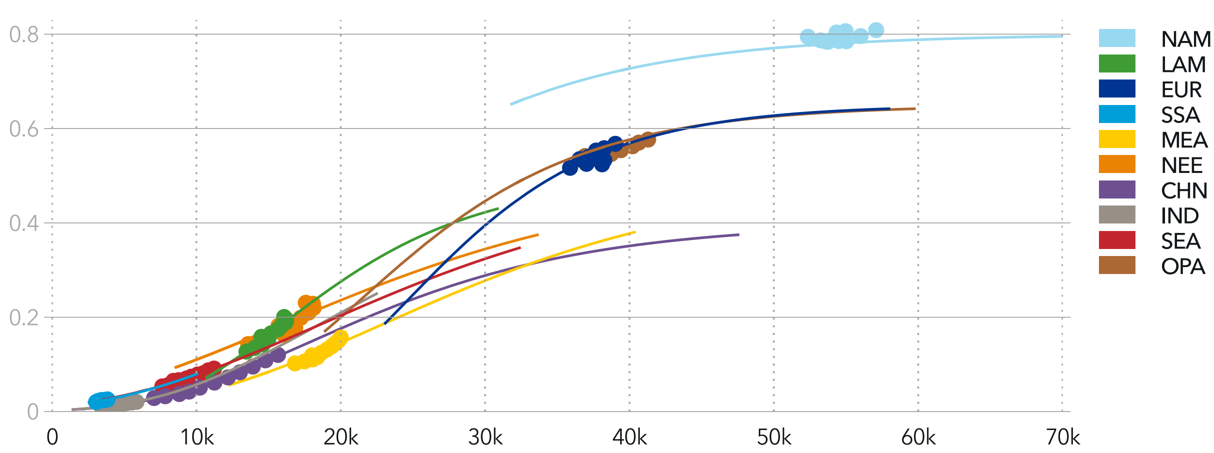
ROAD

Standard of living, defined as GDP/person, is a major driver of vehicle density (vehicles per person) in all regions. This relationship is regional and influenced by a mixture of geographical, cultural, technological, and environmental concerns, as well as support of road-transport alternatives. One extreme case is North America where vehicle density already exceeds 80%. In order to predict future developments of vehicle density in each of the 10 regions related to GDP/person, historical vehicle-density data have been fitted to a Gompertz (type of S-shape) curve, resulting in region-specific growth patterns (Figure 1.3). In some regions, like Greater China, we have used expert opinion to supplement the quantitative prediction, enabling a synthesis of the effects of strong policy support for public transportation. As an example, China's vehicle density will plateau at 40%, as shown in Figure 1.3. Note that the figure shows the sum of both commercial and passenger vehicles per person.

FIGURE 1.3

Road vehicle density by region

Units: Vehicles per person



Excludes two and three-wheelers
Points show historical data from 2005 to 2015 (OICA, 2016). Lines show model estimates from 1980 to 2050

The category "passenger vehicles" encompasses all vehicles with three to eight passenger seats. Thus, it includes most taxis, but excludes buses. Categorization in registration differs between jurisdictions, so our term excludes, for example, sport utility vehicles (SUVs) in North America, but not elsewhere. Other non-passenger vehicles with at least four wheels are commercial vehicles. Commercial vehicles tend to represent a significant fraction of road vehicles in less-developed countries, but, as these become more prosperous, the passenger share of the fleet increases (Table 1.6). Again, North America is something of an anomaly; drivers have increasingly opted for fewer (small) passenger vehicles and more (large) commercial vehicles. This is not because the population of North America has become less affluent. Rather, a mix of lower fuel prices and laxer fuel-efficiency and safety standards for SUVs and pick-ups has resulted in light trucks becoming the current vehicles of choice in North America. However, we expect this trend to bottom out within the next few years. In OECD countries, some data indicate decreasing car ownership among younger people (Dutzik et al., 2014). Nevertheless, after controlling for dropping cohort income, others have not found such relationships (Klein & Smart, 2017). As our database includes recent dynamics that show a falling share of car ownership amongst younger people, we have implicitly incorporated this trend in our analysis.

At present, taxis represent a significant fraction of the global passenger-vehicle fleet. Communal use of passenger vehicles is typically more prevalent in less-developed regions than in OECD countries. However, several recent developments, such as platform-based ride services, support increasing communal passenger transport in OECD countries too, starting with urban transport. One reason for this, is the much higher logistics efficiency of ridesharing services compared with traditional taxis (Tabarrok, 2016). Because platform-based ridesharing services offer improved services at higher efficiency and lower costs, this segment will continue to grow. Similarly, car-sharing platforms will result in an ever-higher fraction of traditional car use becoming obsolete. Our analysis indicates a further reduction in both private ownership and vehicle numbers, especially in North America, Europe, and OECD Pacific, also as a result of the issues noted above.

Both self-driving taxis and automated driving of privately owned passenger vehicles will contribute to increased asset utilization, leading to shorter asset lifetimes and thus faster renewal of the fleet. As a result, emerging battery technologies will experience a significant boost in uptake, and thus help to reduce the average fuel consumption in all passenger-vehicle segments. To account for these developments, we assume that while, on a global basis, annual driving distances for passenger vehicles vary between 15,000 and 25,000 km/year, automated vehicles are driven 50% more, and shared vehicles 5 times as much. The latter is in line with the fact that taxis typically drive five times as much as personally owned passenger vehicles. Consequently, an automated, communal vehicle will be driven 7.5 times as much as a non-auto-

TABLE 1.6

Share of passenger vehicles in total road vehicles by region

	NAM	LAM	EUR	SSA	MEA	NEE	CHN	IND	SEA	OPA
2005	59 %	72 %	87 %	63 %	72 %	82 %	71 %	72 %	64 %	76 %
2020	50 %	75 %	87 %	67 %	74 %	86 %	87 %	78 %	70 %	80 %
2030	49 %	77 %	86 %	69 %	76 %	86 %	89 %	80 %	73 %	81 %

mated private vehicle. The growing use of digitally enabled forms of transport (automation and ridesharing) may happen at the expense of traditional public transportation, as well as walking and bicycle use, but these modal shifts have not been analysed. As we expect several factors to counterbalance each other, we assume that aggregate vehicle-kilometres driven will not be significantly affected by automation or car sharing.

The broad effects of digitalization are starting to gather pace in power systems, industrial production, transport, buildings, and oil and gas, and these effects are captured in our forecast. In the transport sector, digitalization will enable increased car-fleet automation and ridesharing, the effects of which on fleet size and energy use are included in our forecast. Digitalization and connectivity will enable increasing asset utilization across all demand sectors, reducing energy use per unit of service delivered. As the assets themselves become more efficient (e.g., EVs), this will have profound implications for the global energy system.

This does not detract from our main finding: the uptake of EVs – passenger EVs first and commercial EVs subsequently – will occur rapidly. Supported by recent findings (Keith et al., 2018), we assume that entities choosing to acquire an EV will base their choice on weighing costs against benefits. Within our approach, simulated buyers have the choice between EVs (becoming increasingly cheaper and providing longer range over time) and ICEVs. Potential buyers of passenger vehicles will view the acquisition (purchase) price as the main factor and put less emphasis on OPEX, whereas owners of commercial vehicles will take into greater consideration the OPEX advantages of EVs.

Currently, the number of charging stations within range is a major barrier to EV uptake, and significant uptake of EVs cannot be achieved without both the average fleet range leaping forward and charging-station density increasing. As described in more detail in Annex A.4, it is assumed that the historical battery cost-learning (CLR) of 19% (per doubling of accumulated capacity) will continue throughout the forecast period, and the battery cost decrease will drive vehicle CAPEX cost decline. Figure 1.4 shows that as (global) battery prices fall, average battery sizes in all regions will benefit. In Europe, the size will more than double from today's 49 kWh/vehicle to slightly above 100 kWh/vehicle in 10 years, resulting in expanded vehicle range.

FIGURE 1.4

Development of passenger electric vehicle cost, battery size and range in Europe

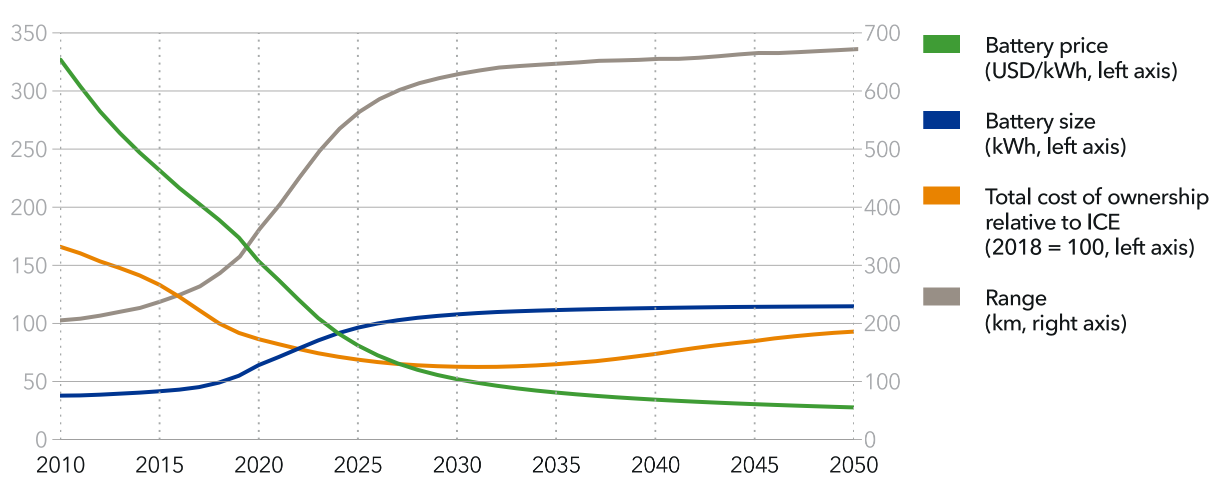


Figure 1.4 shows that EV total cost of ownership (TCO) will decrease only slightly between 2020 and 2025, as battery capacity increases. Passenger-vehicle TCO will further increase from the 2030s onward, mainly due to an increase in vehicle operating costs, based on the increment gain of kilometres driven per passenger EV. After 2023, dramatic cost drops will emerge again, in particular for commercial vehicles. In the case of EV TCO, which is displayed for passenger vehicles only in Figure 1.4, the pattern is similar for commercial vehicles. The two countries with highest EV uptake rates, China (commercial vehicles) and Norway (passenger vehicles), have both used a mixture of mandating electric propulsion and de facto subsidies on the buyers' side. A recent study shows the importance of preferential treatments for encouraging EV uptake (Testa and Bakken, 2018). Given this evidence, we expect a similar boost to come from the EU's emission-reduction plan, giving carmakers a substantial bonus for zero-emissions vehicles when calculating average fleet emissions, and surtaxing fleets that exceed the target (EC, 2019).

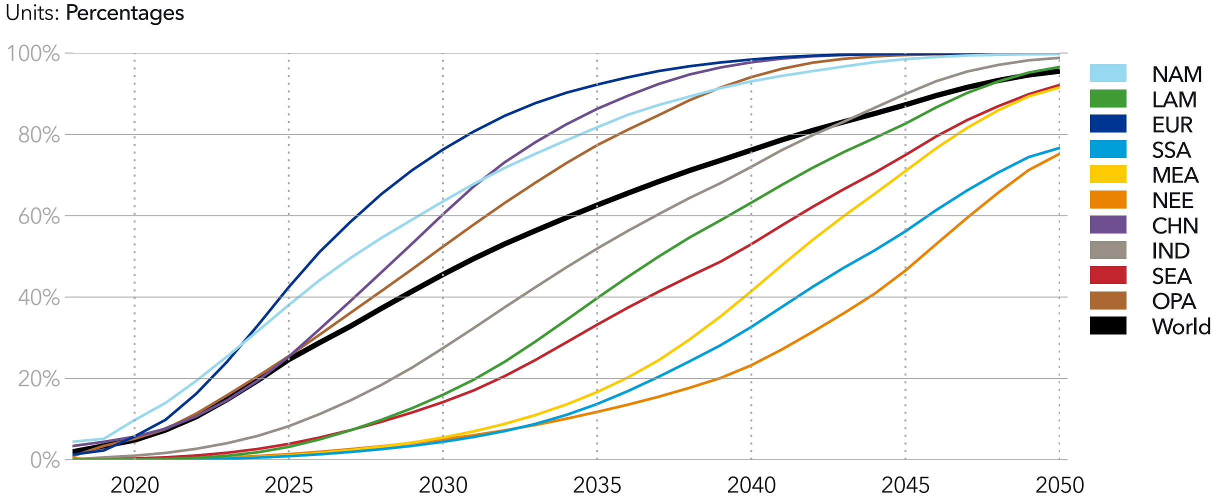
Subsidies for passenger EVs vary from zero, in those parts of the world with lowest GDP per capita, to a few hundred USD in others, to a few thousand USD per vehicle – for a limited period – in OECD countries. Note that these figures also include producer subsidies. For commercial vehicles, the battery costs will be substantial and require significantly higher and more-prolonged subsidy levels. We assume that there will be willingness to continue such support in OECD regions and Greater China.

In addition to direct purchase and manufacturing subsidies, a host of preferential operating treatments for EVs have also been considered, such as permission to drive in bus lanes, free parking, and low-to-zero registration costs or road taxes. Most jurisdictions bake road taxes into fuel use, and many also apply toll charges, but, thus far, EVs have not been taxed at the same levels. With the exception of the oil-rich Middle East and North Africa region (Mundaca, 2017), direct fuel subsidies are not widespread. On the contrary, road taxes are prevalent across the world and, in OECD countries, also typically include an explicit carbon-tax element (OECD, 2018). This element we foresee increasing as carbon prices rise, reflecting local pollution and climate-change concerns.

FIGURE 1.5

Market share of electric passenger vehicle sales by region

Units: Percentages



Electric vehicles include BEVs and FCEVs. Historical data source: OICA (2016), IEA GEVO (2018)

In terms of relative utility of EVs compared with ICEVs, we assume four factors to be of importance, each with a different weight, namely:

– Recharging/refuelling speed
– Charging/fuelling stations within range
– EV convenience
– EV footprint advantage

For example, the EV footprint advantage reflects the weight that various regions are expected to put on whether electric-fuel sustainability is valued (or not). It is multiplied by the share of electricity supplied from non-fossil sources and added to the perceived utility of EVs. However, even EVs that use electricity with high shares of fossil fuel-based power are more carbon efficient over the lifetime of the vehicles than size-equivalent ICEVs (ICCT, 2018).

Considering the aforementioned four factors for comparing the utility of EVs and ICEVs, EV-uptake rates are significantly slower for commercial vehicles than for passenger vehicles – despite the heavy subsidies assumed.

As shown in Figure 1.5, we forecast that Greater China, Europe, and North America will reach 50% passenger market share in the late 2020s, while OECD Pacific will reach this by 2030. The mile-stone of 50% sales share for EVs will happen around 2032 for the world as a whole. In less-developed regions, uptake will come later as charging-infrastructure density is much lower. However, even in these regions, 50% sales figures will be reached before 2046. By 2050, hardly any ICEVs will be sold in China and Europe, while in other regions sales of ICEVs (up to 20%) will continue.

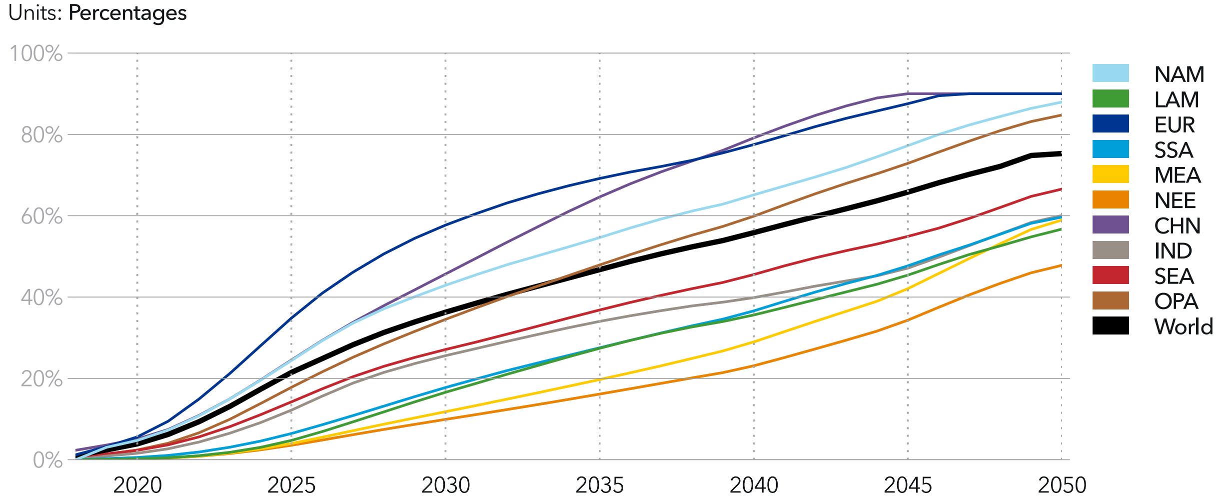
For commercial vehicles, electrification will be more prolonged. However, it is necessary to consider the vast spread of vehicle characteristics in this segment. These vary from buses – where uptake is already high in Greater China – to local smaller trucks, to long-distance heavy trucks.

In less-developed regions, a 50/50 mix of commercial EVs and ICEVs will still be found at the end of our forecast period. In contrast, both Greater China and Europe will have achieved a 50% EV share by 2031 (Figure 1.6). Figure 1.6 includes all EVs, both battery-powered and hydrogen-fuelled via fuel cells.

FIGURE 1.6

Market share of electric commercial vehicle sales by region

Units: Percentages



Electric vehicles include BEVs and FCEVs. Historical data source: OICA (2016), IEA GEVO (2018)

Fuel-cell electric vehicles (FCEVs) will play a significant role after 2030 and will amount to up to 13% of the commercial EV fleet in OECD regions and China by 2050, and to a smaller amount in the other regions. The cost and energy-efficiency disadvantage of FCEVs compared with BEVs will make them less attractive in all but one market segment – heavy and long-haul commercial-vehicle transport. We have limited the sales rate of commercial BEVs to 90%. The remaining 10% are assumed to be unsuitable for BEV use. This segment will continue to use combustion technologies, although it should be noted that this also allows for biofuel use.

For several reasons, we consider it unlikely that hydrogen will be used for passenger (light-vehicle) road transport. Countries such as Japan and South Korea, for example, heavily support the uptake of FCEVs as part of their automotive emission-reduction plans (see Chapter 5 for more details). However, we do not expect this to lead to a significant uptake of FCEVs in the passenger-vehicle segment due to the reasons outlined below.

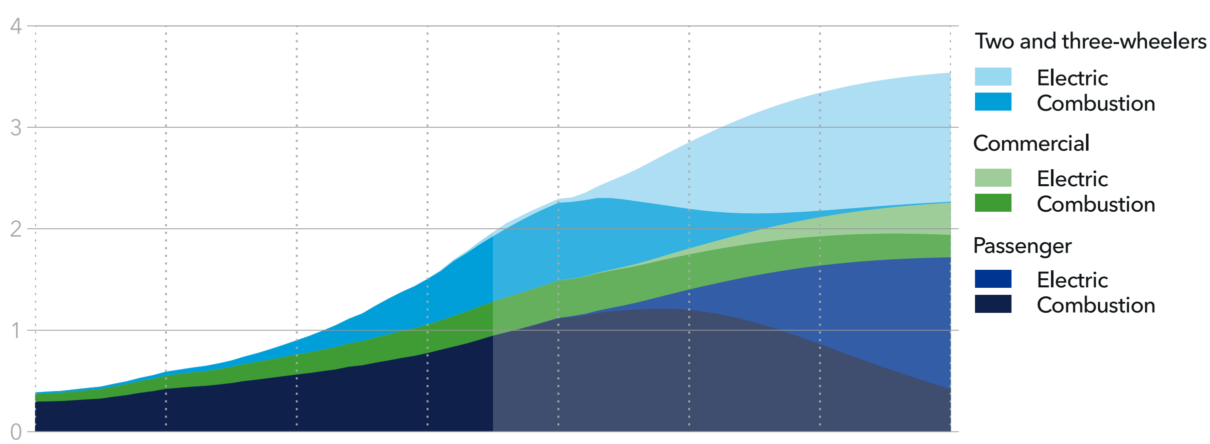
First, there is a significant energy loss when converting power to hydrogen. Second, FCEVs have an energy efficiency that is only half of BEVs. Third, FCEV propulsion technology is much more complicated, and thus more costly, than that of BEVs. Most major vehicle manufacturers share these views and appear to be introducing solely BEV models. Thus, while ten years ago FCEV and BEV target numbers for 2020, in, e.g., California, were similar, current fleet sizes show that less than 1% of zero-emission vehicles today are propelled by FCEV technology.

Two- and three-wheelers are a form of transport that represent only marginal energy use in most regions – with the exception of three: Greater China, the Indian Subcontinent, and South East Asia. Consequently, we have modelled both vehicle demand and electrification of two- and three-wheelers in those three regions, limited to those vehicles requiring registration (electric bikes are included as household appliances rather than road vehicles). We forecast rapid electrification – already over one third of all Chinese two- and three-wheeler sales are BEVs. The combined forecast, including two- and three-wheelers, for

FIGURE 1.7

World number of road vehicles by type and drivetrain

Units: Billion vehicles



Combustion vehicles include ICEs and PHEVs. Electric vehicles include BEVs and FCEVs.
Historical data source: OICA (2016), IEA GEVO (2018)

vehicle numbers – with demand attenuated by rising car sharing, automation, the effects of lower battery costs, and the availability of subsidies – is shown in Figure 1.7. Our forecast indicates a rapid and significant electrification of all parts of road transport, and in all regions.

A drivetrain category much used today is the plug-in hybrid electric vehicle (PHEV), being considered as a bridge. However, its existence will not be sustained once BEVs have sufficient range and charging infrastructure has been implemented widely. This is because of the high purchase price and operating costs of PHEVs due to both an electric and petrol engine.

Despite the dampening effect on demand brought about by car sharing and automation, the size of the global passenger-vehicle fleet will increase by about two-thirds until 2050. As noted previously, vehicle-kilometres will also rise, more than doubling by mid-century. A similar dynamic is anticipated for commercial vehicles, although growth will be slightly lower, with the fleet size expanding by about 50% towards 2050. However, this strong vehicle growth will not result in a similar pattern of expansion in the road-sector energy demand, as BEVs have energy efficiencies that are 3-4 times higher than those of combustion engines. Consequently, road-sector energy demand in 2050 will be lower than it is today (Figure 1.8).

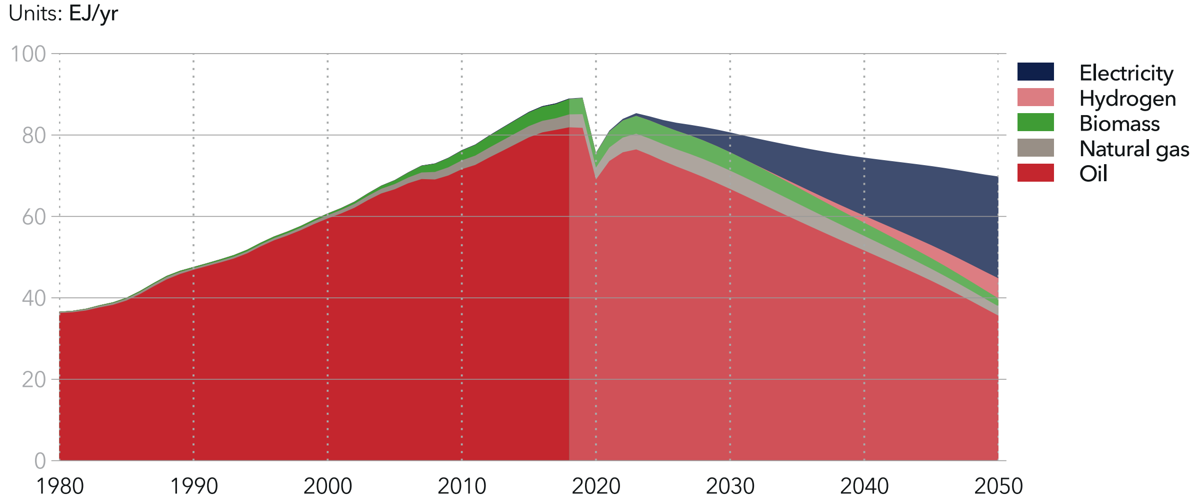
Figure 1.8 shows that although the vast majority of vehicles globally in 2050 will be BEVs, and they will constitute just 36% of the road-subsector's energy demand, their energy consumption will be dwarfed by that of ICEVs with their still-significant use of oil, biofuel, and natural gas. The global road-subsector's energy demand for fossil-fuel oil will be 51%, hydrogen will account for 7%, biofuels will cover almost 3%, while natural gas will be for niche uses only in a global context – with 3%.

> “Despite the dampening effect on demand brought about by car sharing and automation, the size of the global passenger-vehicle fleet will increase by about two-thirds through to 2050

FIGURE 1.8

World road subsector energy demand by carrier

Units: EJ/yr



Natural gas includes LPG. Historical data source: IEA WEB (2019)

SENSITIVITIES

We have examined how sensitive our results are to In particular, we have investigated the effect of changing different factors linked to road transport sector compared to the base case. The results are shown in Table 1.7.

As expected, the effect of battery cost-learning rates (CLRs) is substantial. A 50% higher battery cost-learning results in a larger quantity of both global passenger EVs (+6%) and global commercial EVs (+11%). We also note in our discussion on resource limitations (Annex A.5) that current Li-ion battery technology requires so much cobalt that known reserves will last for less than a decade. Labs are filled with alternative options, and while their cost dynamics are highly uncertain, they will reduce aggregate global battery CLRs, at least for a transition period. Although they may well see even stronger rates later, we cannot rule out that the learning rate over the next thirty years will be significantly slower, with major implications for EV uptake, as well as consequences for future oil and electricity use.

Subsidy levels for passenger and commercial EVs, which are assumed to be substantial – in the tens of thousands of dollars for commercial vehicles – have considerable effect. Cutting them by 90% from the base case, will result in significantly lower passenger EV uptake. Subsidies are even more important for commercial vehicles, and, by doubling them from our base case, will result in a much faster uptake. Note, however, that the main conclusion is that EV uptake over time is not insensitive to subsidies.

Our sensitivity analysis indicates that larger battery sizes in new EVs will be detrimental for their sales, especially in the short term. Both passenger and commercial EVs would be affected by this. As savings from cheaper batteries are going to be mostly used to produce cars with longer ranges, the uptake of EVs would slow down. For example, a 25% increase in battery sizes in 2025 would lead to a 40% reduction in EV sales. The long-term impact, however, would be negligible. Even if battery sizes increase to a level that is one third higher than the base situation, the reduction in the 2050 EV fleet would only be by 1%.

There is ongoing discussion regarding how long vehicle batteries will last. In our analysis, shorter lifetimes will affect TCO, as future operating costs will be discounted over a shorter lifespan. More interestingly, however, a shorter lifetime will also mean that batteries (the assumed lifetime of which is identical to that of the vehicle in which they are operating) will be discarded sooner. This would result in higher turnover and more-rapid new battery additions, which, again, would cause battery prices to fall more quickly.

> “Shorter battery lifetimes would cause battery prices to fall more quickly.

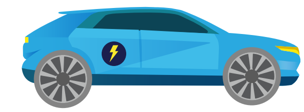
TABLE 1.7

The impact of technology and fuel options on carbon and energy efficiency

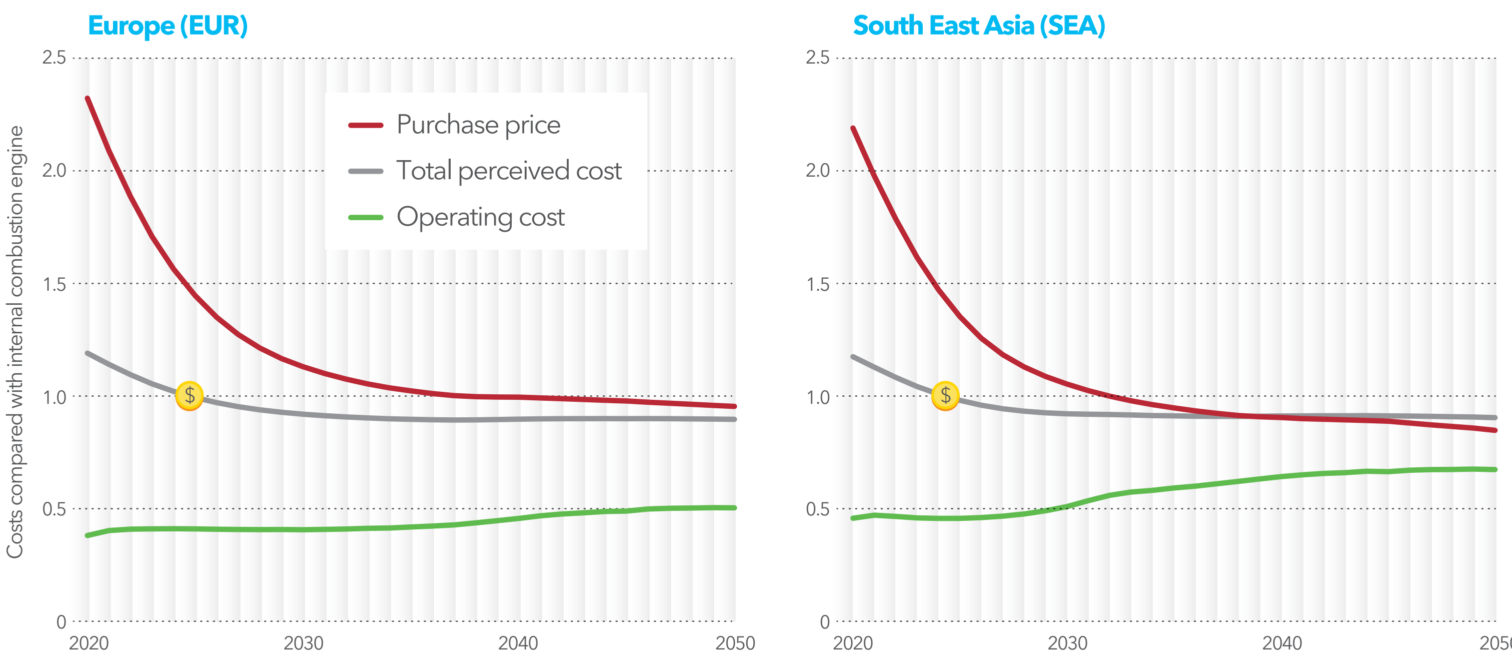
2050 level			Battery cost learning rate		EV subsidy level		EV lifetime	
		Base (19%)	-50%	+50%	Double	10%	No increase from 2018 level	2050 level 1/3 higher than base
Passenger EV fleet size	Millions	1299	1140	1381	1395	1188	1304	1288
Commercial EV fleet size	Millions	318	242	354	357	275	328	305
Passenger EV fleet fraction	%	76%	67%	80%	81%	70%	76%	75%
Commercial EV fleet fraction	%	59%	45%	66%	66%	51%	61%	57%
Road sector energy use	EJ/yr	70	77	67	67	73	70	70
Road sector oil use	EJ/yr	36	46	31	31	41	35	36
Road sector electricity use	EJ/yr	25	21	27	27	23	25	25

Image: Creative commons by Korbitr - https://imgur.com/a/INiuj, Public Domain, https://commons.wikimedia.org/w/index.php?curid=67201954

UPTAKE OF ELECTRIC VEHICLES

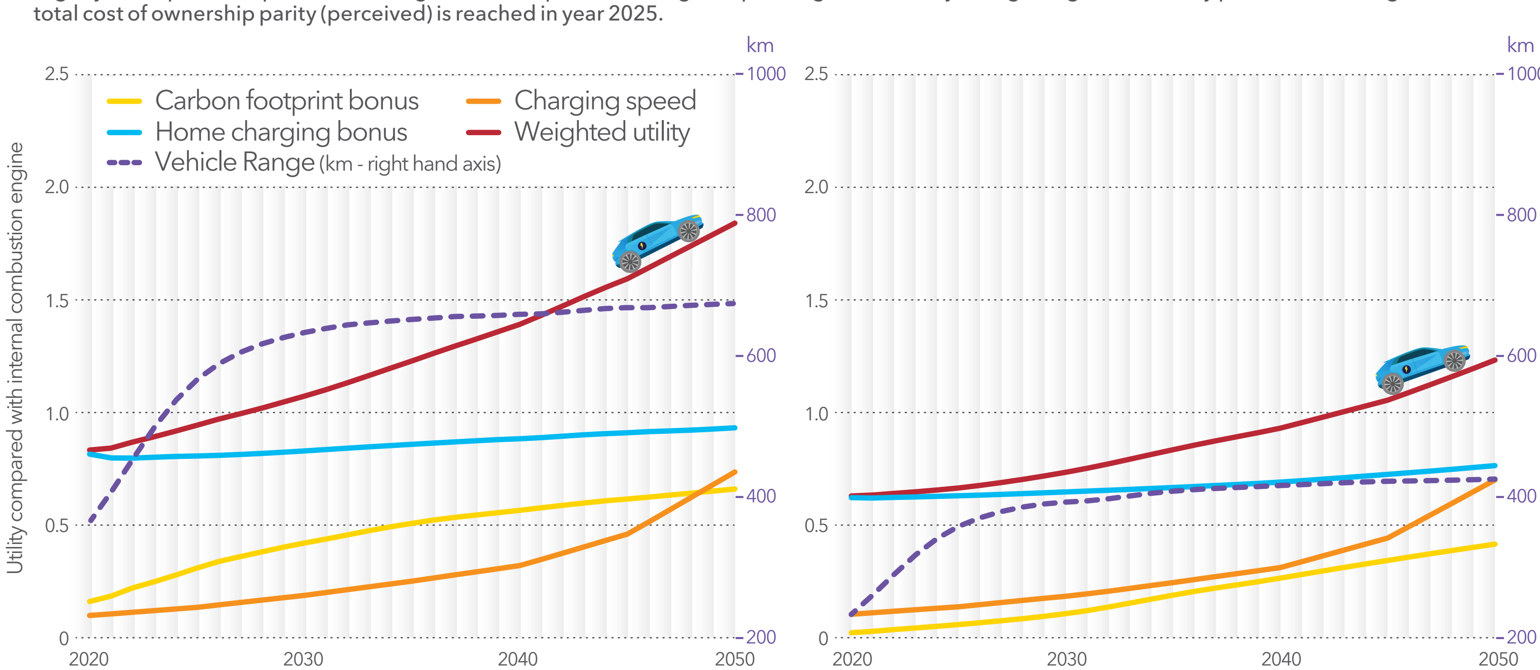


Passenger



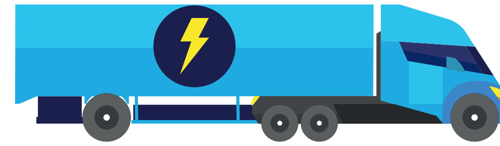
PERCEIVED COST

Private individuals are much less aware than commercial buyers of the total cost of ownership – they tend to largely ignore the present value of lower operating costs. For private individuals, purchase price is a key determinant, hence the perceived overall cost is closer to the purchase price. In SEA, slightly lower purchase prices in the longer term compensate for higher operating costs (mainly owing to higher electricity prices). In both regions, total cost of ownership parity (perceived) is reached in year 2025.



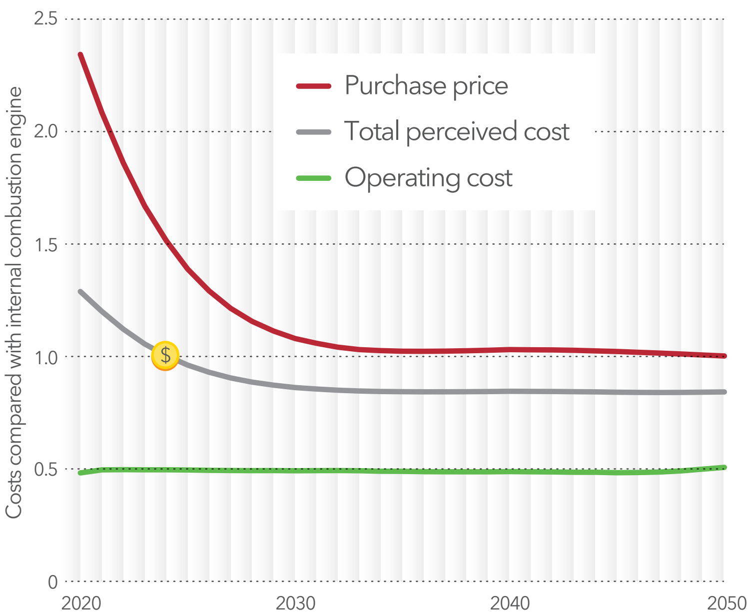
WEIGHTED UTILITY

The weighted utility of passenger EVs differs markedly between these two regions. In SEA, lower household income restricts purchases to EVs with smaller batteries and limited range – decreasing utility. In Europe higher importance is attached to the decarbonization contribution from EVs. Despite sharing similar perceived costs, EV uptake will be more rapid in Europe due to relatively higher weighted utility, which surpasses ICE vehicles in 2027.

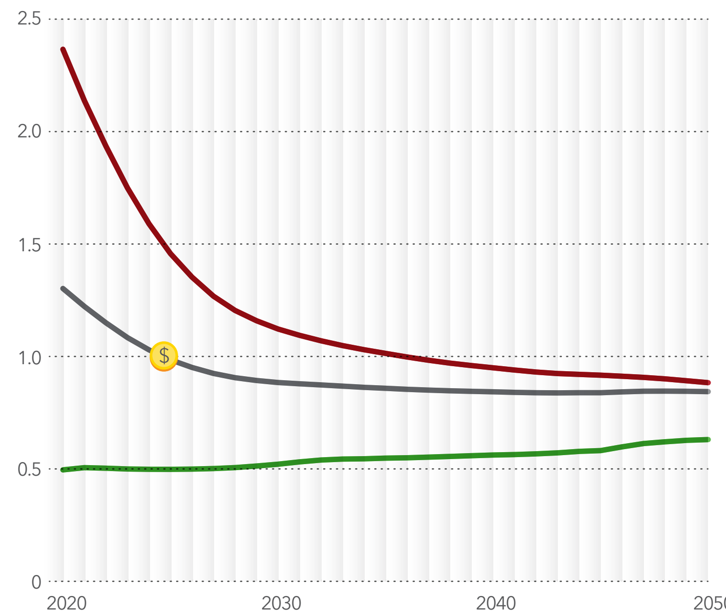


Commercial

EUR Commercial

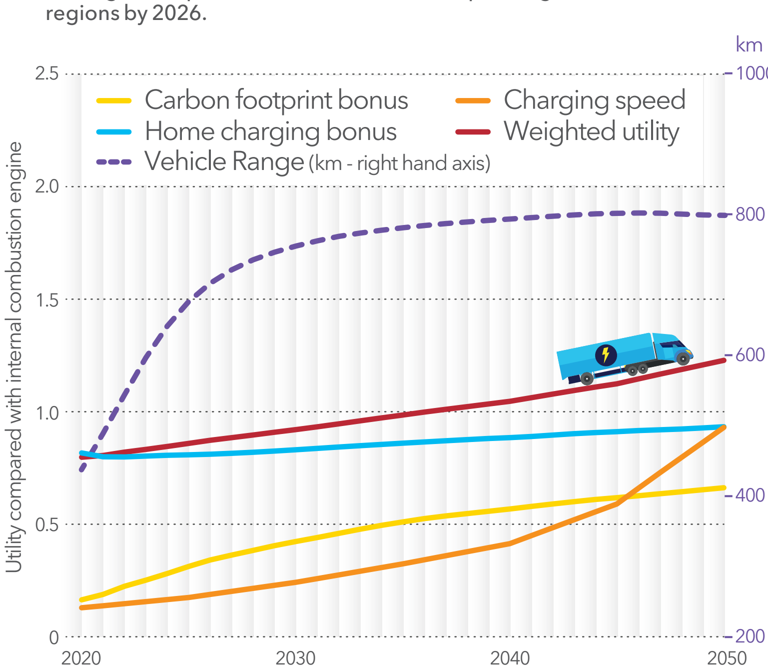


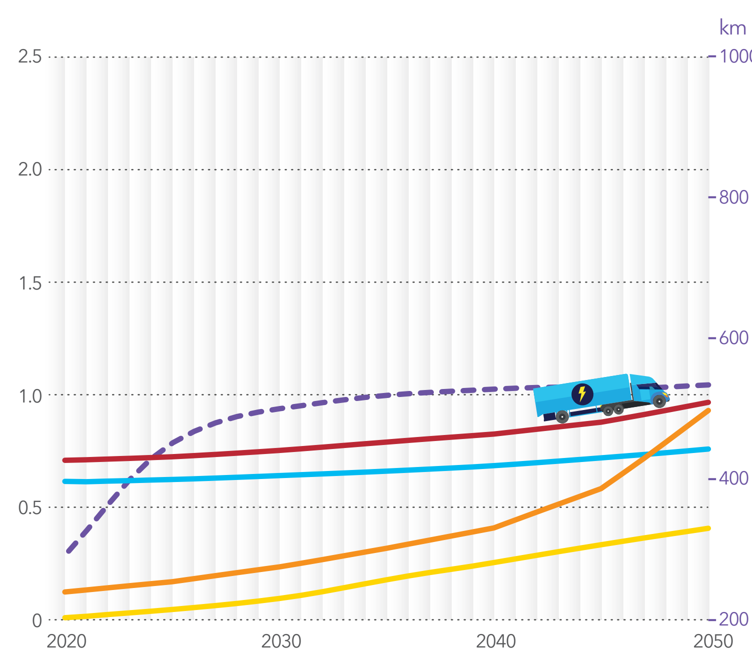
SEA Commercial



PERCEIVED COST

Commercial buyers of EVs will typically run comprehensive discounted cash flows of the total cost of ownership – hence operating costs are more important. Bigger battery costs initially drive upfront purchase prices much higher for trucks and buses relative to passenger EVs. However, owing to the great importance attached to lower operating costs, commercial vehicles reach perceived cost parity with their ICE counterparts in both regions by 2026.





WEIGHTED UTILITY

Initially, higher importance is attached to decarbonization by Europe for commercial vehicles, while in SEA lower commercial budgets restrict purchases to vehicles with smaller batteries and more limited range. In Europe weighted utility reaches parity with ICE vehicles in the mid 2030s, but that point is reached much later in SEA. Perceived cost is a more important driver of EV uptake in that region.

MARITIME

Maritime transport is by far the most energy-efficient mode of transport in terms of joules/tonne-kilometre. Almost 3% of the world's final-energy demand, including 8% of the world's oil, is consumed by ships, mainly international cargo shipping.

In 2020, the IMO regulation on a global sulphur cap came into force, dramatically altering the types of fuel used by the fleet. The main shift has remained within the category of oil-based fuels, where we see a much larger share of lighter distillates, or other variants of fuels with less sulphur, as well as a decent share of marine heavy fuel oil still being used on ships with scrubbers.

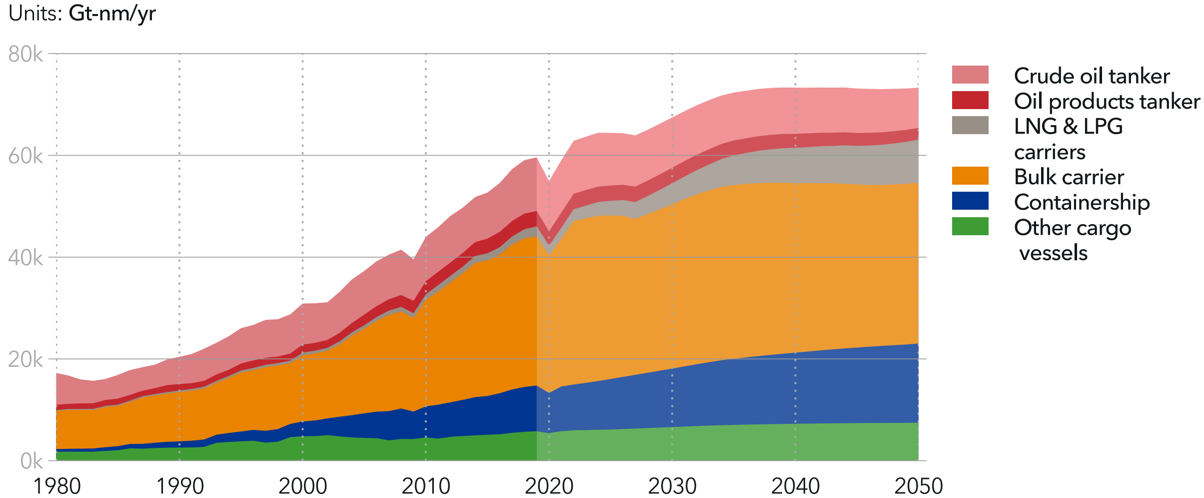
In the longer run, the IMO – supported by both shipowners and governments – targets a 50% reduction in CO_2 emissions from 2008 to 2050. Our forecast is that a mixture of improved utilization and energy efficiencies, combined with massive fuel decarbonization, and including conversion from oil to gas and ammonia and other low- and/or zero carbon fuels, will enable this goal to be met.

World cargo shipping is an integral part of our analysis. Fossil-fuel demand and supply are regionally determined, and any mismatch is rectified by shipping from regions in surplus to those with a deficit. Similarly, base-material supply and manufactured products are partly shipped on keel within regions, but, more importantly, between regions. Logistics efficiencies and supply-chain improvements, resulting from digitalization, sensors, and smart algorithms, will increase fleet efficiencies. However, a world with a GDP that doubles until 2050 will see cargo needs that considerably outweigh efficiency improvements. Therefore, cargo tonne-kilometres will increase in almost all ship categories (Figure 1.9). The exception is coal and oil transport, where tonne-miles will be reduced by more than 50% and 30%, respectively. In the later part of the forecast period, the growth is minor - or non-existent - for most segments, as efficiency improvements outweigh demand growth.

FIGURE 1.9

World seaborne trade in tonne-miles by vessel type

Units: Gt-nm/yr



Historical data source: Clarksons Research (2020)

Driven by the decarbonization push, the fuel mix will change dramatically. Unlike with road transport, the potential for electrification in the maritime sector is limited to short-sea and in-port operations, limiting the efficiency gains afforded by electrification (e.g., 3-4 times efficiency improvement in road transport) in the maritime sector.

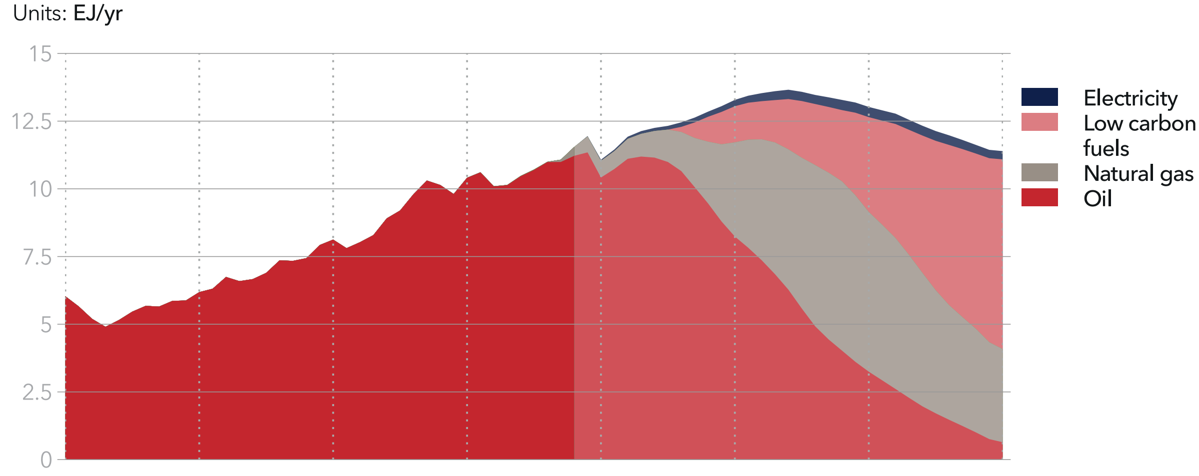
Instead, the efficiency improvement is achieved through a mixture of logistics and efficiency measures in hulls and engines. The fuel-mix in 2050 switch from being almost entirely oil dominated today, to a mix dominated by low- and/or zero carbon fuels (60%) and natural gas (30%, mostly LNG) as is shown in Figure 1.10 and is supported by a host of successful, regionally imposed, decarbonization efforts. The low-carbon fuels here are a mixture of ammonia, hydrogen, and other electrofuels such as e-methanol. We refer to our special Maritime Outlook companion report (DNV GL, 2020c) for further details on the maritime segment's fuel mix and use. In our main ETO forecast, we use one of the "IMO ambition" scenarios used in the maritime report. The report's fuel-mix information is included here, converted into the main energy-carrier categories used in this Outlook.

> "A mixture of improved utilization and energy efficiencies, combined with massive fuel decarbonization, and including conversion from oil to gas and ammonia and other low- and/or zero carbon fuels, will enable the [IMO's GHG] goal to be met

FIGURE 1.10

World maritime subsector energy demand by carrier

Units: EJ/yr



Natural gas includes LNG and LPG. Biomass includes advanced biodiesel and LBG.
Historical data source: IEA WEB (2019)

AVIATION

Almost 4% of the world's energy is consumed by civilian aircrafts. Driven by increasing standards of living, influenced by regional geographies and travel cultures, aviation has shown strong growth in the past decades, but with dramatic reduction due to COVID pandemic. Still, the number of annual air trips is forecasted to more than double until 2050 compared with 2018 numbers (Figure 1.11) with fuel use in aviation only increasing by 9%. This is due to efficiency gains, as higher load factors and developments in engines and aerodynamics will yield impressive improvements in energy efficiency. We see strong passenger – and also cargo - growth ahead. As with shipping on keel, we envisage that pockets of short-haul flights will become electrified. A more significant driver of reductions in emissions will be sustainable aviation fuels (SAF), in particular biofuel blends. The exact low-carbon or even zero-carbon solution or mix of solutions is not known yet, with the same way as our forecast regarding maritime sector, but with regard to current known advantages and disadvantages of available technologies, we forecast SAF`s to mainly contribute to emission reduction in aviation sector. This may change with adjusted aircraft designs (e.g. for hydrogen storage) or changing perception on the use of biofuels (land use, water use, etc.).

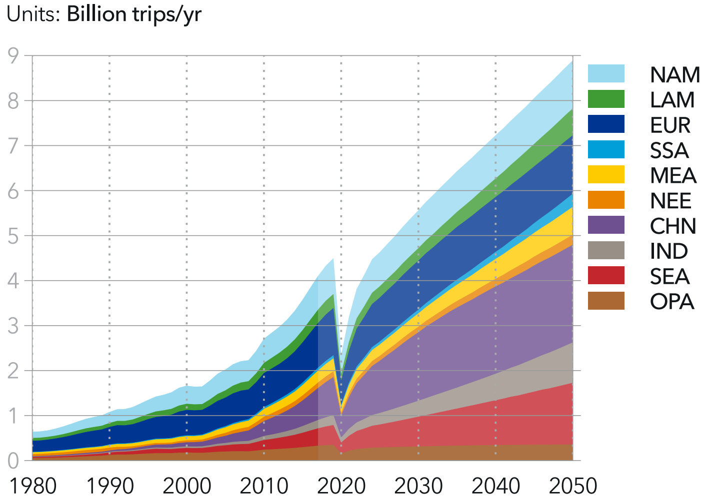
The fuel mix will contain 6.5 EJ (41%) biofuels by 2050 – 3.5 times more than the road sector - and electricity will account for 3%, as shown in Figure 1.12. A combination of technology advances, supply-chain buildout, and successful decarbonization policies will prompt the strong growth in biofuels, as driven by the CORSIA scheme that aims to achieve carbon-neutral growth to 2050 (from a 2019 baseline). In Appendix A.5 we discuss the challenges of provisioning such a large biofuel demand.

Figure 1.11 shows how income growth and increasing populations drive air travel to more than double until 2050 – as measured in trips per year, with cargo also converted into passenger-trip equivalents. We assume that the average trip distance will remain constant, but the numbers of air trips will rise. Whereas trip numbers will grow very strongly in less-affluent parts of the world, quintupling in Sub-Saharan Africa and quadrupling in South East Asia, the OECD regions will see less than a doubling in growth.

FIGURE 1.11

Air trips by region of origin

Units: Billion trips/yr

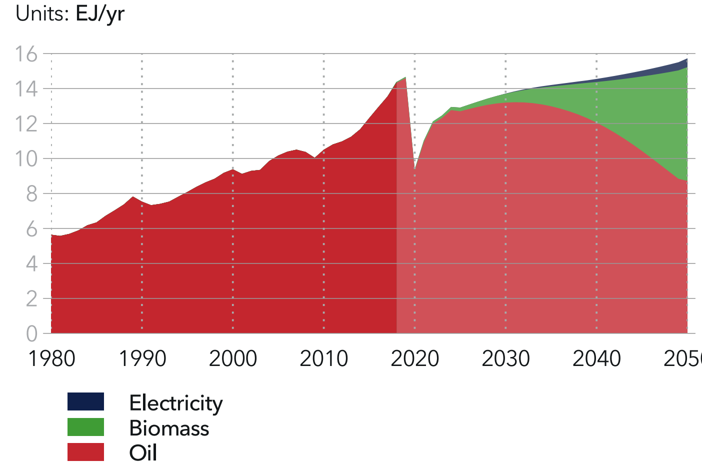


Historical data source: ICAO (2016), Airbus GMF (2018)

FIGURE 1.12

World aviation subsector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2019)

RAIL

The rail subsector consists of all rail-using transportation, including urban rail systems. Presently, little more than 2% of global transport, or about 0.5% of global energy use, is provided by the rail sector. The rise in passenger numbers will be substantial, due to income growth elasticity to above unity, with a global passenger increase of about 135% by 2050. Rail-freight transport will, however, continue on its downward slope in many regions, although not all.

For passenger transport, especially in urban areas, the space efficiency of rail transport is superior to other options, and the ease of electrification also makes it a favourable alternative for transport decarbonization. Another related reason for growth is the increasing speed and competitiveness of high-speed trains vis-à-vis aviation, again with decarbonization as a main driver. The greatest passenger growth will occur in India and Greater China, driven by a combination of a significant rise in standards of living and a strong public push for rail-transport development – resulting in preferential treatment to this subsector. As shown in Figure 1.13, almost the entire global passenger rail growth will occur in these two regions, which will see, respectively, about 55% (India) and 28% (Greater China) of global rail-passenger transport in 2050.

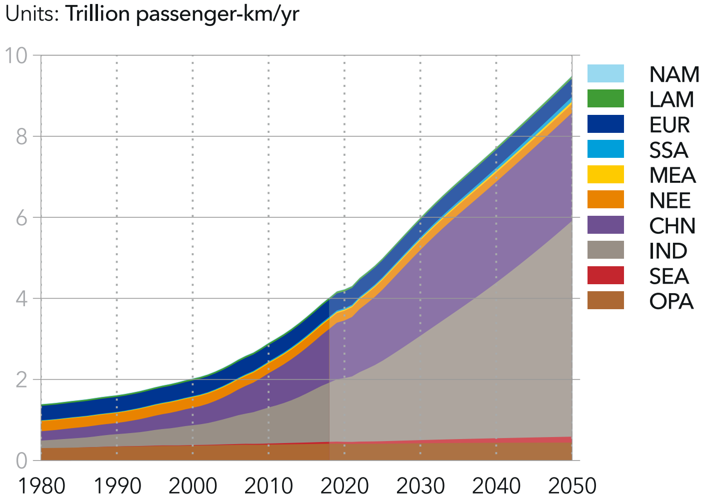
In all regions, apart from Europe, where rail freight has traditionally been strong, GDP is a driver of increased rail-freight volumes. Europe has seen the greatest increase in road-freight demand, as the potential for further growth in rail freight already meets crowded tracks, better roads, and prioritization of passenger rail transport. The world will see about an 80% growth of rail-freight demand by 2050.

Energy-efficiency improvements will be strong and related to electrification. However, diesel-powered units will also experience significant efficiency gains. As shown in Figure 1.14, we forecast current growth trends in electrification to be sustained, with a 54% electricity share, 41% diesel share, and 5% biofuel share by 2050 to meet rail demand. No significant use of gas (including hydrogen) is foreseen.

FIGURE 1.13

Rail passengers by region

Units: Trillion passenger-km/yr

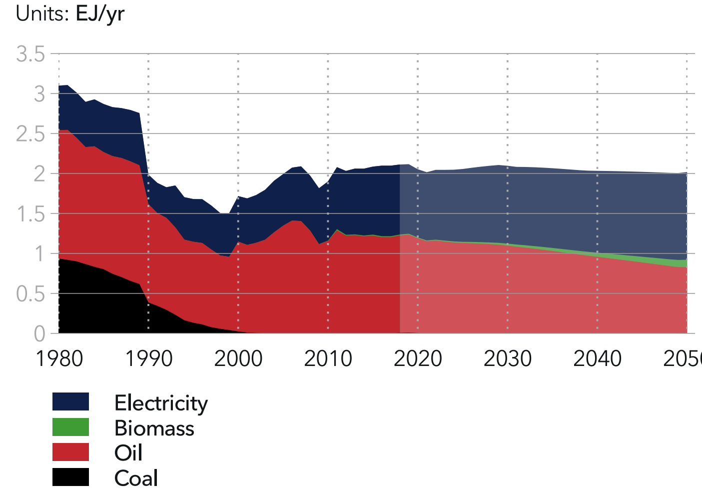


Historical data source: IEA UIC (2019)

FIGURE 1.14

World rail subsector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2019)

1.2 BUILDINGS

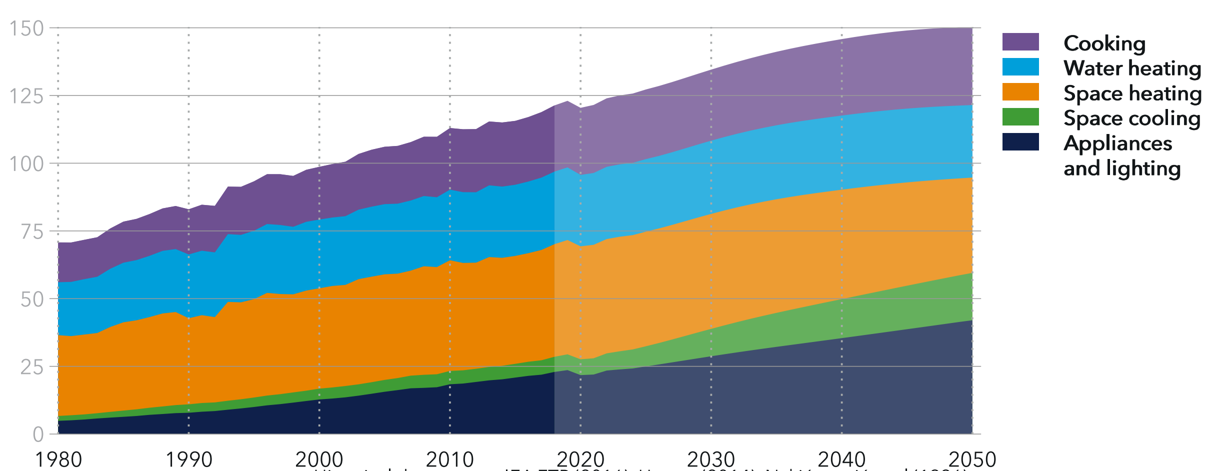
Total energy consumption in the world's buildings will grow by 24% from 2018 to 2050. Space cooling and appliances and lighting will be responsible for much of the growth.

In 2018, about 29% of the world's energy was consumed in buildings, with most of it used for heating (Figure 1.15), and about three-quarters consumed in residential buildings. For these, we estimate a final-energy demand for five end uses: appliances and lighting, cooking, space cooling, space heating, and water heating. As direct historical data are not available for end uses, the relevant figures presented in this Outlook are our own estimates, based on information gathered from various related studies.

FIGURE 1.15

World buildings sector energy demand by end use

Units: EJ/yr



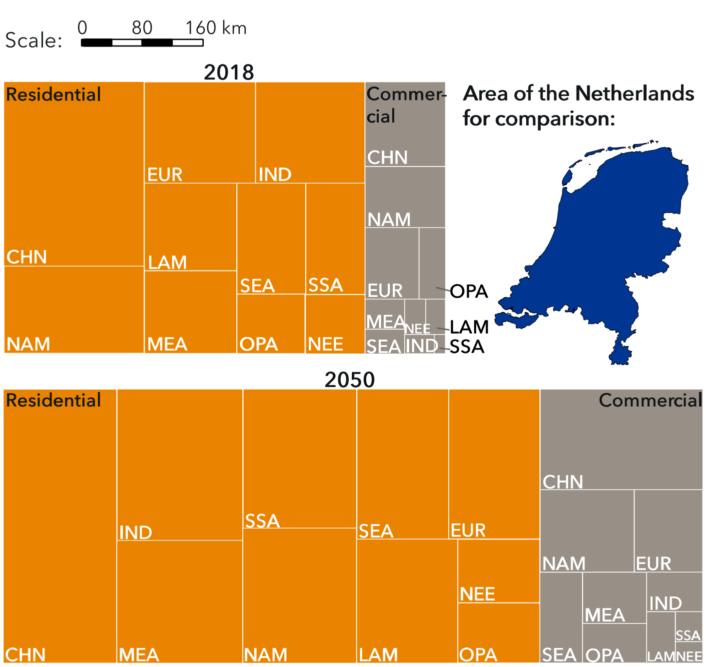
Historical data source: IEA ETP (2016), Harvey (2014), Nakićenović et al (1996), IEA WEB (2019), EIA RECS (2015), Ürge-Vorsatz et al (2015)

Floor area is one of the most important drivers of energy demand in buildings, as energy consumption in key end uses, such as space heating and cooling, scale with floor area. Figure 1.16 shows that in 2018 the total floor area of residential and commercial buildings covered 230,000 km², 5.5 times the size of the Netherlands. The floor area of residential buildings will grow by 52% until 2050, while commercial floor area will more than double to meet the demands of a world population that is 23% higher than in 2018, with economic activity double that of today. While Greater China will remain the region with largest floor area to mid-century, Sub-Saharan Africa will show the largest percentage increase during this period.

The energy consumption of cooling equipment will more than triple, whereas appliances and lighting will show a growth of 83%. The expected growth in these end uses is linked to massive economic growth in less-developed regions. Other end uses – cooking, space heating, and water heating – will stay relatively stable, as efficiency improvements will balance out any additional demand.

FIGURE 1.16

Floor area of buildings in 2018 and 2050



Historical data source: IEA ETP (2016)

APPLIANCES AND LIGHTING

The residential appliances and lighting subsector encompasses everything from reading lights, phone chargers, and computers, to refrigerators, washing machines, and dryers. Despite improvements in the energy efficiency of appliances and lighting, historical evidence suggests that, as GDP per capita increases, the electricity use for appliances and lighting per person also rises. For people on lower incomes, this shift may happen when disposable income reaches a level sufficient 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 the porch lights on all night.

We therefore estimate the energy demand of residential appliances as a function of regional GDP, adjusted for a continuation of the historical 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 to a higher electricity demand for appliances per unit GDP.

The energy demand of commercial buildings for appliances and lighting is a function of a region's service-sector GDP. As income per capita increases, the tertiary-sector's share in GDP tends to rise. Consequently, the energy demand of appliances in commercial buildings rises in all regions, albeit 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, 2017a), to increase by 2.5% annually (Sverdlik, 2016), reaching 1.6 EJ/yr, or 5% of the electricity demand of commercial buildings in 2050.

We forecast that the combined energy demand for appliances and lighting for both residential and commercial buildings will double between 2018 and 2050 (Figure 1.17). Three regions – Greater China, the Indian Subcontinent, and North America – will account for half the growth.

In Sub-Saharan Africa and the Indian Subcontinent, 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 to grid connection for lighting and basic applications such as mobile phone charging. Nonetheless, global off-grid solar PV demand will reach only 130 TWh in 2050, meeting 48% of Sub-Saharan Africa's energy demand for appliances and lighting, and 14% of that of the Indian Subcontinent.

SPACE COOLING

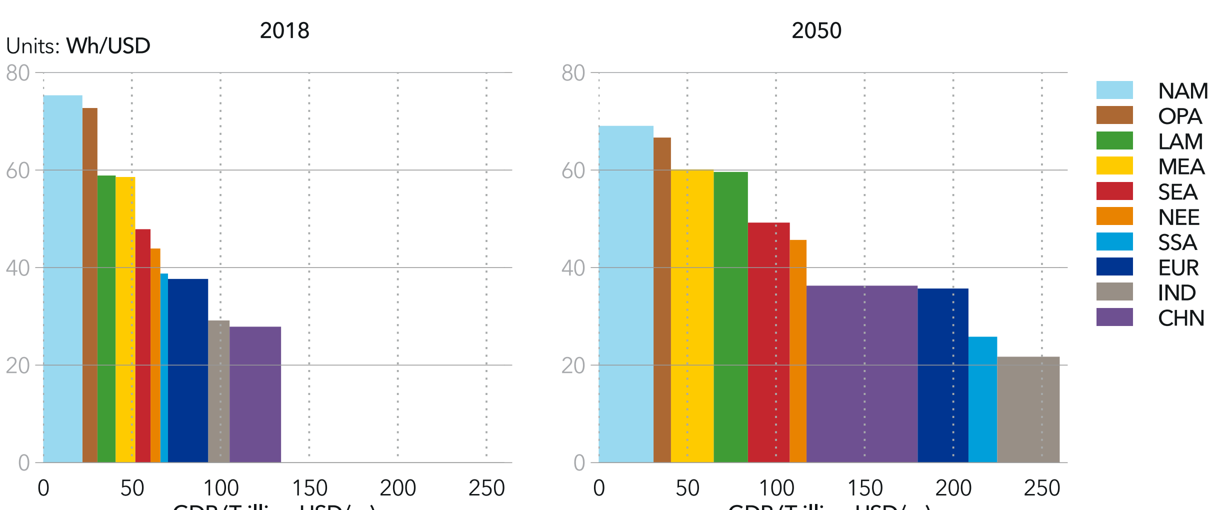
We estimate that space cooling accounted for only 4.6% of the energy demand of the buildings sector in 2018, but predict that its share will increase to 12% by 2050 (Figure 1.15), split roughly equally between residential and commercial buildings. Demand for space-cooling energy is shaped by:

- Growth in floor area that requires cooling;
- Increasing market penetration of airconditioners, as rises in both income levels and standards of living mean more people can afford them;
- Greater air-conditioner usage as a result of climate change;
- Developments in building-envelope insulation that reduce the loss of cool air inside buildings;
- Improved efficiency of air conditioners.

The increase in final-energy demand for space cooling – due to larger floor space and more use of air conditioners – will exceed savings from insulation and improved equipment efficiency. The result will be a net increase of 11.9 EJ, or 3,330 TWh per year, from 2018 to 2050 (Figure 1.18).

FIGURE 1.17

Appliances and lighting specific energy demand vs GDP by region



Areas show annual energy use. Historical data source: WorldBank (2018), Harvey (2014), IEA ETP (2016), IEA WEB (2019)

This is despite an average efficiency improvement of 46%, and an insulation-driven reduction in energy losses of 8% over the 2018-2050 period.

North America presently accounts for about 55% of global electricity demand for cooling. However, in 2050, about 40% of cooling demand will come from Greater China, and only 15% from North America. As Table 1.8 shows, those regions with greatest growth in their economies are also those that demand the most cooling, measured in cooling degree-days (CDD; the cumulative positive difference between daily average outdoor temperature and reference indoor temperature of 21.1°C). Climate change further amplifies this effect.

TABLE 1.8

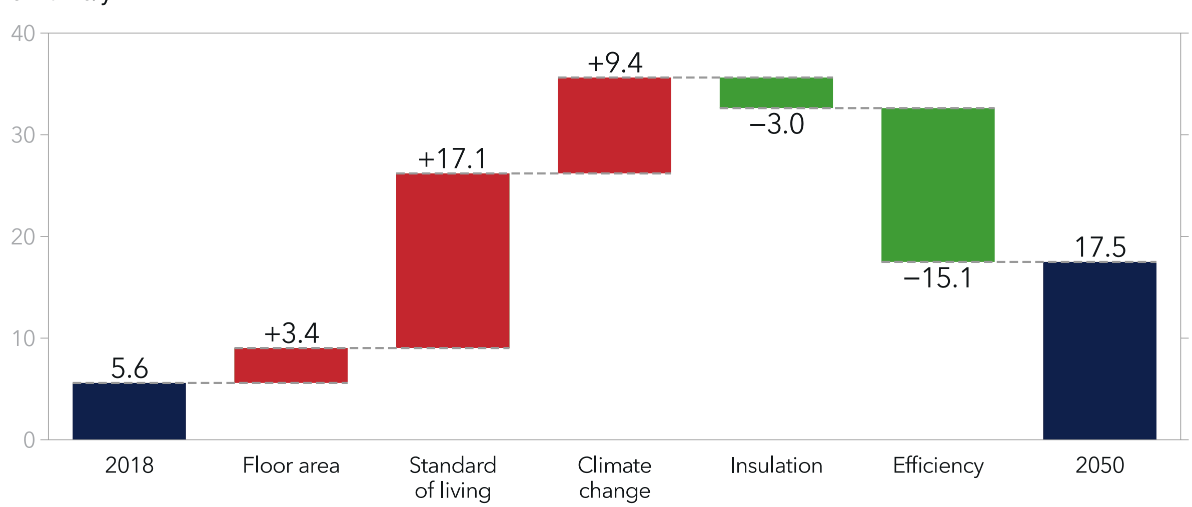
Comparison of regions in terms of cooling degree-days and GDP growth

	NAM	LAM	EUR	SSA	MEA	NEE	CHN	IND	SEA	OPA
CDD in 2018 (°C-days/yr)	429	784	160	1 296	1 225	279	495	1 961	1 563	299
CDD in 2050 (°C-days/yr)	619	1 066	289	1 682	1 621	527	742	2 291	1 884	472
Growth in GDP, 2018-2050	40%	87%	26%	276%	119%	70%	116%	269%	174%	16%

FIGURE 1.18

Sources of change in world energy demand for space cooling between 2018 and 2050

Units: EJ/yr



SPACE HEATING

In terms of market penetration and potential efficiency gains, space heating is a more mature market than space cooling. 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. That is, it is the amount of energy used for buildings (or for any other demand sector). Useful energy is the amount of heat actually 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 greater floor area, useful-energy demand for space heating will continue to grow towards 2050. Two other drivers affecting this trend downwards are improvements in insulation and fewer heating degree days due to climate change, without which useful heat demand would be 13% and 6% higher, respectively.

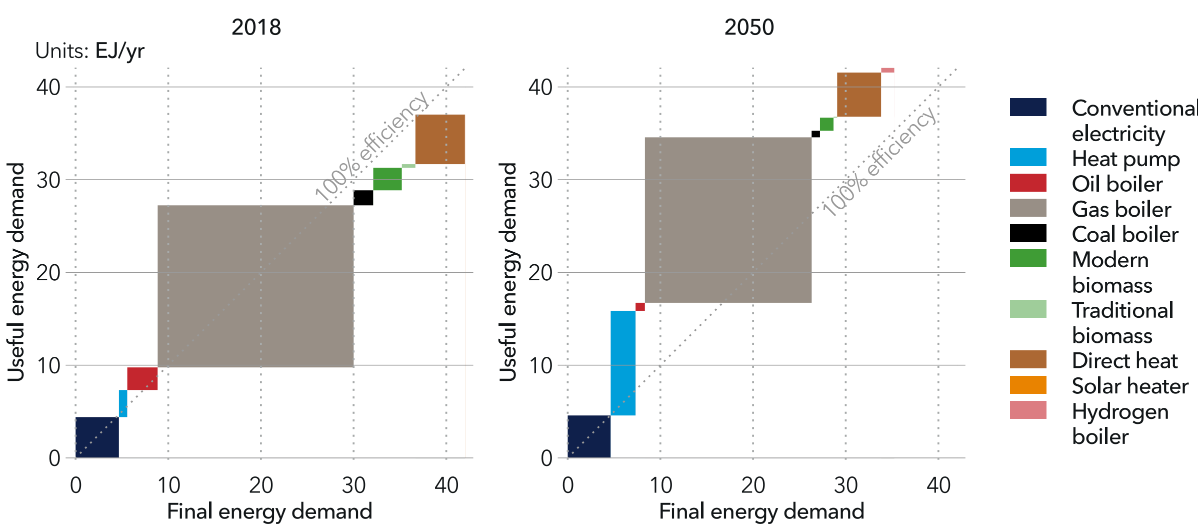
For buildings, energy-efficiency improvements typically have a short payback time, but developers and retrofitters frequently fail to implement them. Smarter policy interventions will continue to target this short-sightedness and the split incentives that frequently result in underinvestment in efficiency measures; the potential gains to society are too positive to ignore. We expect a 10% reduction in space-heating demand by 2050 due to better insulation.

The ratio of useful-energy demand to final-energy demand demonstrates the average efficiency of 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 equipment such as heat pumps, the average efficiency of space heating will increase from about 88% in 2018 to more than 122% in 2050 (Figure 1.19). Consequently, the final-energy demand for space heating will decline from 42 EJ/yr in 2018 to 17 EJ/yr in 2050, while the useful heat

FIGURE 1.19

Final vs. useful energy demand for space heating



provided will increase from 37 EJ/yr to 43 EJ/yr. As market penetration and income are not as significant in space heating as in cooling, the regional split in demand will remain stable, with North America, Europe, North East Eurasia, and Greater China constituting around 90% of the final-energy demand for heating.

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 dishes. In some less-developed countries, water is heated on demand by inefficient methods and used only for basic needs. For residential buildings, income level (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 27% of global final energy used for water heating – is driven primarily by floor area.

Globally, we forecast that final-energy demand for water heating will stay around 27 EJ/yr, with a slight shift from residential to commercial buildings. However, due to efficiency gains, the useful hot water provided will increase for both residential and commercial buildings (Figure 1.20). The average efficiency of water heating will increase from 47% in 2018 to 54% in 2030, reaching 75% in 2050.

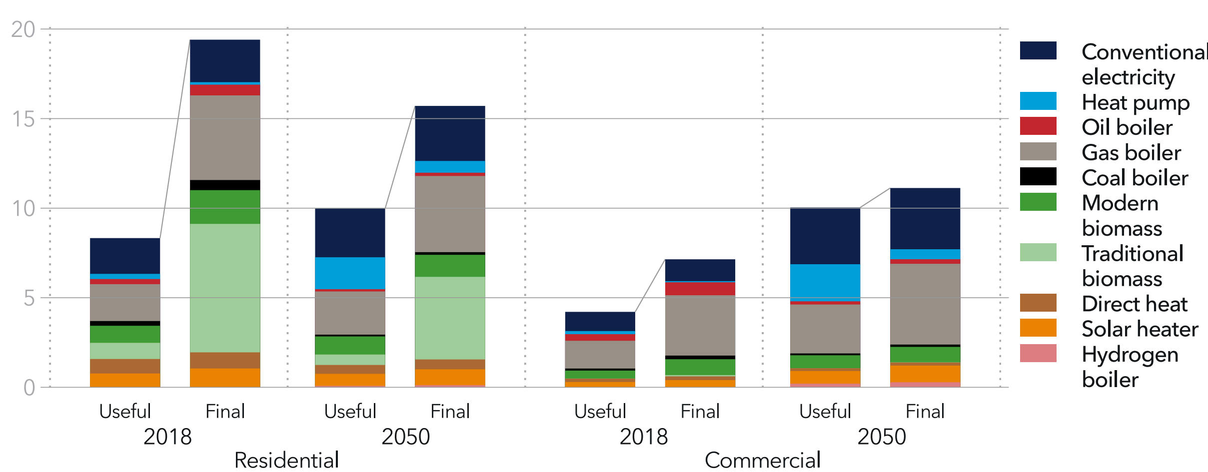
One big driver of efficiency increases is the reduction in traditional biomass stoves. While consuming 37% of the final energy provided to residential buildings for water heating in 2018, traditional biomass only provided 11% of the useful energy. Increased energy access will bring this number to 6% by 2050, which will result in 2.5 EJ per year being saved.

Another important trend to watch is the widespread use of heat pumps for water heating. While a heat pump is the preferred water-heating technology of only 3% of households today, we forecast that heat pumps will be used for water heating in 18% of residential buildings and 21% of commercial buildings worldwide by 2050. Despite lower coefficients of performance in colder climates, continued improvements in performance and declines in costs will increase the heat-pump market share significantly.

FIGURE 1.20

World useful and final energy mix for water heating

Units: EJ/yr



Solar water heaters are also used for both residential and commercial water-heating applications, ranging from supplying hot water and heating pools to space heating. With government support and established knowhow in the development and installation of evacuated-tube technology, China has a 70% market share in the global solar water-heater market. We forecast that energy supplied from solar water heaters will continue to grow.

COOKING

Cooking is responsible for one fifth of the energy consumed in buildings. We estimate that a typical household needs 3.1 GJ of useful heat for cooking annually, based on 2014 estimates of final-energy use for cooking (IEA, 2017b). Due to heat losses, this much cooking requires 11 GJ of final energy, in the form of fossil fuel, biomass, or electricity. To put numbers into context, a woman aged around 20-30 years, with a moderately active lifestyle and a body weight of 55 kg, needs to consume 3.7 GJ of food per year (FAO, 2004). Considering that the global average household size is about 3.5 people, we consume roughly as much energy to cook our food as the calorific content of our food.

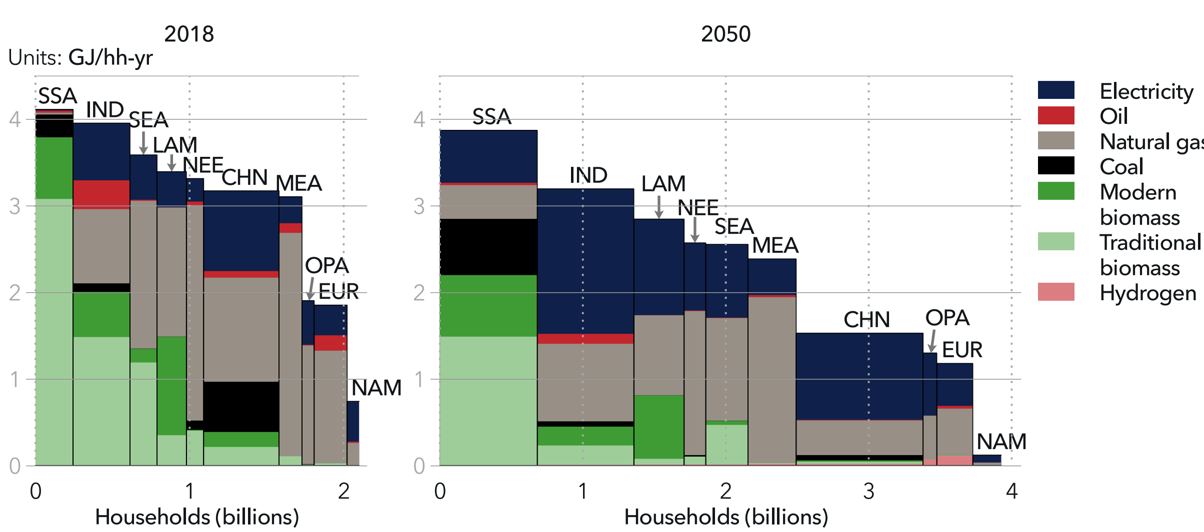
Regions with more people per household and less economic means to eat out or buy ready meals tend to cook more often (Figure 1.21). These regions also tend to utilize less-efficient cooking methods. These two factors create large gaps between regions in terms of final-energy consumption for cooking. At the two extremes lie Sub-Saharan Africa, where final-energy consumption per household is 33 GJ/yr, and North America, where a household consumes only 1.6 GJ of final energy for cooking in a year.

By 2050, the average household size is expected to decline to 2.4 (Ürge-Vorsatz et al., 2015), which will reduce useful-energy demand for cooking per household to 2.4 GJ/year. Accounting for the increase in the number of households, we expect global total useful-energy demand for cooking to rise from 6.8 EJ/yr in 2018 to 9.6 EJ/yr in 2050.

Globally, 26% of the population uses traditional cooking methods, burning biomass (animal waste, charcoal, wood) with efficiencies of around 10-15%. This involves about 2 billion people, with the majority in Sub-Saharan Africa and the Indian

FIGURE 1.21

Cooking specific useful energy demand vs number of households by region



Subcontinent. Developing countries will seek to reduce both burning of solid biomass for cooking and local use of kerosene, a major health hazard that is responsible for more deaths than any disease. By 2050, populations without access to modern cooking fuels will decline by 37%, bringing large efficiency improvements that will be further boosted by switching from coal to gas or from gas to electricity everywhere.

More information about energy access is presented in the Energy Access feature overleaf.

ENERGY ACCESS: PROGRESS ACROSS FIVE REGIONS

ENERGY ACCESS

This infographic shows improvements during the forecast period in energy access across five regions. Energy access has multiple facets: affordability, reliability, sustainability and modernity of fuels. Moreover, each of these facets lie on a continuum, for example in terms of hours per day that electricity is available. Thus, measuring energy access is complicated. Nonetheless, building on the definition in the IEA's Energy Access Outlook (2017), we assume that having electricity access means having at least several lightbulbs, 'task lighting' such as a flashlight, phone charging, and a radio. Access to modern cooking and water heating means having access to natural gas, LPG, electricity, coal and biogas, or improved biomass cook stoves.

Two regions (Sub-Saharan Africa and Indian Subcontinent) with limited expansion of grid infrastructure will benefit from leapfrogging opportunities to off-grid PV systems, owing to declining costs of solar panels and batteries. When it comes to access to both modern cooking and water heating, the world will not achieve universal access to modern fuels. In 2050, 800–900 million people in the world will still rely on traditional biomass for their cooking and water heating needs, the majority being in Sub-Saharan Africa.

1 Access to electricity

2 Access to modern water heating

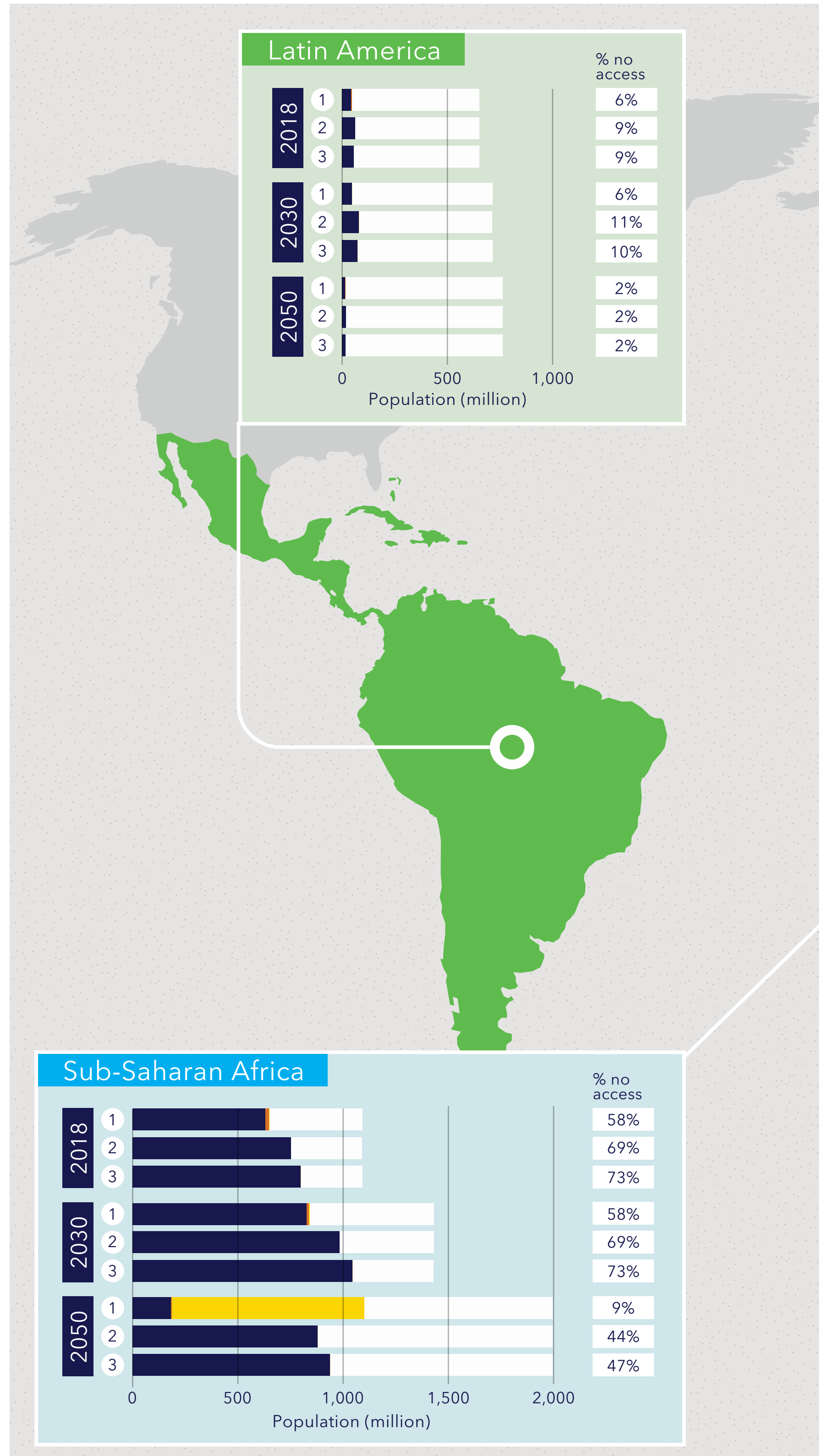
3 Access to modern cooking

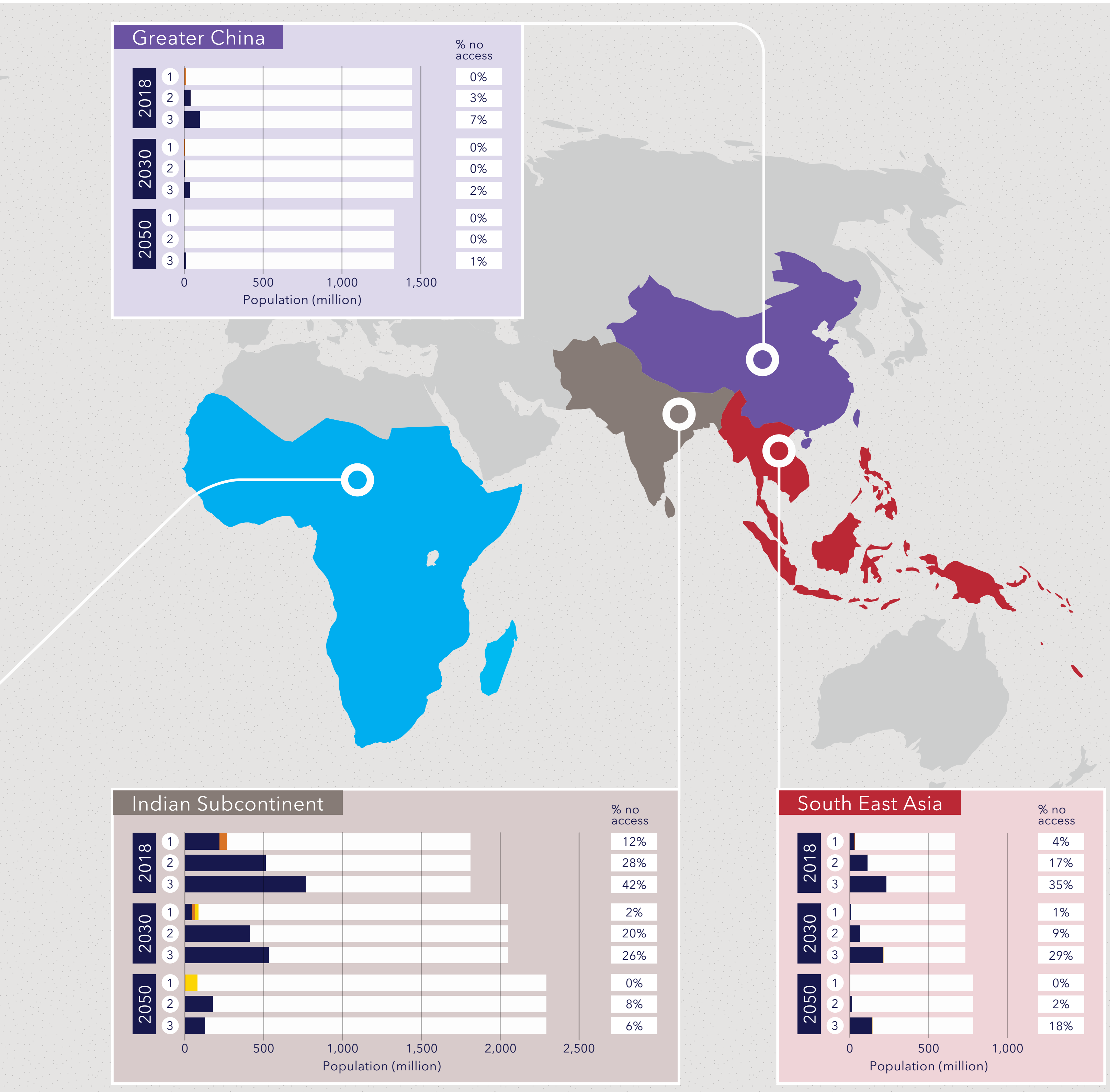
Have no access

Have access

Have access to off-grid diesel generator

Have access to off-grid solar




Greater China
% no access
2018
1 0%
2 3%
3 7%
2030
1 0%
2 0%
3 2%
2050
1 0%
2 0%
3 1%
0 500 1,000 1,500
Population (million)
Indian Subcontinent
% no access
2018
1 12%
2 28%
3 42%
2030
1 2%
2 20%
3 26%
2050
1 0%
2 8%
3 6%
0 500 1,000 1,500 2,000 2,500
Population (million)
South East Asia
% no access
2018
1 4%
2 17%
3 35%
2030
1 1%
2 9%
3 29%
2050
1 0%
2 2%
3 18%
0 500 1,000
Population (million)

1.3 MANUFACTURING

Manufacturing energy demand, at 133 EJ in 2018, is forecast to fall slightly by 2050, in spite of a 70% rise in the production of manufactured goods and a 27% increase in base materials.

The manufacturing sector consists of all activities from the extraction of raw materials to their conversion into finished goods. However, we do not consider fuel extraction – coal, oil, natural gas, and biomass – and its conversion, as part of this sector. Manufacturing, in our Outlook, covers three separate categories:

- Manufactured goods – includes general consumer goods; food and tobacco; electronics, appliances, and machinery; textiles and leather; paper, pulp, and print; and vehicles and other transport equipment.
- Base materials – includes non-metallic minerals (including conversion into cement), chemicals, and petrochemicals; non-ferrous materials, including aluminium; and wood and its products. This category also includes energy used in the mining and construction sector.
- Iron and steel – includes the production of iron and steel, as well as the energy required for the conversion and the use of energy for coke ovens and blast furnaces used in the iron ore-reduction process and steel-manufacturing process.

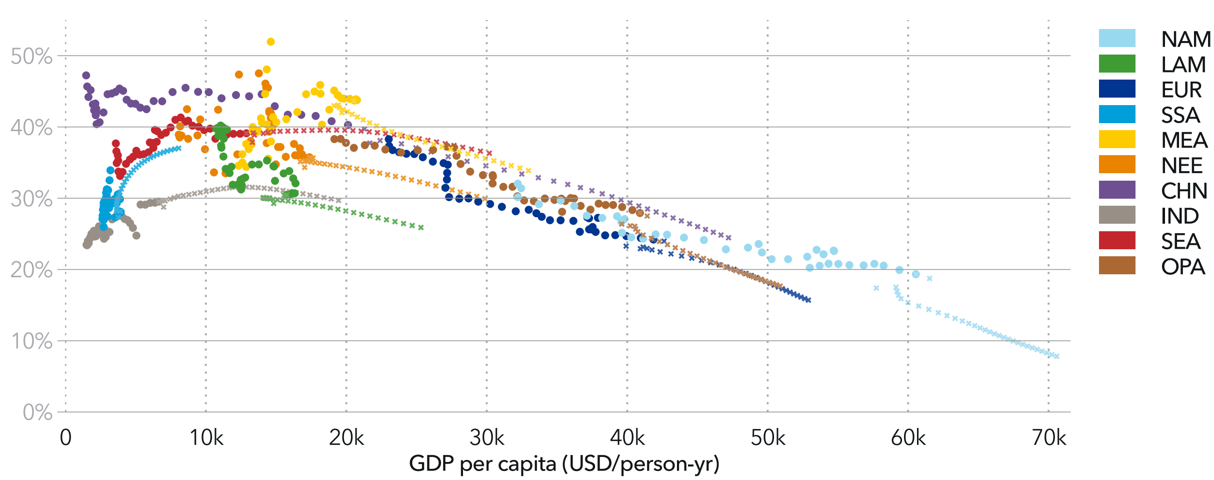
MANUFACTURING DEMAND

There is historical evidence that the industrial sector of a region evolves as the standard of living increases – as measured by GDP per capita. As affluence per person rises, a region transitions

FIGURE 1.22

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

Units: Percentages



Points show historical data from 1980 to 2018 (World Bank, 2018). × markers show forecast until 2050.

from an agrarian (primary) economy to an industrial (secondary) one, and then to a service-based (tertiary) economy, whereupon the industrial sector declines. In our analysis, we have mapped the share of the secondary sector of the economy from historical records and then extrapolated that trend into the future (Figure 1.22). The least-developed regions, the Indian Subcontinent, South East Asia, and Sub-Saharan Africa, display growing secondary-sector shares. In the remaining regions – most notably in Greater China – economies are transitioning to become increasingly dominated by the tertiary (services) share of the economy.

The demand for manufactured goods is assumed to be proportional to each region's GDP. Consequently, Greater China, the Indian Subcontinent, North America, and Europe will be the biggest consumers of manufactured goods by 2050. A well-established trend is that the contribution to manufacturing GDP from the manufactured-goods subsector outpaces its the relative share of manufacturing GDP, compared to base materials. We forecast reduced requirements for raw materials, partly because of circular economic processes (reuse, recycling, and remanufacturing), improving production efficiencies and reducing waste, and partly because of innovation in the types of manufactured goods produced. The combined effect of efficiencies is that the manufacturing share of GDP will grow more slowly than our overall forecast of GDP (Figure 1.23).

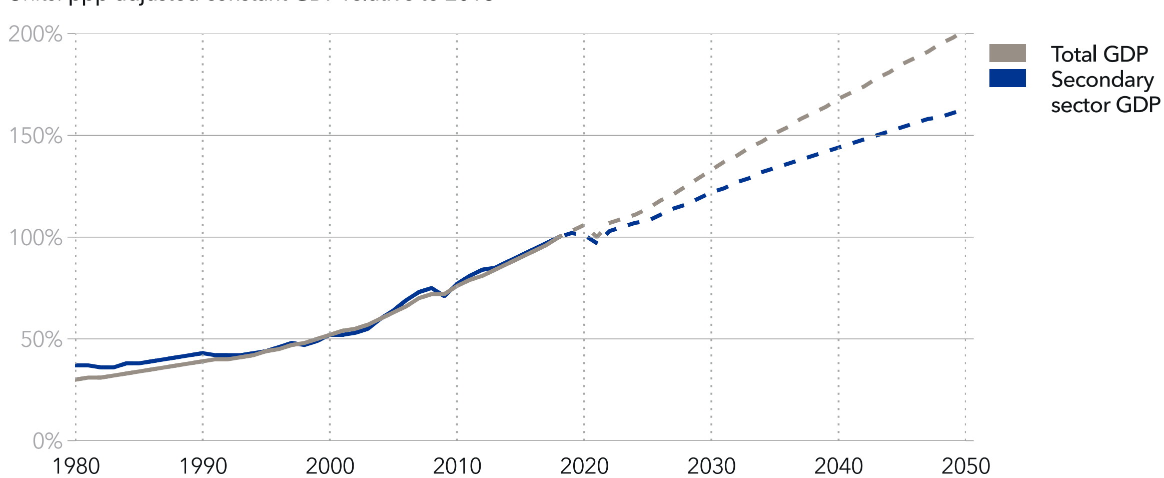
The regions producing the greatest proportion of manufactured goods are also those with the largest demand for base materials. Since regions with large demand also will be big producers of base materials, the need for inter-regional trade will diminish and global trade will grow more slowly than manufacturing growth in base materials. Simultaneously, transport of manufactured goods will continue its growing trend.

There is a strong historical correlation between increasing share of GDP from manufacturing and output of manufactured goods. Shifting manufacturing to low-cost regions has been the main basis for this relationship. In Greater China, for instance, it is possible to deliver more output per dollar. As standards of living rise in low-cost regions, this trend will level off and then reverse, as indicated in Figure 1.22. We have reviewed historical levels of

FIGURE 1.23

Indices for global total GDP and secondary sector GDP

Units: ppp-adjusted constant GDP relative to 2018



Historical data source: World Bank (2020)

GDP output from manufactured goods and the associated demand for base materials, and we expect the trend of a declining need for base materials to continue per output of manufactured goods.

There are four major drivers of iron and steel demand: building and construction, production of road vehicles, shipbuilding, and other uses (machinery, appliances, and electronics etc.). The three first subsectors are integrated in our model and can therefore be used to estimate material demand directly. The latter driver is connected indirectly to manufactured-goods output and our estimate is based on historical trends.

Iron and steel are produced from extracted iron ore, combined with increasing shares of recycled steel. We forecast a reduction in overall steel demand, as requirements in the region with the biggest demand previously, Greater China, will level off; this is a pattern typically experienced in developed regions. With a growing stock of iron and steel in circulation and becoming available as recycled feedstock, electrification becomes increasingly possible with a growing share of electric arc furnace (EAF) usage, as opposed to basic oxygen furnace (BOF) usage for which virgin iron ore is commonly used for steelmaking. This will result in virgin iron-ore demand plateauing, as it is replaced by recycled materials. Figure 1.24 shows overall steel demand in the different subsectors, with construction as the biggest user. We forecast increasing production of steel by EAF, reaching just over 50% by 2050.

Total manufacturing output of base materials will continue to grow in the next 10 years and then plateau, as the structure of some regions with large populations, like Greater China, change; populations start declining and there will be a further shift towards a tertiary economy. The demand for base materials will grow to some extent in other regions, but not enough to offset the large decline in Greater China. Regions that are currently importers will continue to import, with the biggest jump occurring in Sub-Saharan Africa, going from net importer to net exporter (Figure 1.25).

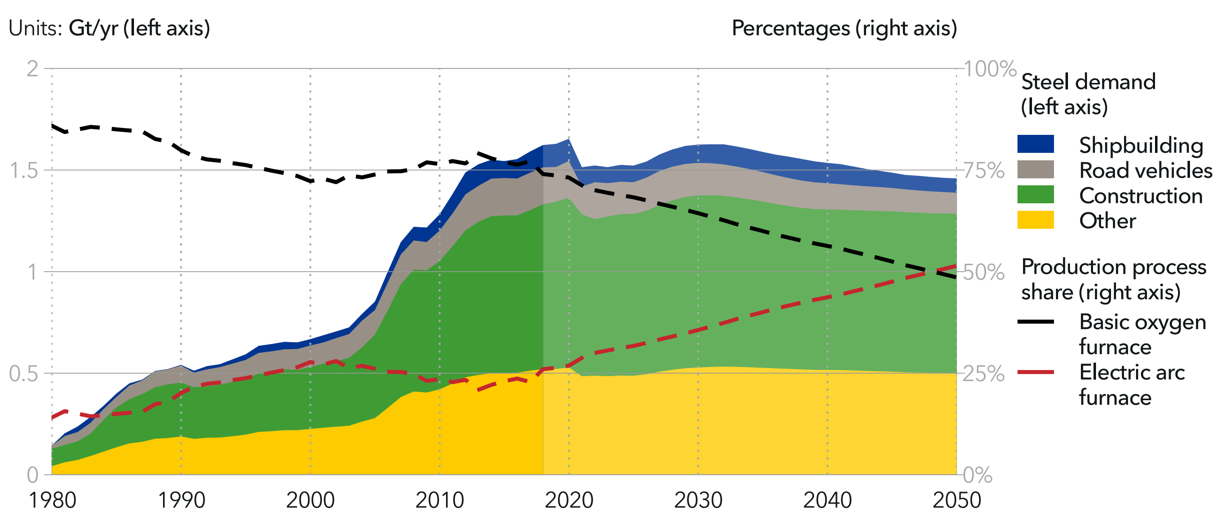
ENERGY DEMAND

The manufacturing sector is the largest consumer of energy, with 133 EJ or 31% of final-energy demand in 2018. Base materials and manufac-

FIGURE 1.24

World steel demand by subsector, shares steel production processes

Units: Gt/yr (left axis)



Historical data source for total demand: World Steel Association (2019). Sectoral breakdown: DNV GL's own esimates.

tured goods use an equal share of around 40% each, whereas iron and steel represent the final 20% of manufacturing-energy demand. We forecast manufacturing-energy demand to increase by 4% towards its peak in the mid-2030s, and then decline by some 10% towards 2050. As recycling and efficiencies continue to affect the energy demand, the split between the three categories (base materials, manufactured goods, iron and steel) will alter; by 2050 manufactured goods will use 52% of manufacturing-energy demand, 30% will go to base materials, and iron and steel will stay almost the same at 17% (Figure 1.26).

FIGURE 1.25

Base materials production and consumption

Units: Gt/yr

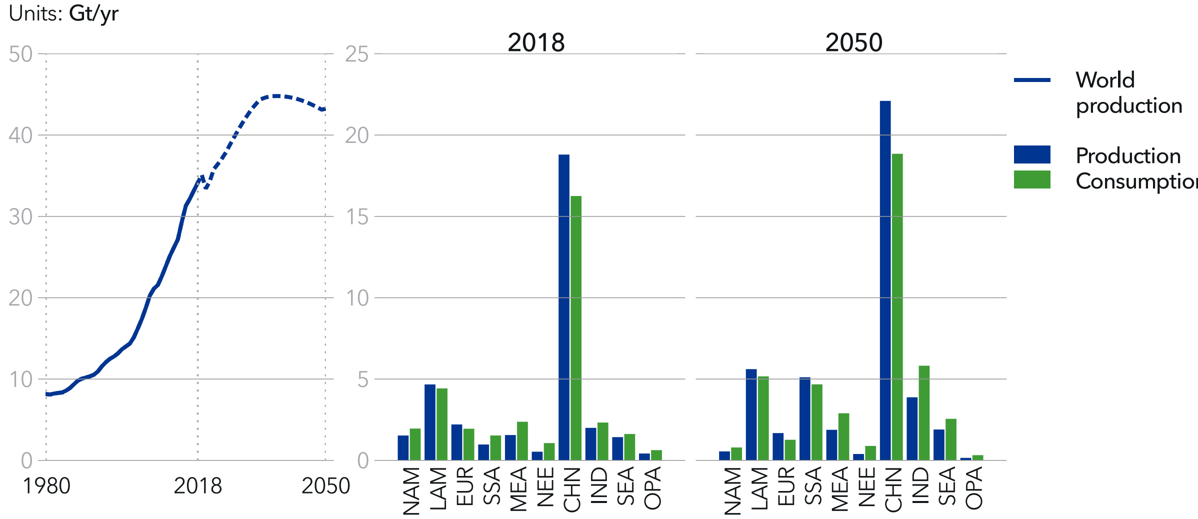
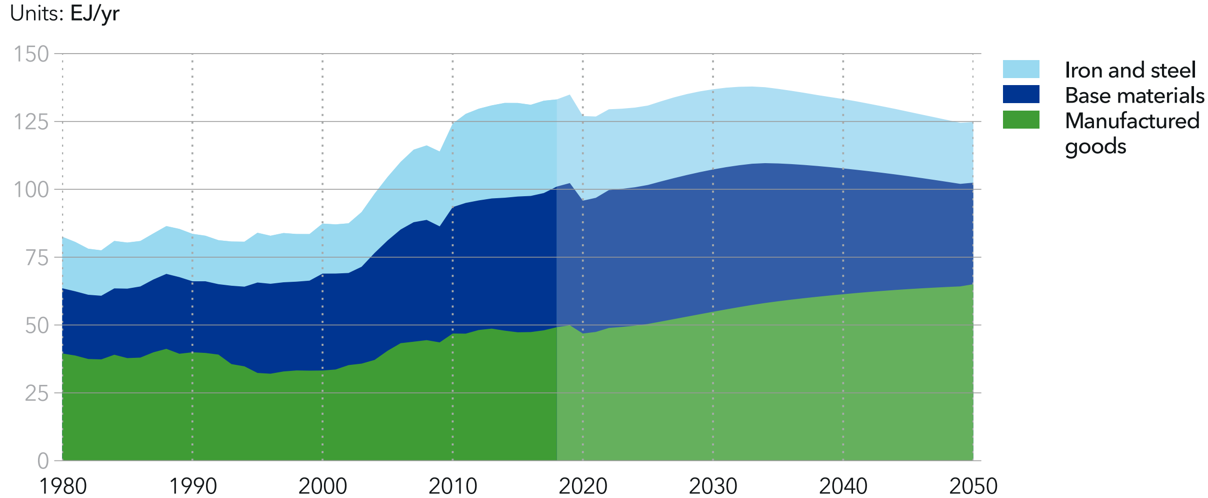


FIGURE 1.26

World manufacturing final energy demand by subsector

Units: EJ/yr



Historical data source: IEA WEB (2019)

In 2018, the manufactured-goods subsector energy demand was almost as big as that of base materials at 49 EJ. As economies grow, the demand for finished goods experiences a similar rise, and this subsector will increase its 2050 energy demand by 32%. Of this energy demand, 70% is used for heat, and almost all the rest is to operate machines, motors, and appliances (MMA). Energy demand from MMA will experience a strong growth of 40% towards 2050, driven by automation and digitalization (Figure 1.27).

The base-materials subsector is energy intensive (51 EJ in 2018) in its extraction and conversion of raw materials into feedstock for other industries. Most of the energy use is for industrial high-heat processes (80%) and the rest is for MMA operation (Figure 1.27). Energy demand will initially drop in 2020, due to COVID-19 pandemic-related lock-downs and lower activity, but will return to 2018 levels by 2030. Thereafter, there will be a steady decline to 2050, ending at 37 EJ. This reduction of 30% compared to today's level is largely driven by increasing efficiencies from reuse of already processed materials, rather than from extracting and processing virgin raw materials, as secondary-production processes require much less high-grade heat. A relevant example is aluminium, where aluminium produced from recycled material requires 95% less energy than the transformation from bauxite (Hydro, 2020).

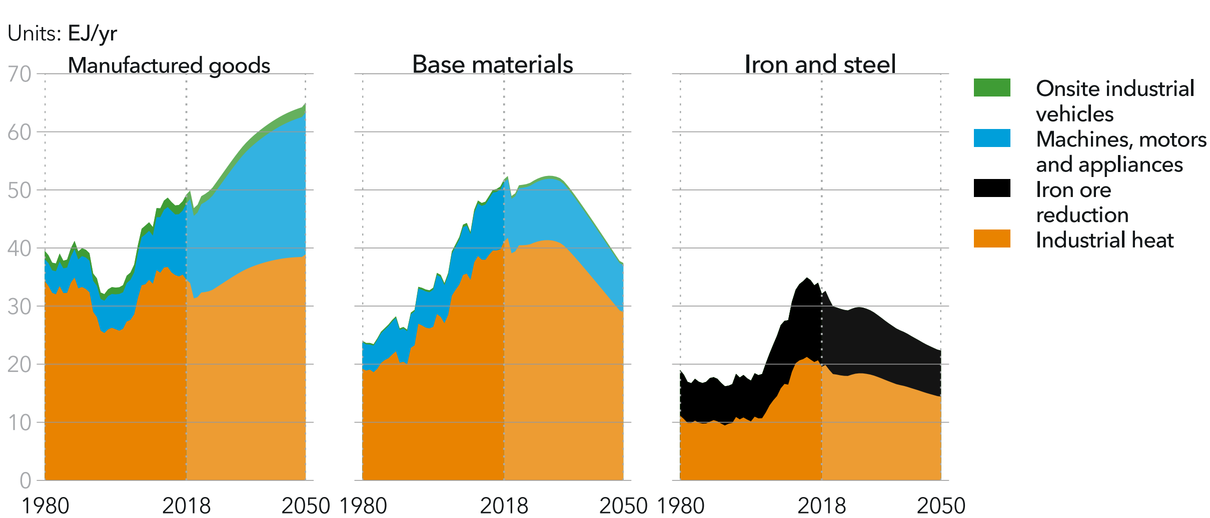
The iron and steel subsector currently uses 60% of its energy demand for heat, and the rest for reduction of virgin iron ore. Increasing shares of recycled steel will decrease the need for new iron-ore reduction, triggering a shift towards steel-making by the EAF method. This, in combination with a plateau in overall steel demand, will lower the energy demand from iron and steel production (Figure 1.27).

ENERGY MIX

The evolution of the energy mix within the manufacturing sector is dependent on technological innovation and resource availability, together with policies and economic incentives. We estimate the mix separately for the different energy end-uses, including heat, iron-ore reduction, MMA, and onsite industrial vehicles. Currently, about 72% of the global energy used in manufacturing is for heating purposes, which includes both process

FIGURE 1.27

World manufacturing subsector energy demand by end use



Historical data source: IEA WEB (2019)

and non-process heating. Another 17% is used for MMA operation, 9% for iron-ore reduction, and 2% for onsite vehicles. Energy use for heating purposes will see the largest efficiency gains towards 2050, due to changes in feedstock and technology, as well as structural changes in the manufacturing sector towards more efficient use of materials. As a result, the share of heat in total-energy use will decrease to 66% by 2050. Due to continuing trends of automation and digitalization, MMA will see its share increase to 26%, most evident in the manufactured-goods subsector. This results in significantly reduced amounts of coal and an increasing share of electricity in the energy mix for the manufacturing sector (Figure 1.28).

HEAT ENERGY MIX

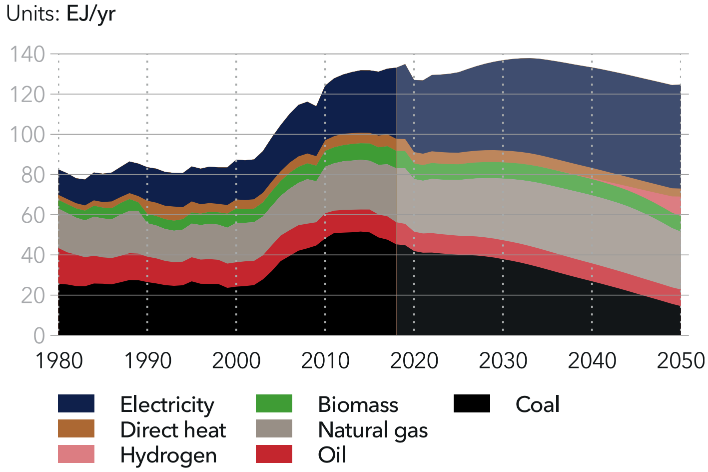
We forecast changes in the energy mix for heat by estimating the levelized cost of heating for manufacturing processes in the different regions. Important factors that affect the levelized costs include: technology cost, fuel price, heating efficiencies, and policy measures such as carbon prices, local air-pollution policy interventions, and other preferential treatments for cleaner technologies. The changes in policy measures will increase the attractiveness of electricity as a heat source. Nevertheless, for high-heat processes, fossil fuels will dominate the heat mix as they have the lowest levelized cost of heat, and are thus also a hard-to-abate sector (Figure 1.29).

In the manufactured-goods subsector, where average temperature requirements are lower, there is competition between boilers using different fuels and industrial heat pumps. The latter will become increasingly available for low-grade heat processes (e.g., temperatures up to 200°C). The relatively lower per unit investment cost of gas boilers offsets the lower cost of coal in most regions, which means that gas is already the most-economic fuel choice. In 2018, natural gas had a 36% share compared with 12% from coal. The share of natural gas will continue to increase in all regions, especially in Greater China, which is by far the largest producer of manufactured goods globally. Due to local-pollution concerns, the Chinese government has implemented a coal-to-gas switching programme that we expect to be continued.

FIGURE 1.28

World manufacturing sector energy demand by carrier

Units: EJ/yr

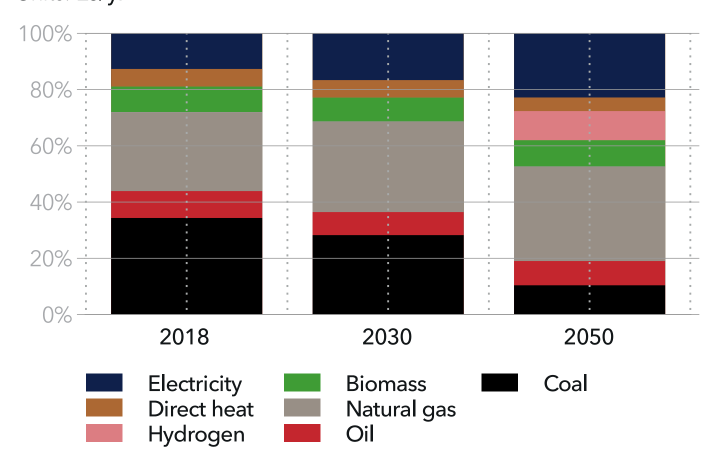


Historical data source: IEA WEB (2018)

FIGURE 1.29

World manufacturing sector heat mix by carrier

Units: EJ/yr



Globally, we see the natural-gas share in the heat mix increasing to some 40% by the mid-2030s, then levelling off due to the uptake of industrial heat pumps. These will become increasingly competitive due to technology-cost reductions, efficiency benefits, carbon pricing, and policies favouring industrial electrification. All in all, the global share of electricity in the manufactured-goods subsector's heat demand will increase from about 15% in 2018 to almost 30% by 2050.

In the base-materials subsector, we forecast a different transition. Due to high-grade heat requirements, fuel costs will have a stronger effect on the levelized cost; and few, if any, options for decarbonizing industrial high-heat processes are well developed or available at scale. Hence, we see coal remaining the dominant source of high-grade heat until the 2030s, with a share of 40% in the heat mix, declining quickly thereafter to 20% by 2050. Natural gas will see its share grow more slowly than for manufactured goods, but will be the biggest energy carrier by 2050, contributing 40% of the heat energy mix.

In all regions, electrification of heat processes in base-material production will be significantly less pronounced than in the manufactured-goods subsector due to the limited efficiency gains from switching to electricity in high-heat furnaces. Since, in the near term, electricity is still mainly produced from fossil-fuel sources, there are significant heat losses during its production. Thus, the losses and increased costs associated with electrification compared with direct-heat use from fossil-fuel sources make the base-materials subsector reliant on fossil fuels for the coming decades, and this is hard to abate. Hydrogen will start to become a viable heat medium in those regions where it can compete with natural gas, something not visible until 2040. Hydrogen's share of energy demand in global manufacturing in 2050 will be 7%.

IRON-ORE REDUCTION

The energy used in the process of iron-ore reduction has, historically, been dominated by coal and still represents 40% of the total-energy demand in iron and steel production today. We do not forecast a significant shift away from coal use initially, as the growth in steel production will occur predominantly in regions where coal is competitive.

However, we forecast an ongoing transition to direct reduced steel production, which is less coal intensive and relies on electricity and/or natural gas. Much of this transition is based on increasing shares of recycled steel that does not require reduction processing. Consequently, we predict significant growth in regional natural-gas use, for example in the Middle East and North Africa, Latin America, and North America. Hydrogen is an alternative for use in iron-ore reduction, but will only enter the mix in Europe and OECD Pacific, where the hydrogen price will be most competitive due to higher demand for hydrogen in other energy sectors. This will increase the overall utilization rate of electrolysers, making the CAPEX investment less important.

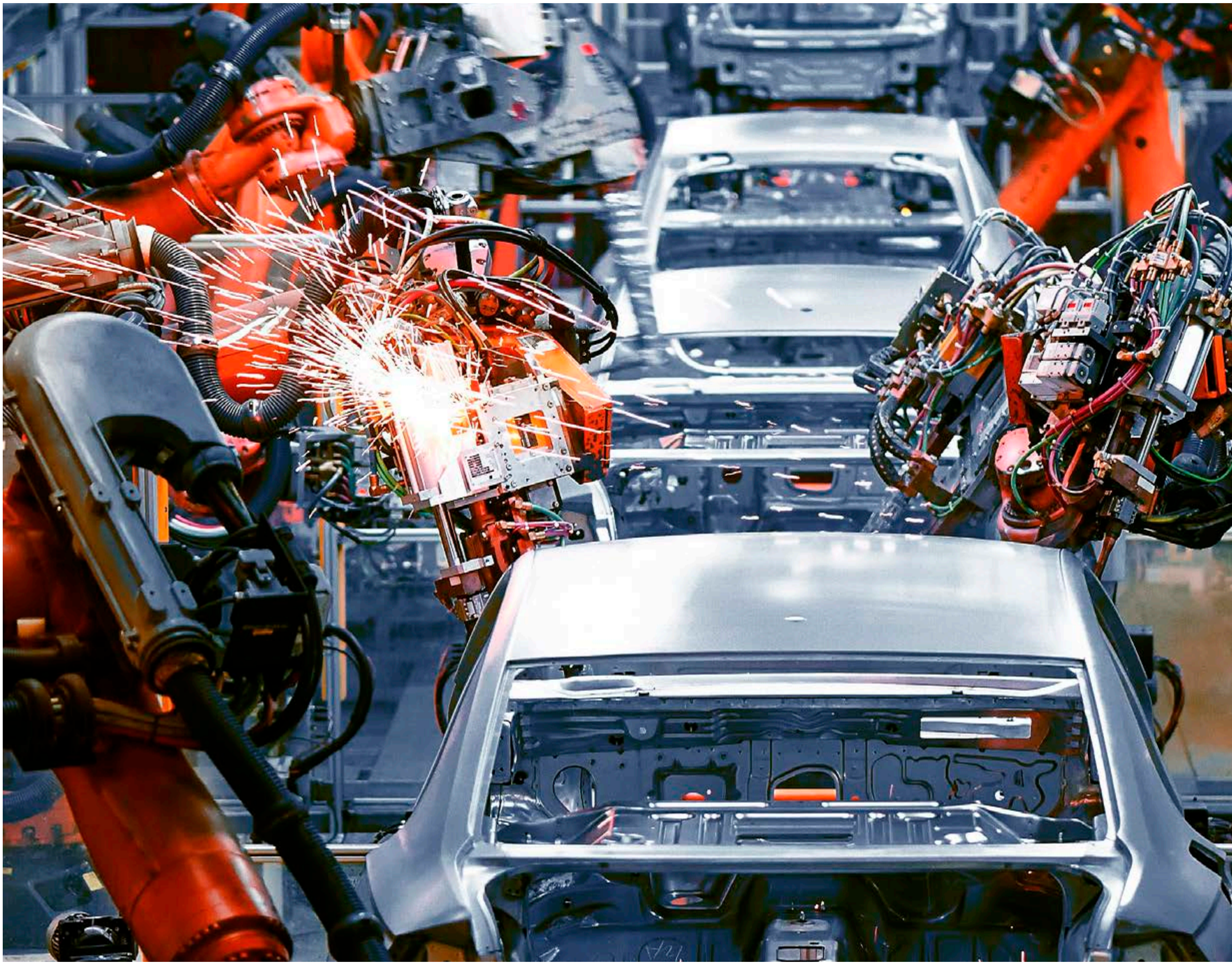
MACHINES, MOTORS, AND APPLIANCES (MMA)

MMA relies predominantly on electricity as an energy carrier. The manufactured-goods subsector will experience the largest jump in energy demand from MMA, growing by almost 90% towards 2050, due mainly to increasing output and automation. The base-materials subsector shows a steady increase in energy demand from MMA until 2033 at 10.6 EJ. However, with plateauing demand for base materials, the energy demand from MMA will decline and, in 2050, will be 20% lower than the present level at 8 EJ.

ONSITE INDUSTRIAL VEHICLES

Most onsite vehicles in use today are fuelled by gasoline or diesel, and represented 1.5% of overall manufacturing-energy demand in 2018. In certain regions, where fuel prices or policies dictate, some biofuels and natural gas are also used. We forecast a growth in electrification, similar to the dynamics for the commercial-vehicle road sector where cost compression of batteries improves the commercial viability of electric transport. By 2050, oil use will have reduced to 55% of the energy mix, electricity will represent 26%, and we expect some of the heavy vehicles to rely on hydrogen (12%).

Even with the efficiency gains from EVs, it will not be possible to offset the associated increase in energy demand from the growth in demand for manufactured goods. The energy used for onsite industrial vehicles will see a slight growth towards 2050. Most of the energy demand is from the manufactured-goods subsector (75%), which will experience the strongest growth in output.



1.4 NON-ENERGY USE

In 2018, about 8% of global primary fossil-fuel supply was used for non-energy purposes. This category represents the consumption of coal, oil, and natural gas as feedstock. Petrochemicals are the largest consumer of feedstock and, of the consumption in this sector, about 45% was used to produce plastics in 2018, with the rest going to the manufacture of cosmetics, fertilizers, paints, and other chemicals. We expect that in 2050 the plastic proportion will have grown to about 60% of petrochemical feedstock demand.

We have calculated the feedstock for plastic production using global plastics demand and feedstock intensities for the major plastic types. In our forecast, global plastics demand is driven by GDP per capita, efficiency gains reducing plastics needs, and recycling rates. While plastic demand continues to grow to 2050, recycling grows more rapidly. We estimate the global rate of plastic recycling will improve from around 13% in 2018 to 47% in 2050 as it is bolstered by more efficient (and potentially circular) chemical recycling, which supplements or replaces traditional, mechanical recycling. Recycling rates in Europe, OECD Pacific, and Greater China will rise considerably, reaching about 70% in 2050, but Sub-Saharan Africa's recycling rate will remain relatively low, at only 27% by 2050.

Figure 1.30 shows that the resulting non-energy use of coal, oil, natural gas and biomass as feed-stock will peak in around 2033, then, due to improved efficiency and recycling rates, will decline fast to about 66% of its current level by mid-century.

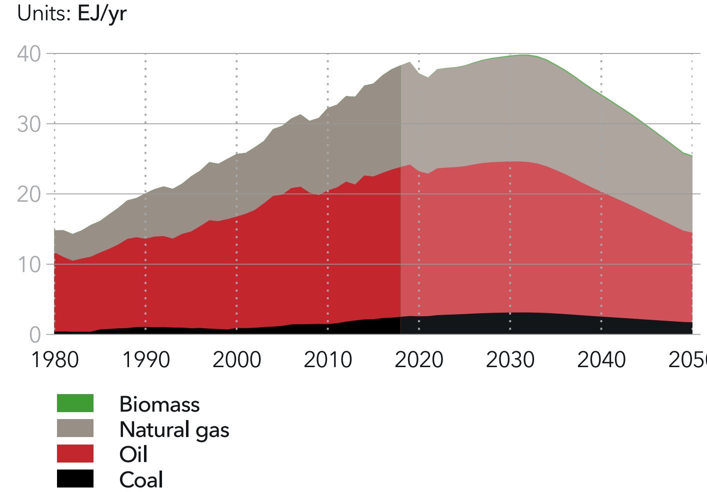
Oil currently dominates the feedstock energy mix and will continue to do so, albeit with a diminishing role, accounting for half of global feedstock-energy demand by mid-century. The share of natural gas as feedstock is forecast to grow, rising from 38% in 2018 to 42% in 2050. Coal will remain an important feedstock in Greater China and Sub-Saharan Africa. Bio-based feedstocks have the potential to reduce fossil-fuel demand in the long term, but will need strong policy support to take off and grow. We do not expect such support to become significant; as non-energy use does not produce the carbon emissions that are accounted for in national inventories, wherefore governments are likely to focus their efforts elsewhere.

> “We estimate the global rate of plastic recycling will improve from around 13% in 2018 to 47% in 2050

FIGURE 1.30

World use of energy carriers as feedstock

Units: EJ/yr



Historical data source: IEA WEB (2019)

1.5 FINAL-ENERGY DEMAND FROM ALL SECTORS

By combining the energy demand of each of the energy-demand sectors, we forecast the world's final-energy demand by energy carrier, as illustrated in Figure 1.31. 'Final' energy here means the energy delivered to end-use sectors, excluding losses and excluding the energy sector's own use in power stations, oil and gas fields, refineries, pipelines, and similar ways.

The ongoing transition is extraordinary in relation to the growing dominance of electricity in the final-energy demand mix. In 2018, electricity represented just 19% of the world's final-energy use, but in 2050 will represent 41%, growing from 82 EJ/yr to 174 EJ/yr. The annual average growth in electrification in our forecast is 2.4% per year, which is double that experienced since 2000.

The reason for a steady rate of electrification is the combination of cost, technology, and policy. As the share of renewables in the electricity mix increases, and the costs of solar and wind continue to decline rapidly, electricity will become cheaper relative to other fuels. Electric systems have smaller losses than fossil- and biomass-fuelled systems, and when technological progress makes electricity available and viable for use in ever-more subsectors and new applications, more and more users will make the switch. Furthermore, new applications requiring energy are emerging – e.g., modern communication appliances and air conditioning – for which there are few, or no, alternatives to electricity. Finally, more ambitious decarbonization policies favour electricity, especially the fraction generated by renewable low-emission energy sources.

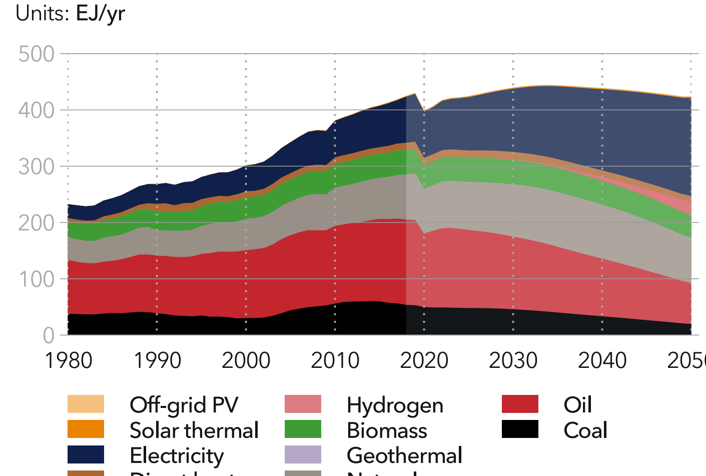
As total demand starts to reduce, electricity will replace coal, oil, and – later – gas in the final energy-demand mix. For coal, oil, gas, and biomass, additional energy use from electricity, direct heat, and hydrogen production will be added to the final-energy demand figures. Total demand and supply of these energy sources is discussed in subsequent chapters.

“The ongoing transition is extraordinary in relation to the growing dominance of electricity in the final energy demand mix

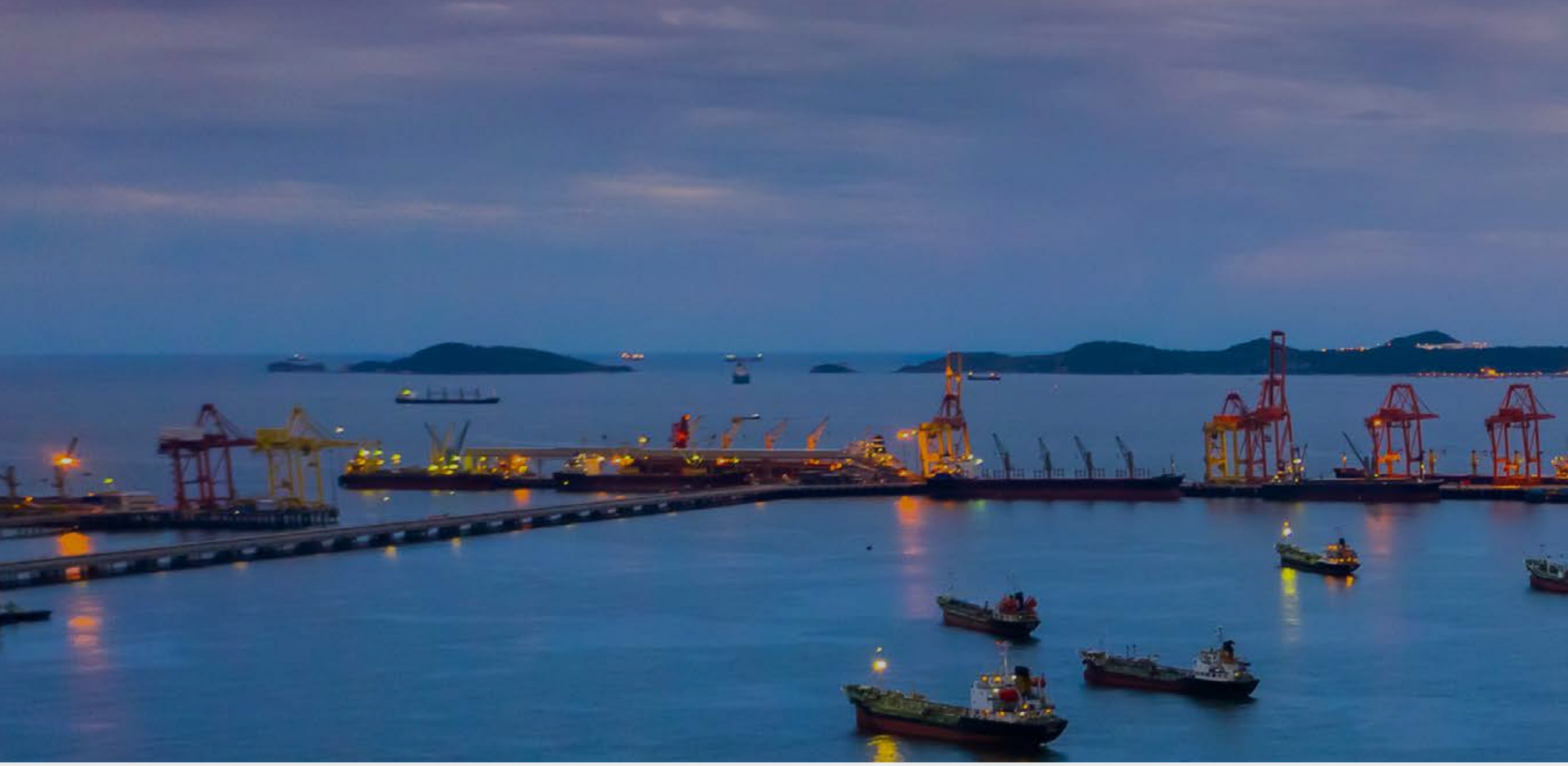
FIGURE 1.31

World final energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2019)



HIGHLIGHTS

In an energy future characterized by expanding electrification, decarbonization and a flattening energy demand curve, fossil fuels are under pressure.

The coal peak is behind us, and its use is expected to decline rapidly in our forecast period to less than a third of its current level by 2050.

The dominance of oil in the energy mix will give way in the coming years. Without COVID-19 we estimate oil would have reached a supply plateau in the early 2020s. However, the pandemic will lead to a 13% reduction in global crude oil demand in 2020 and although demand will recover it will not surpass the 2019 level. Oil has therefore already peaked. Mainly due to the electrification of transport, oil will decline steadily to reach half current consumption levels by 2050.

Gas use on the other hand will continue to expand, surpassing oil as the largest energy source by 2026, and will then peak in 2035, thereafter tapering off gently to 2050. The use of gas in power generation will greatly expand, underlining its role as a 'bridge' fuel. The oil and gas industry will however, be under mounting pressure to decarbonize natural gas, which will start to scale from the mid-2030s, reaching 13% of natural gas supply by mid-century.

CHAPTER

2

ENERGY SUPPLY AND FOSSIL FUELS

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2 ENERGY SUPPLY AND FOSSIL FUELS

We are approaching a future in which the world will need less energy, even as the global population increases and the economy continues to grow. Large energy-efficiency improvements in all sectors and accelerated electrification will see global primary-energy supply peak in 2032, at a level only slightly higher than today's energy use. The fossil-fuel share of the energy mix will decline steadily, falling from 81% today to 54% by 2050.

PRIMARY SOURCES OF ENERGY

Primary-energy supply is the total amount of energy that the world needs in order to meet its energy demand. There are several ways in which to measure primary energy, as we detail in the fact box on Energy Counting. In this Outlook, we use the Physical Energy Content Method.

In the energy system, considerable losses occur. These mainly happen when energy is converted from one form to another – such as heat losses in a power plant converting coal to electricity – but they also occur during transport of energy, such as electrical power lost as friction in the grids. World primary-energy consumption is, therefore, considerably higher than final-energy consumption, with conversion losses alone exceeding 100 EJ. Primary energy also includes the energy sector's own use of energy, which is considerable, typically being around 7% of the primary-energy consumption.

The historical and forecast world energy supplies, derived from various primary-energy sources, are shown in Figure 2.1 and Table 2.1. A key result from our analysis, as shown in Figure 2.1, is that global primary-energy supply will peak within the forecast period. This will occur despite the fact that the global population and economy will still be expanding by mid-century, albeit both at slower rates than now. Although the world will be engaging in more energy-consuming activities, such as heating, lighting, and transport, and will also be producing more goods, it will do so with a lower energy requirement, owing to the steady electrification of the world's energy system and to cumulative advances in energy efficiency.

Our forecast shows that the world's annual primary-energy supply, currently 603 EJ, will grow by only 3%, reaching a peak of 624 EJ in 2032. Admittedly, this period includes the 6% reduction experienced in 2020 due to effects of the COVID-19 pandemic. After 2032, primary-energy supply will decline gradually, reaching some 570 EJ in 2050.

The energy mix will change significantly over this period. In recent decades, the share of fossil-fuels in the mix has remained steady, at just above 80%, but that dominance will diminish in the coming decades. By 2050, the global fossil-fuel supply is expected to be 305 EJ, about 38% lower than the current level. Decarbonization of the energy mix will occur throughout the forecast period, such that by mid-century the mix will comprise 54% fossil fuels, 6% nuclear, and 40% renewable energy. Gas will overtake oil as the largest energy source as early as 2026 and will then hold the dominant share through to 2050, when it will still be 29% of the energy mix. Wind and solar will both show impressive growth from 2018 to 2050, with 14-fold and 30-fold increases, respectively. However, starting from a low base, their combined share will still be less than a quarter of the world's primary-energy supply by 2050.

TABLE 2.1

World primary energy supply by source

Units: EJ/yr

	2018	2030	2040	2050
Wind	5	16	35	63
Solar PV	2	15	41	68
Solar thermal	2	2	2	2
Hydropower	16	22	27	31
Biomass	57	62	62	63
Geothermal	3	5	5	5
Nuclear fuels	30	36	35	33
Natural gas	154	177	179	165
Oil	173	149	120	89
Coal	162	139	93	52
Total	**603**	**622**	**600**	**570**

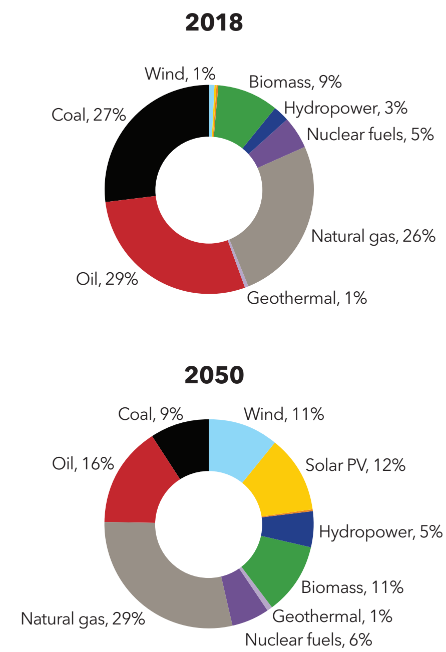
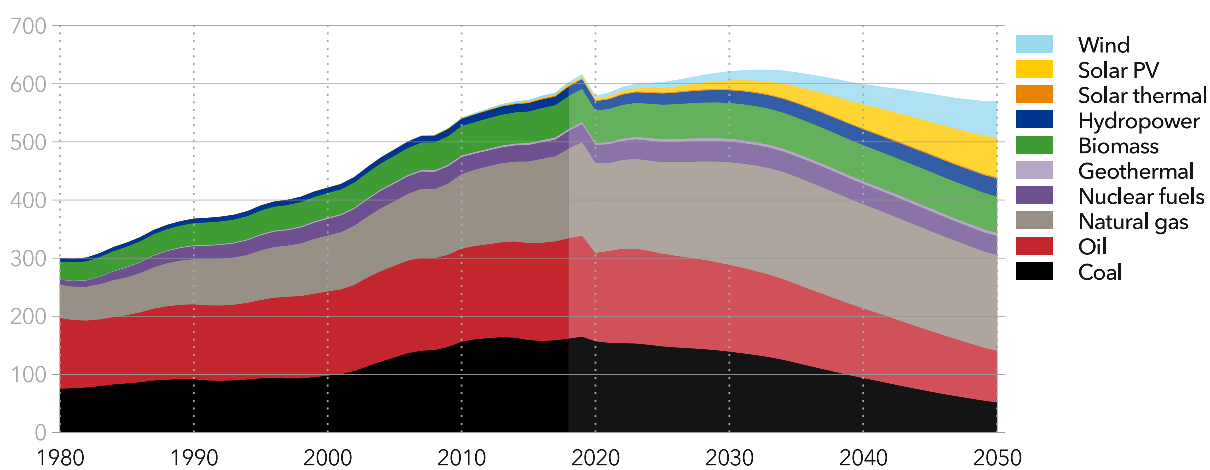


FIGURE 2.1

World primary energy supply by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

ALTERNATIVE WAYS TO COUNT ENERGY

There are several ways of calculating primary energy, each producing a different energy mix as every method assigns a different efficiency value to each energy source. The differences are most pronounced when measuring primary energy from non-combustibles, such as renewables. As the share of renewables in the energy mix rises, the differences between the methodologies also increase, and it is important to understand these differences.

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

These differences are apparent in the two most commonly used primary energy-counting methods: The Physical Energy Content Method and the Substitution Method.

- **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, solar heat, and fossil fuels is primary energy, while for non-thermal sources, such as wind, solar PV, and hydro-power, the electricity generated from these sources is primary energy.
- **The Substitution Method** computes the primary-energy content of non-combustible sources by determining 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-combustible sources.

There are also variations of these two methods. The Direct Equivalent Method, used by e.g., IPCC, resembles the Physical Energy Content Method. The Resource Content Method resembles the Substitution Method.

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

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

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

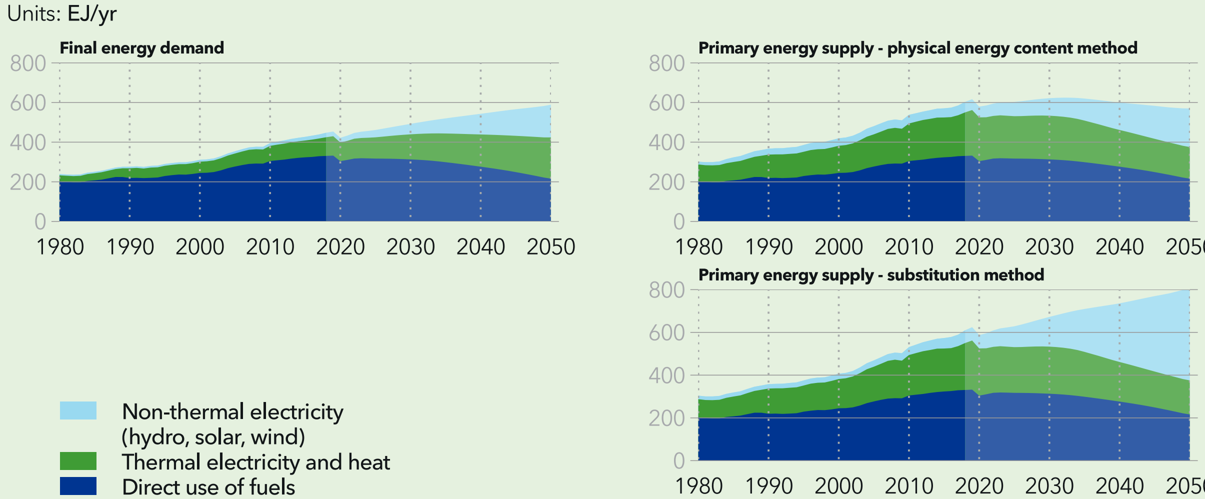
The choice of energy-counting methods significantly affects energy forecasts. When the renewables share of the energy mix was low, this hardly mattered. However, as the share of renewables is now growing rapidly, and will continue to do so, the different energy-counting methods produce different results, and it becomes important to understand the variations.

Figure 2.2 illustrates how the main Outlook results for primary-energy demand will change if we use another counting method. If the Substitution Method is used, then peak energy supply would not be reached during the DNV GL forecast period. Had we used that method, the argument that renewable energy and electricity had much higher efficiencies than fossil-energy sources would not be used; instead, we would have discussed the much lower carbon intensity of these fuels.

FIGURE 2.2

Primary energy supply using two methods of primary energy accounting

Units: EJ/yr



2.1 COAL

The world's coal demand has previously shown a rapid growth, from below 5 Gt/yr in 2000 to a peak of 7.7 Gt/yr in 2014 (Figure 2.3). Since then, total demand for coal has been on a bumpy ride. There has been a strong reduction in coal use in North America and Europe, driven by low gas prices and the expansion of renewables, a flattening in coal use in China, due to implementation of policies aiming to curb air pollution in manufacturing and power supply, and an increase in coal use in the Indian Subcontinent and South East Asia.

Summarizing these opposing trends, we do not expect coal demand to rebound and exceed its peak demand in the coming years, but to decline fast, shrinking to less than a third of its current level by 2050. In the long term, all regions will show a reduction in coal demand. By mid-century, coal demand in North America and Europe will reduce by 87% and 80%, respectively, compared with current levels. In the period until 2030 especially, coal demand in Greater China, the Indian Subcontinent, and South East Asia will remain strong.

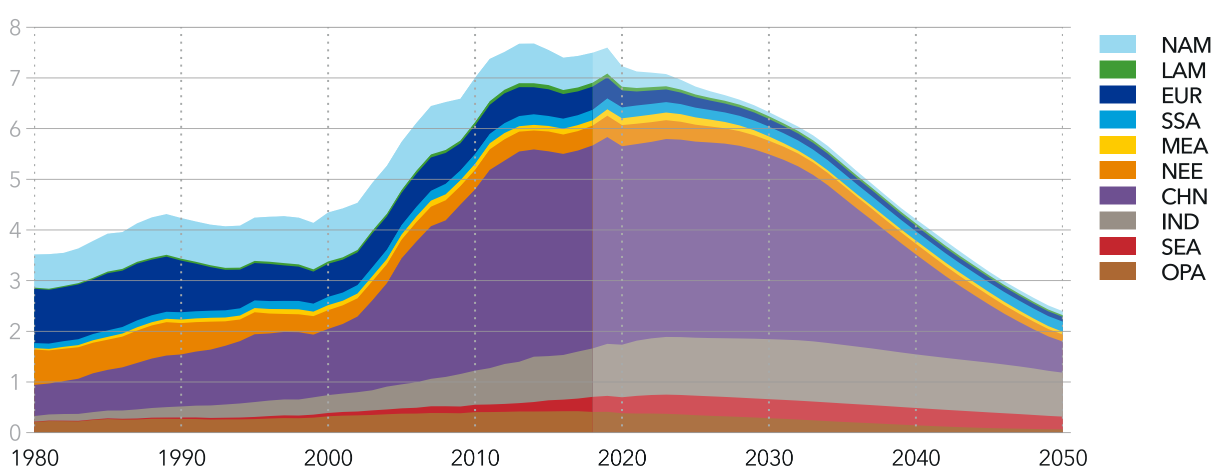
Recent and near-future build-up of coal-fired power stations and coal use in manufacturing will create an inertia, and this will result in these three regions continuing to retain 82% of global coal demand in 2030. China will see a large decline after 2030, such that its coal use by 2050 will be only 15% of its current level.

In 2018, 62% of the world's coal consumption was used for power generation (Figure 2.4). As a cheap and reliable source of power, coal has been the preferred technology for electricity generation in many countries. However, in the last few years, there have been signs of a downturn for coal-fired power worldwide, resulting in the closure of old power stations, particularly in Europe and North America, and the cancellation of several projects in their pre-construction phase, especially in China. We expect the COVID-19 pandemic to result in the global coal demand declining by 5% in 2020, largely due to a reduction in steel production, manufactured-goods supply, and power generation.

FIGURE 2.3

Coal demand by region

Units: Gt/yr

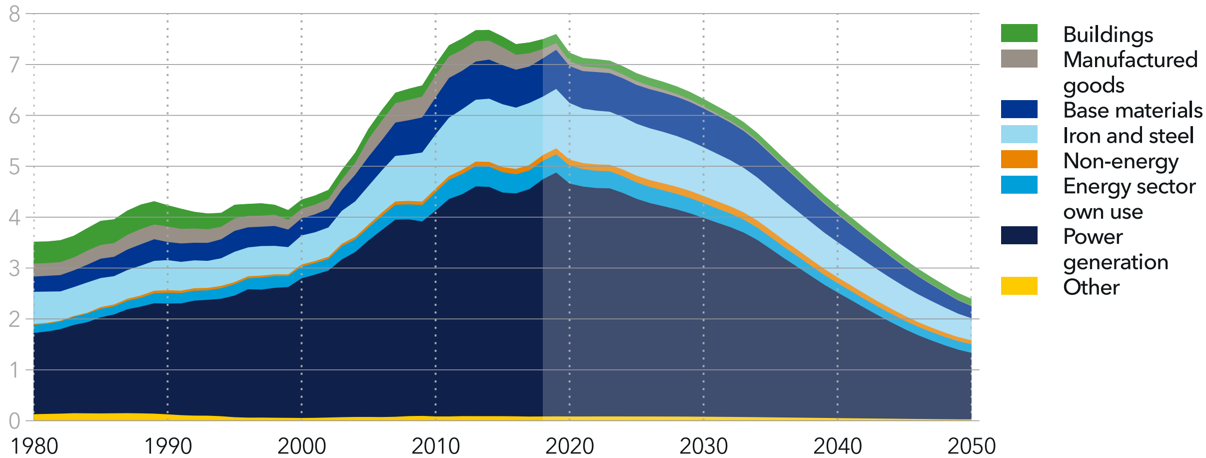


Historical data source: IEA WEB (2019), US DOE (2010), Heat Roadmap Europe (2015)

FIGURE 2.4

World coal demand by sector

Units: Gt/yr

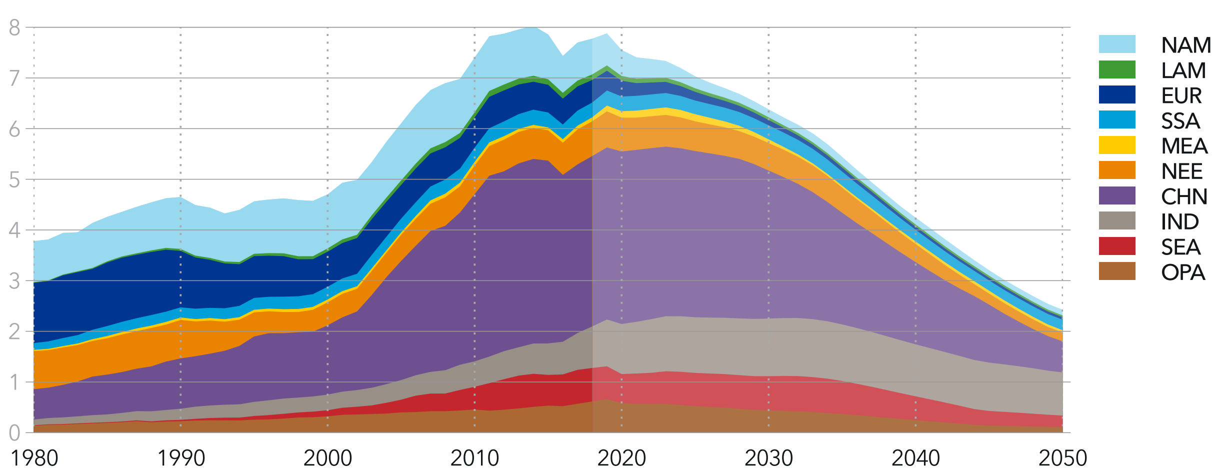


Historical data source: IEA WEB (2019), US DOE (2010), Heat Roadmap Europe (2015)

FIGURE 2.5

Coal production by region

Units: Gt/yr



Historical data source: IEA WEB (2019)

The coming decade will see large regional variations, with coal losing out to gas and renewables in many OECD countries, but continuing to expand in many developing countries. After 2030, stricter climate and emission policies, ever-increasing competition from renewables, and ramping-up of various sources of flexibility and energy-storage technologies will reduce the value of coal-fired power plants in terms of providing both energy and flexibility. Consequently, capacity utilization will decrease further, and capacity additions will gradually fade away, while retirements increase.

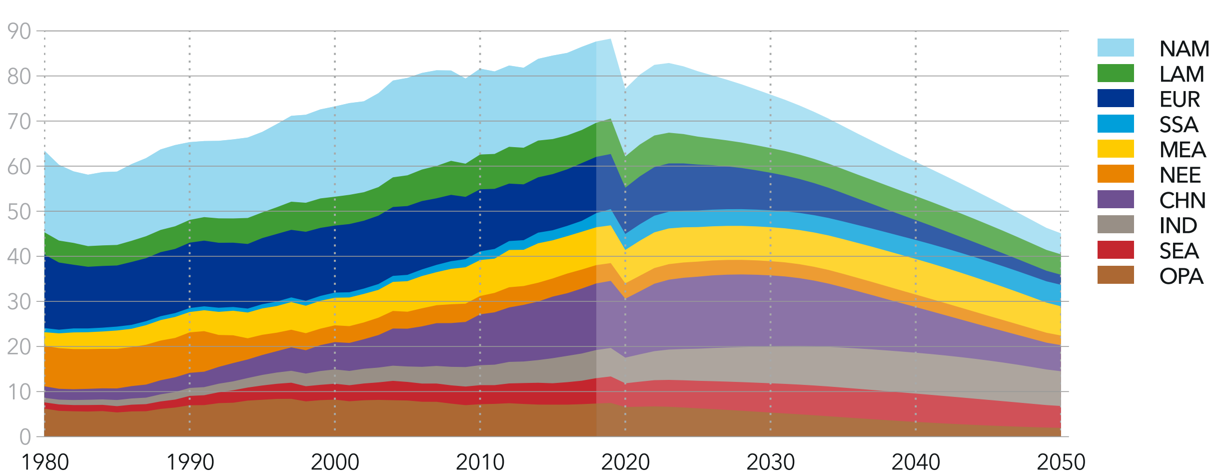
Coal is also used as a heat source in the manufacturing sector, and for iron-ore reduction in steel manufacturing. For low-heat processes, used for sectors that we classify under manufactured goods, we foresee a diminishing role for coal. China's policies to switch from coal to gas for industrial processes in order to curb local pollution will continue, and, in other regions, gas boilers and electricity will gradually contribute to the phasing out of coal. Requirements for higher temperatures in the base-materials sectors (such as aluminium and non-metallic minerals) will make the switch from coal more difficult. Coal demand for high-heat processes will first increase slightly and then fall rapidly after 2030. We expect that the global coal demand in the iron and steel sector will decrease by 63% by 2050 compared with today's use. Greater China will see a larger reduction of 78%, mainly due to a decreasing demand for steel production.

The regional breakdown of the world's coal production (Figure 2.5) resembles that of coal demand (Figure 2.3), as almost all brown coal, and a significant share of hard coal, is consumed within the region of production. Four of the 10 regions are net importers of coal, namely: Europe, Middle East and North Africa, Greater China, and the Indian Subcontinent. China, the largest producer and consumer of coal, is also the largest importer. After 2033, however, the phasing out of coal-fired power plants and lower use of coal in manufacturing in China will reduce the demand for coal import. Similarly, driven by India's efforts to increase self-sufficiency, the Indian Subcontinent will reduce its share of imported coal. Indonesia, Russia, Australia, and South Africa will continue to be major exporters, albeit each with diminishing shares.

FIGURE 2.6

Oil demand by region

Units: Mb/d



Does not include natural gas liquids and bioliquids. Historical data source: IEA WEB (2019)

2.2 OIL

For the last 30 years, the world's oil demand has been increasing at an average rate of 1.1%/yr, with Greater China, the Indian Subcontinent, and South East Asia experiencing growth rates exceeding 4%/yr. As Figure 2.6 shows, there has been a slight decline (less than 1%/yr) in oil demand for North America and OECD Pacific over the past decade. Europe has experienced a higher reduction rate of 3%/yr over the past 10 years.

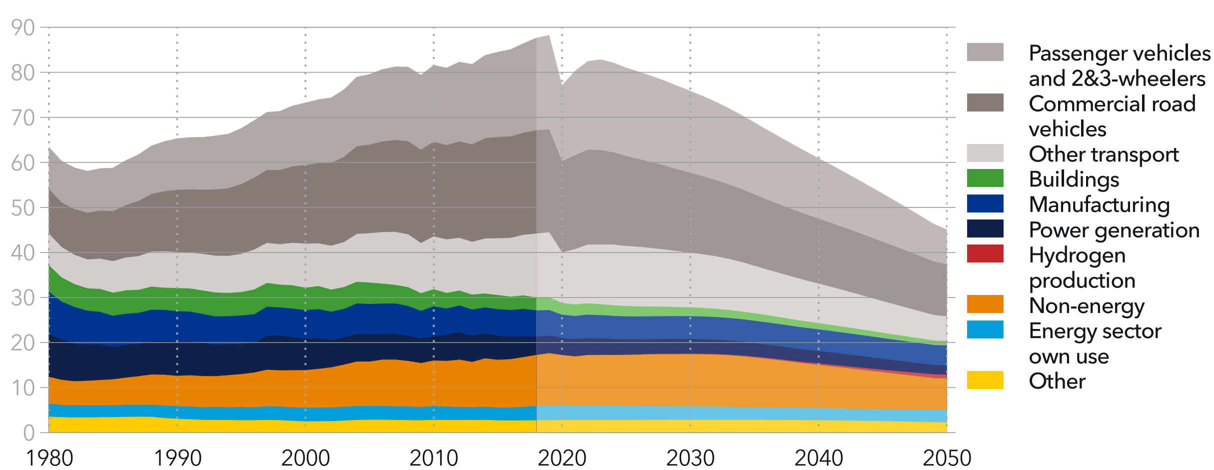
North America is still the largest consumer of oil, but will be overtaken by Greater China after 2025. Oil demand in Greater China will peak in around 2027 and then start to decline, reaching 41% of its current level by 2050. By mid-century, oil demand in North America and OECD Pacific regions will decrease to 26% and 25% of current levels, respectively. Europe will see the largest reduction among all regions, being only 18% of the current level in 2050. Global oil demand will gradually decline to almost half the current consumption level by 2050.

The transport sector accounts for two thirds of oil demand, and the rest is divided between non-energy use, particularly as petrochemical feedstock, and other energy uses (Figure 2.7). The transport-sector's share of oil demand has increased in recent decades, but will now start to reduce. In 2018, most of the transport sector's 53 Mb/d oil demand was from road vehicles; passenger vehicles and two- and three-wheelers will experience the most dramatic conversion to electricity, and the decline in oil demand from commercial road vehicles will be slower.
By 2050, the oil demand in the road-transport sector will have reduced by 56% compared with 2018. Maritime will see a faster reduction, reaching only 6% of its current oil demand by 2050. Aviation will be dependent on oil for longer, not reducing below 61% of current consumption by 2050. In the aviation and maritime segments, synthetic fuels, biofuels, and other low-carbon fuels, rather than electrification, will drive decarbonization.

FIGURE 2.7

World oil demand by sector

Units: Mb/d



Does not include natural gas liquids and bioliquids. Historical data source: IEA WEB (2019)

The Middle East and North Africa region will continue to dominate the oil-supply picture and later strengthen its position further (Figure 2.8), as this is where the cheapest oil resources with the easiest access are located. North America will maintain its production level in the next two decades, despite its own regional demand decreasing, with shale oil taking a larger share in total production.

Our companion publication for the Oil and Gas industry (DNV GL, 2020b) details our projections for oil production in terms of onshore conventional, unconventional, and offshore fields. Although conventional oil production will decline by, on average, 1.4%/yr until 2050, it will continue to play a critical role in production.

Our analysis shows that without the COVID-19 effects, oil would have reached a supply plateau in 2023, and by mid-century, it would have been 11% higher than our COVID-affected base case (Figure 2.9). We expect that the effects of the COVID-19 pandemic lead to a 13% reduction in global oil demand in 2020, mainly due to the impact on the transport sector. Our view of oil demand is that it has already reached a plateau, peaking in 2019 and will not increase further.

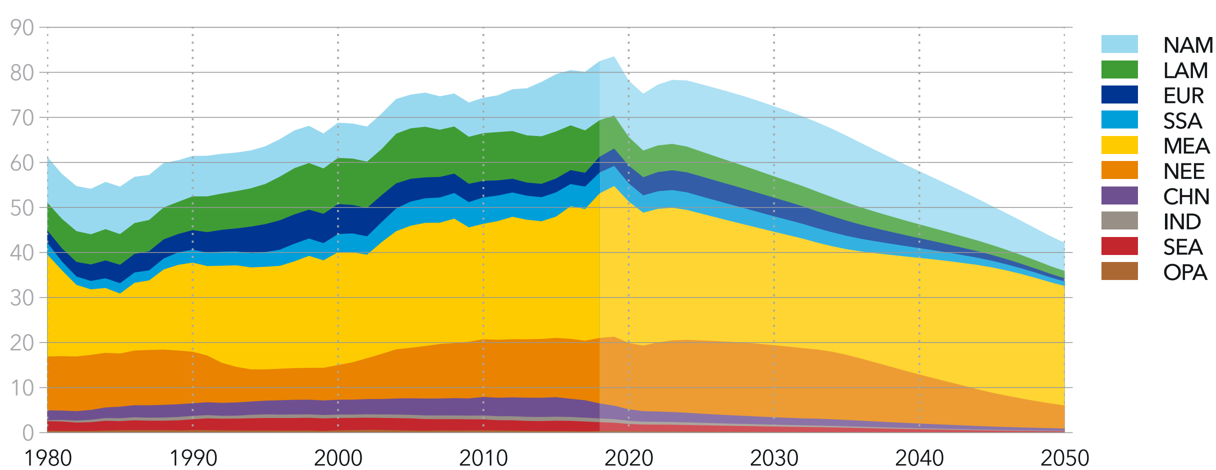
Figure 2.9 shows how our oil-production estimate alters in response to changes in the Li-ion battery learning rate and EV subsidies. Should the learning rate of Li-ion batteries be 50% higher than our estimate of 19%, then a more rapid decline in EV costs will accelerate the share of EVs, and by 2050 oil supply would decline by 7%. Should there be an equivalent 50% change, but in the opposite direction, then oil supply would be 15% above the base case in 2050. By doubling the level of EV subsidies with respect to our base case, oil supply would fall globally by only 7% in 2050. Should EV subsidies follow a path corresponding to a 90% reduction of our base case, the long-term oil supply will grow by 8%.

Our sensitivity tests are conducted on an individual basis, but obviously there could be a combination of factors that would lead to continued

FIGURE 2.8

Crude oil production by region

Units: Mb/d



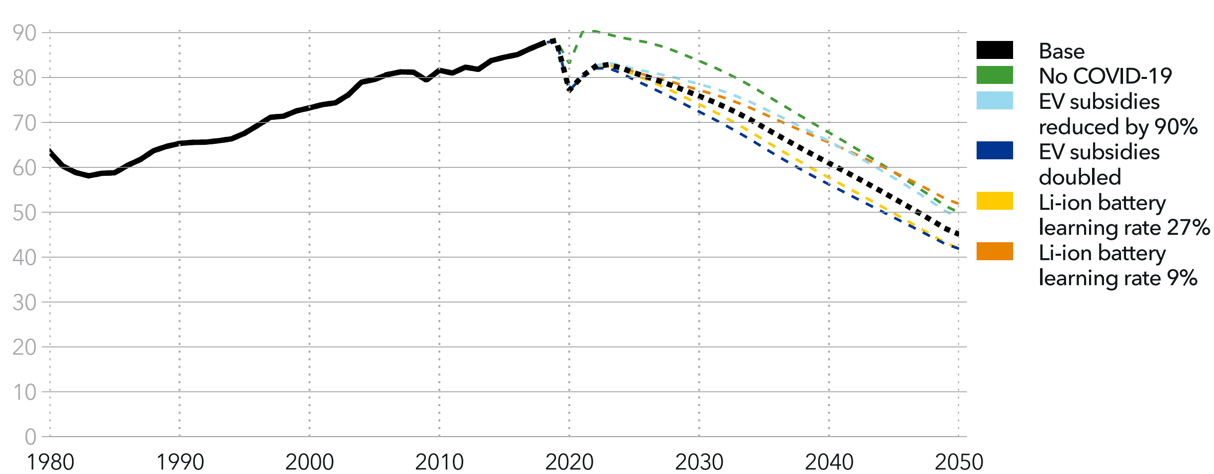
Crude oil production only. Does not include natural gas liquids. Historical data source: IEA WEB (2019) oil-production growth for longer; for example, a high vehicle demand in combination with large oil subsidies and minimal support for EVs, the latter driven by a lack of political will for decarbonization. The COVID-19 pandemic is adding to uncertainties, and more volatile prices and the realization that returns on investments in development projects are not guaranteed, and nor is a steady flow of dividend income a sure thing – a critical issue for institutional investors. Understandably, investors are now looking at standard hydrocarbon assets with a greater degree of caution. Employment preservation is likely to extend the continuation of pro-extraction policies, but these concerns will probably reduce over time as economies transform, with skill sets and expertise transferred to other industry areas.

As oil fields are depleted faster than the demand for oil declines, continued investment in new fields will be required (Figure 2.10). Investment in the high unconventional share in North America will prevail until the late 2030s, as depletion rates in unconventional fields are higher. The reduction in oil demand will make it less attractive for the industry to expand production into challenging environments, such as deep water and/or Arctic locations. Except for Middle East and North Africa, other regions that are dominated by conventional fields will require very little capacity additions after 2040.

FIGURE 2.9

Sensitivity of world oil demand to changes in input parameters

Units: Mb/d



Does not include natural gas liquids and bioliquids. Historical data source: IEA WEB (2019)

OIL OR NATURAL GAS?

There are many types of hydrocarbons, with differences in chemistries and properties. However, we have used the umbrella terms "oil" and "natural gas" to describe a collection of fuels.

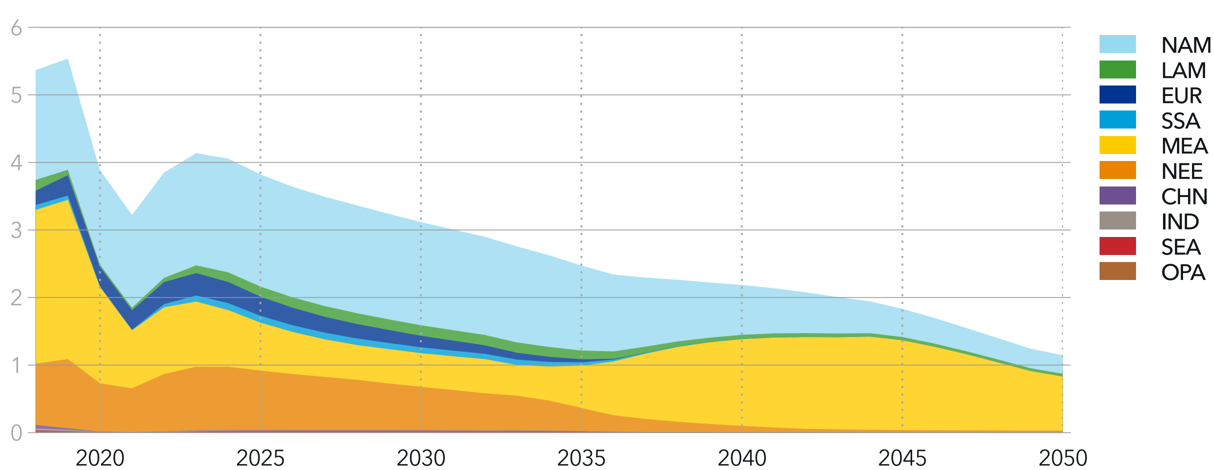
Oil (petroleum) is in liquid form at room temperature, whereas natural gas is mainly methane gas. In addition to methane, raw natural gas also contains fuels like natural gas liquids (NGLs). These include ethane, propane, butane (mixes of propane and butane are also known as liquefied petroleum gas; LPG), pentane, etc. These other fuels are separated from methane during the processing of raw natural gas. In this Outlook, we categorize all these side products under the energy carrier "natural gas", whereas elsewhere others have sometimes categorized them as "oil".

As extracted in its natural form, crude oil is also made up of various hydrocarbons, and must also be processed in refineries for conversion into usable "oil products", such as gasoline, diesel, fuel oil, lubricants, or asphalt. About 6% of refinery outputs are fuels that fall under our "natural gas" category, such as LPG.

FIGURE 2.10

Crude oil production capacity additions by region

Units: Mb/d/yr



Crude oil production only. Does not include natural gas liquids and bioliquids.

2.3 NATURAL GAS

World natural gas demand will grow until 2035, and thereafter taper off gently towards 2050, as illustrated in Figure 2.11. In 2026, natural gas will surpass oil to become the largest primary energy source, a position that it will retain throughout the forecast period. The natural-gas forecast varies markedly by region. In OECD countries, gas consumption will gradually decline. In Greater China, it will peak around 2035 and then start to decline. Natural gas demand in the Indian Subcontinent will grow rapidly, reaching 650 Gm^3/yr by 2050, 2.7 times higher than its current level.

In Figure 2.12, we show that while 41% of all gas use in 2050 will be for power generation, the manufacturing and buildings sectors will be responsible for about 18% and 21%, respectively. Some 7% will be used as feedstock and 10% will be for the energy sector's own use. Some of this use in the energy sector will be for liquefaction and regasification of gas transported as liquefied natural gas (LNG; see Figure 2.14 for the separate LNG forecast).

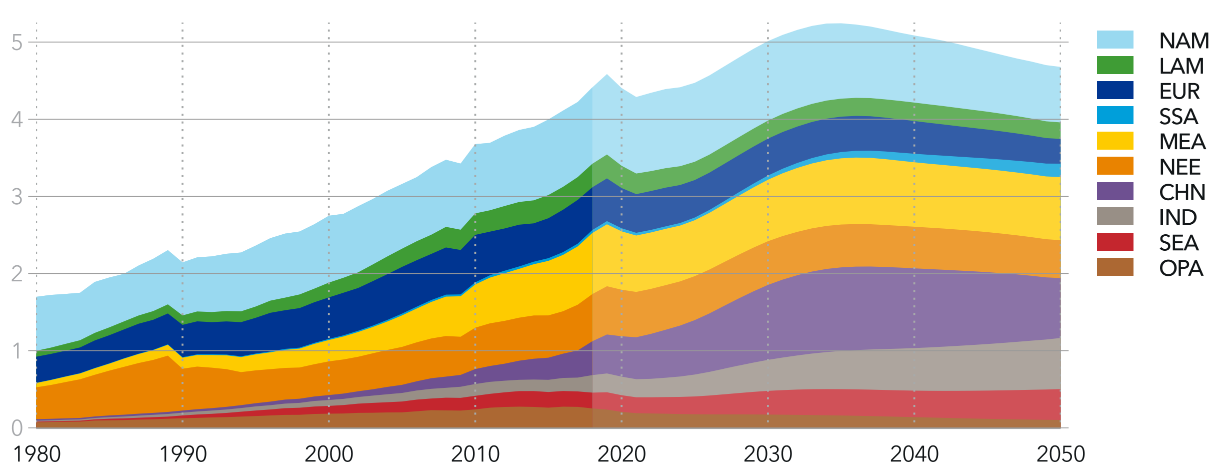
The direct use of gas in the buildings sector (for heating) will grow gradually, levelling off during the 2030s, and later decline towards 2050. Gas demand in the manufacturing sector will peak in the early 2040s, whereas the major gas user, the power sector, will see natural-gas generation peak in the early 2030s, and then remain fairly flat towards 2050. The use of natural gas in transport, mainly in the maritime and road-transport subsectors, will peak in 2037.

Gas production will need to keep up with demand. In summary, gas production will increase and move to new locations around the world. Although already small in relative terms, Europe is the region that will experience the most dramatic reduction in production, falling by 58% from now through to 2050. In terms of absolute output, the three dominant players at present, North East Eurasia, North America, and the Middle East and North Africa, will maintain their current levels of production throughout the forecast period (Figure 2.13).

FIGURE 2.11

Natural gas demand by region

Units: Tm^3/yr

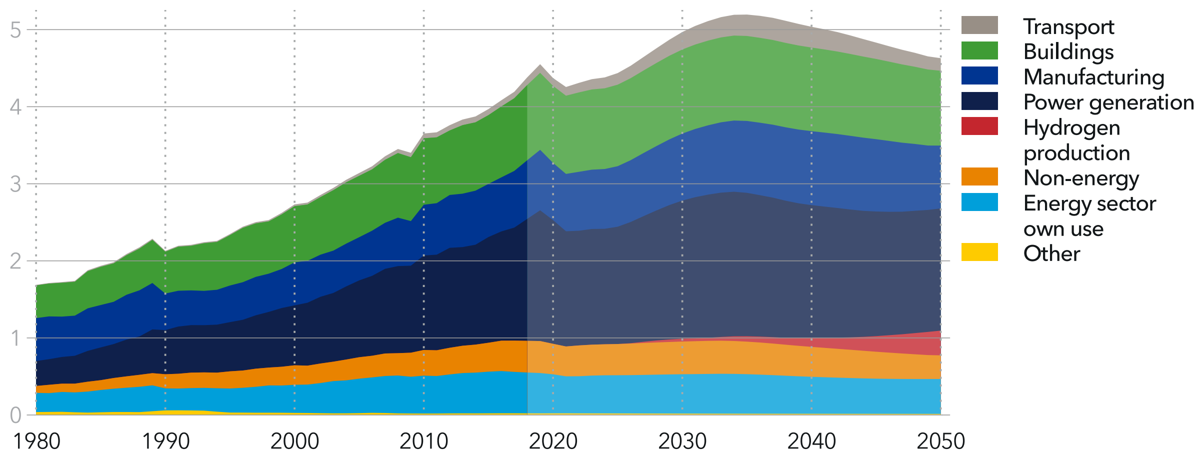


Includes natural gas liquids. Historical data source: IEA WEB (2019)

FIGURE 2.12

World natural gas demand by sector

Units: Tm³/yr

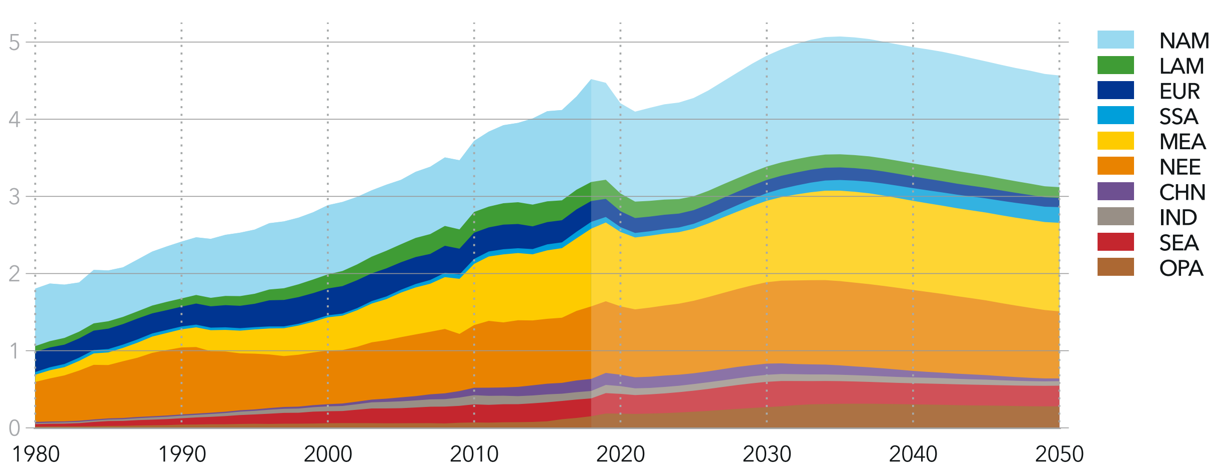


Includes natural gas liquids. Historical data source: IEA WEB (2019)

FIGURE 2.13

Natural gas production by region

Units: Tm^3/yr



Includes natural gas liquids and refinery outputs. Historical data source: IEA WEB (2019)

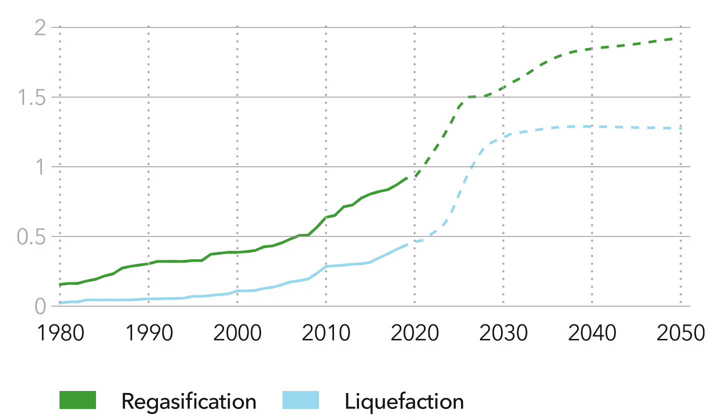
As there will be large regional shifts in demand, LNG and pipeline transport will experience larger changes than changes in production. Gas transport is expensive and accounts for a significant proportion of the cost of delivered energy. Although piping is cheaper than shipping for transport over shorter distances, and will expand as production sites and consumption sites move steadily further apart, shipping will increase its share of inter-regional gas transport. Transport costs will continue to rise, as both transformation of gas-to-liquid forms (liquefaction) and on-keel transport, in the forms of LNG and LPG, will increase, as shown in Figure 2.14. Most importing regions increase their imports, and, consequently, exporting regions will export more, resulting in the global capacity for regasification more than doubling by 2050, while the global capacity for liquefaction more than triples. North America will see the largest growth in liquefaction, accounting for 44% of global capacity by 2050. Middle East and North Africa will be second largest, representing about 17% of global liquefaction capacity. By mid-century, nearly half (47%) of the global regasification capacity will be in the Indian Subcontinent and Greater China (Figure 2.15).

As gas fields are depleted, especially the unconventional ones, production capacity will need to expand. Figure 2.16 shows that annual capacity additions will reach a maximum level of 350 Gm³/yr in the early 2030s. North America's high share of global gross capacity additions is partly explained by its production being mainly shale, i.e., unconventional. Unconventional fields tend to have disproportionally higher gross capacity additions because they usually have a significantly shorter lifetime than the other extraction technologies.

FIGURE 2.14

World LNG trade capacity

Units: Gt/yr

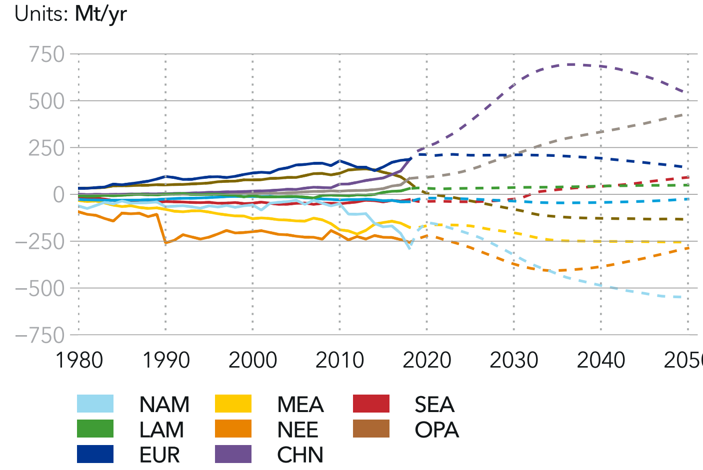


Historical data source: IGU (2019)

FIGURE 2.15

Net natural gas imports by region

Units: Mt/yr

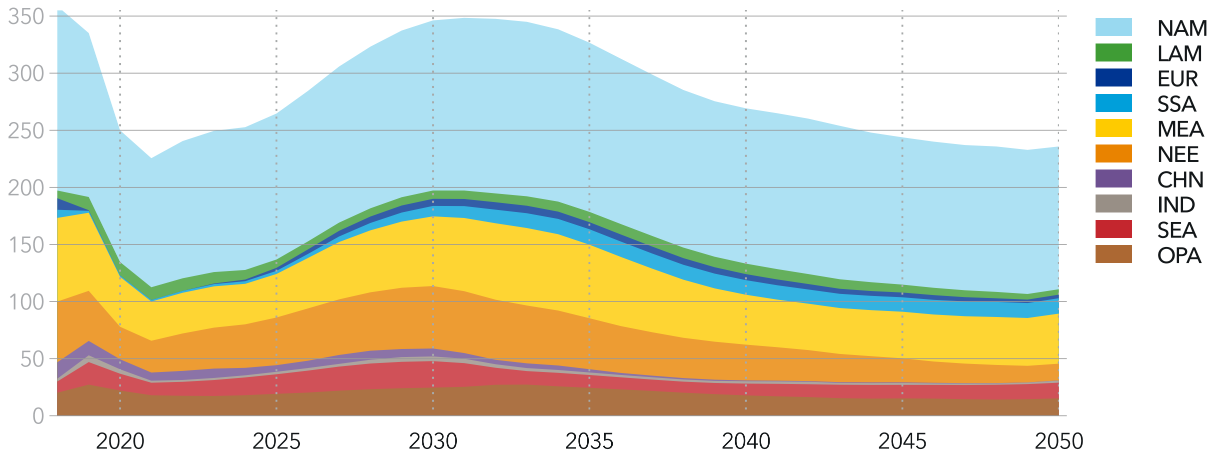


Historical data source: IEA WEB (2019)

FIGURE 2.16

Natural gas production capacity additions by region

Units: Gm^3/yr/yr



Includes natural gas liquids from wells, but not refinery outputs.

TABLE 2.2

Gas sensitivity analysis

2050 level		Parameter uncertainly tested: Coal price		Gas price		Carbon price		PV learning rate		Wind learning rate	
Sensitivity range	Base	-50%	+50%	-50%	+50%	+100%	+300%	-50%	+50%	-50%	+50%
Natural gas primary supply EJ/yr	165	201	140	160	168	169	178	165	165	168	161

GAS AS A BRIDGE?

Gas is frequently considered as a bridge to a decarbonized future, as its unit CO_2 emissions per energy output are typically about half those of coal, as explained in Section 7.1. However, gas use can also be perceived as a destination, rather than as a bridge, in a decarbonizing energy future. In this case, the gas needs to be carbon-free, which can be achieved by converting CH_4 (natural gas – methane) to hydrogen or to other carbon-free gases by capturing the CO_2.

Although purported to be a low-cost solution for decarbonizing heat in buildings, and also in manufacturing, as it enables (re-)use of existing infrastructure, we currently do not foresee gas being a more viable long-term solution compared to boosting renewable electricity. The main reason is that the lower costs for gas infrastructure will be offset by costs for energy production, that are higher than those for carbon-free electricity. Additionally, much of the gas infrastructure will have to be replaced before 2050, and the cost advantage of gas-grid replacement compared with that of power-grid newbuilds is assumed to be relatively minor. The role of hydrogen as an energy carrier is further discussed in Section 3.2.

The transition path to greener shipping will see significant uptake of gas-driven propulsion. Most of the fuel will be LNG and LPG, but some will be LBG (liquid biogas), which is included in our biomass category. Biomethane is currently in vogue as a carbon-neutral fuel, and many cities require that a significant share of their buses run on such fuels, which is mainly derived from organic waste. Production costs of biomethane are, however, 2-3 times higher than those of natural gas, and we envisage only modest uptake. For the road and aviation sectors, biofuel-blend mandates will gain momentum, but as liquid, not gaseous, fuels, due to less-costly combustion, storage advantages, and the higher energy density by volume. For green shipping, however, the big increase in propulsion gases will be in synthetic fuels and ammonia.

In our analysis, as shown in Table 2.2, we have investigated the sensitivity of natural-gas demand to the assumptions regarding natural gas and carbon prices, as well as to solar PV and wind learning rates. Our analysis indicates that gas demand is very sensitive to changes in gas price. Shifting the gas price down by 50% will increase the demand for gas production by 22%. However, the equivalent relative increase in gas price would result in a 15% drop in gas demand in 2050.

Should the carbon price in 2050 be 50% lower than our base case, then gas demand would fall globally by only 3%. Gas lies in-between more carbon-intensive coal and zero-carbon nuclear and renewables. Hence, changes in carbon price will favour and disfavour gas, depending on the competition. Higher carbon prices, however, will benefit the share of green gas in the total gas supply. Similarly, wind and solar power cost-learning rates will have very limited effects on reducing the demand for gas-fired power stations.

It should be noted that buildings-sector dynamics are not included in the above uncertainty discussions, as these have been modelled differently in our forecast. Hence, total sensitivity might be somewhat higher than indicated in Table 2.2.

> “Changes in carbon price will favour and disfavour gas, depending on the competition

HIGHLIGHTS

This chapter covers electricity demand and electricity generation in our forecast period.

We show how electricity demand will more than double over the next 30 years (25 PWh/yr in 2018 to 56 PWh/yr in 2050), with an ever-increasing proportion of power generation supplied by variable renewables (vRES). Solar PV and wind will each supply 31% of electricity in 2050, with 14% coming from hydropower, and 5% nuclear. The fossil share of generation will decline to just 17% of the power mix.

The growing complexity of the power mix, with a blend of non-dispatchable and dispatchable sources (with or without storage constraints) makes for complex modelling of future market dynamics. We show how our model finds the market equilibrium at each hour by adding up the potential supply and demand at different prices and calculating the price at which total supply equals total demand.

We cover the very rapid growth of solar PV and wind to 2050, and their impact on the storage market and global grid buildout. We detail the role that hydrogen is likely to play as an energy carrier, which will accelerate with the growth of hydrogen production through electrolysis powered by surplus renewable power from the mid-2030s.

Photo: The world's first floating offshore wind farm. Equinor's Hywind Scotland project off the coast of Peterhead.
Image courtesy Equinor/Øyvind Gravås/Woldcam

CHAPTER 3

POWER AND RENEWABLES

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3.1 ELECTRICITY

ELECTRICITY DEMAND

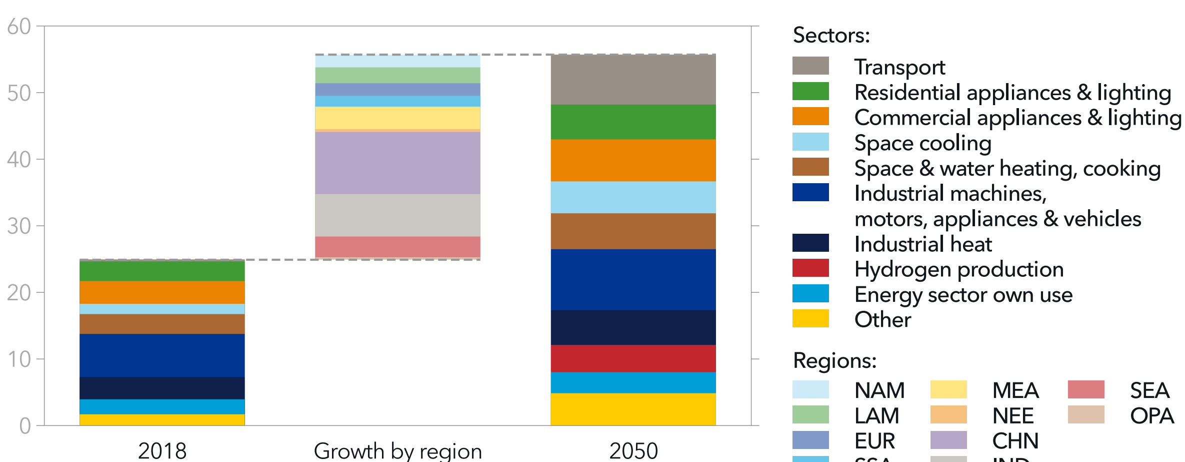
Figure 3.1 shows world electricity demand growing 123% from 25 PWh/yr in 2018 to 56 PWh/yr in 2050, with buildings and manufacturing continuing to consume the lion's share, and demand for mobility growing quickest. Over the same period, the growth in electricity demand will be 46% for manufacturing, 100% for buildings, and 26-fold for the transport sector. Buildings will retain the highest sectoral share in total electricity demand, 39% in 2050, with manufacturing accounting for 26%. With the electrification of road vehicles, transport's share rises from 1.1% in 2018 to 13% in 2050. We expect COVID-19 to reduce global electricity demand by 3.4%, 880 TWh, in 2020. Average annual growth in global demand will be 2.4% between 2020 and mid-century.

Electricity's share in total final energy increases from 19% in 2018 to 41% in 2050. As discussed in Chapter 1, this share is sensitive to many parameters. On the demand side, electricity for road vehicles is significantly affected by battery cost-learning rates, EV subsidy levels, and EV lifetimes. Relative prices of electricity and competing sources of energy are also relevant. On the supply side, as prices of fuels (e.g. gas and oil) used for power generation remain an important determinant of electricity prices in coming decades, changes in these fuel prices do not create significant differentials in the price of electricity versus other transport fuels such as gasoline. However, once the rising share of renewables in power generation starts to decouple electricity prices from the prices of fossil fuels, carbon prices will impact fossil-fuel prices without significantly affecting electricity prices. This will result in electricity becoming even more competitive.

FIGURE 3.1

World electricity demand by sector, growth by region

Units: PWh/yr



Historical data source: IEA WEB (2019), IEA ETP (2016), Harvey (2014), Nakićenović et al (1996), EIA RECS (2015), Ürge-Vorsatz et al (2015)

ELECTRICITY SUPPLY

The transition in electricity generation from fossil fuels to renewables will accelerate (Figure 3.2). In 2018, only 26% of electricity was supplied from renewable sources, and two thirds of this was hydropower. With continued declines in the costs of solar, wind, and related technologies such as batteries, variable renewable energy sources (vRES) will gradually but steadily transition from being marginal to become the major electricity sources in 2050. By then, 78% of the world's electricity will be generated from renewable sources, and 62% alone from variable renewables.

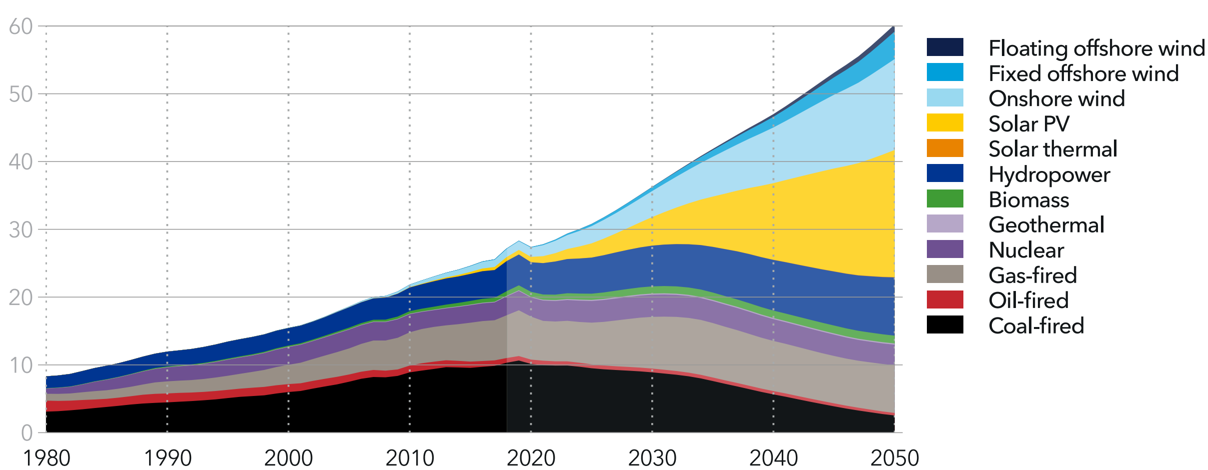
By 2050, solar PV and wind will be the leading sources of the world's electricity, each providing 31%. An additional 14% will come from hydropower. The role of fossil fuels in power supply will still be central in some regions, such as North East Eurasia and the Middle East and North Africa, due to their lack of financial support and infrastructure for renewables. In developed regions, however, fossil fuels will become increasingly marginal in terms of their share in electricity supply. Their role will be reduced to providing flexibility and back-up in power systems when vRES are unavailable, especially through low-CAPEX gas-fired power stations. In 2050, fossil fuels will generate 17% of power needs, and nuclear 5%. Nonetheless, dispatchable power will still be price-setting and hence continue to play a pivotal role in the power system. Therefore, we are still likely to see considerable attention being paid to maintaining fossil-fuel generation, despite its declining role in electricity supply.

The share of variable renewables in the electricity mix is sensitive to many parameters. Increasing the learning rate of solar and wind also affects the results, but only marginally. With a one-third increase in the wind-turbine cost-learning rate, the share of vRES increases from 62% to only 64%. However, differences in wind and solar learning rates will create shifts between the two. Doubling the carbon price has a similarly limited effect on the share of renewables in the energy mix, as they are already the most competitive technologies in our base case.

FIGURE 3.2

World electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2019), IRENA (2019)

TECHNOLOGIES AND THEIR ROLES IN AN EVOLVING POWER MARKET

Our Energy Transition Outlook Model (ETOM) represents the power sector in 10 regions. It covers 12 power-station types, namely coal-fired, gas-fired, oil-fired, nuclear, geothermal, biomass-fired, hydropower, solar thermal, solar PV, onshore wind, fixed offshore wind and floating offshore wind. The ETOM also incorporates four storage technologies: pumped hydro; storage provided by EVs via vehicle-to-grid / grid-to-vehicle solutions; Lithium-ion battery storage dedicated to providing flexibility to the grid; and long-duration storage that entails any storage technologies other than lithium or classic pumped hydro that provide cost advantages for longer duration storage – e.g. redox flow batteries, zinc/air or zinc/bromine, alternative electrochemical cells / flow batteries, and mechanical and thermomechanical systems.

We have divided these supply options into four categories.

The first category is non-dispatchable generation – solar PV, onshore wind, and offshore wind. Only limited control is possible over how much electricity these technologies provide. We have used normalized deterministic profiles for their generation patterns. The generation profiles vary over years, representing technological improvements and geographical changes.

The second category is dispatchable generation with no storage constraints – coal-fired, gas-fired, oil-fired, biomass-fired, and nuclear power stations. Operators of such plants can control how much power to generate, and have no limit on duration (their fuel supply is assumed to be unlimited). Power stations in this category use variable cost calculations to determine how much they are willing to generate. By doing this, we have ignored constraints such as start-up times, ramp-up / ramp-down rates, or the heat demand of combined heat and power (CHP) plants. The variable costs of power stations are assumed to follow a normal distribution, estimated from the variances in efficiencies, fuel prices, and the costs of operations and maintenance.

The third category is dispatchable generation with storage constraints – hydropower and solar thermal. The inflow to the storage (water reservoir or thermal storage) is uncontrollable and estimated from a representative year. As the total energy output is limited, opportunity cost-based operation is simulated by making the supply quantity of these power stations proportional to the electricity price. The supply curve is calibrated over the course of simulation using the previous year's price distribution, such that total generation is equal to total inflow.

The last category is storage. Storage technologies are also constrained by their capacity but can control both inflow and outflow. Both charging and discharging behaviour of storage is guided by price. Each storage technology has a 'forecast horizon' varying from hours to days depending on its capacity. Using recent simulated history, an 'expected price' within this horizon can be calculated and used to determine how much of their charging/discharging capacity they are willing to use at what price level. Expected price is constantly updated as the simulation proceeds.

On the demand side, we take into account 12 categories of end-uses. Each demand segment has a normalized profile that represents the regional demand over the year. These normalized profiles are established on the basis of a representative year and do not change between years. In addition, power-to-hydrogen conversion through electrolysis is modelled. We do not consider hydrogen-based electricity generation in the model, as we expect the costs associated with storing and using hydrogen to be prohibitive, due to efficiency losses in the process. Instead, we assume that all hydrogen from electrolysis will be used as an energy carrier in the transport, manufacturing, and buildings sectors. EV charging, heating, cooling, and manufacturing segments respond to price, with varying price elasticities, and this 'demand response' is strengthened over the years.

The model finds the market equilibrium at each hour by adding up the potential supply and demand at different prices and calculating the price at which total supply equals total demand. If the reduction in price is insufficient to reduce an oversupply case, then supply is curtailed. However, as discussed in Section 3.2, there will be a host of takers for cheap electricity and we consequently do not expect curtailment to be necessary for significant periods. The graphic overleaf summarizes how the ETOM's power-market module operates on different time-scales.

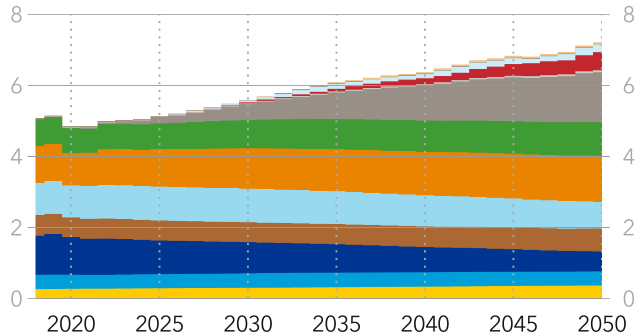
Geothermal power station
Tuscany, Italy.

HOW OUR MODEL'S POWER SECTOR OPERATES ON DIFFERENT TIME SCALES

Here, we illustrate how our model determines the operating hours of power stations, using North America as an example. Annual electricity demand by sector use comes from the corresponding parts of the model.

North America electricity demand by segment, 2018-2050

Units: PWh/yr

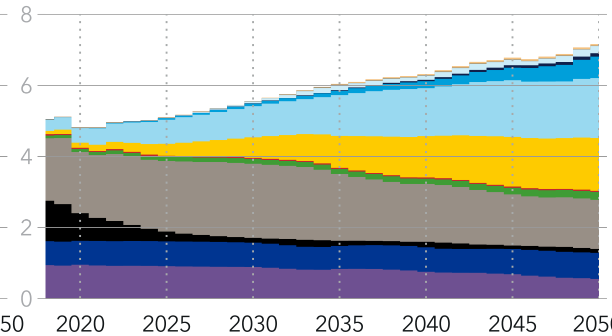


Battery storage
Pumped hydro
EV storage charging
Hydrogen production
Rail, aviation, shipping
Road vehicles
Resid. appl.& lighting
Comm. appl.& lighting
Space cooling
Heating & cooking
Manufacturing
Energy sector own use
Other

T&D losses are allocated to demand.

North America electricity supply by source, 2018-2050

Units: PWh/yr

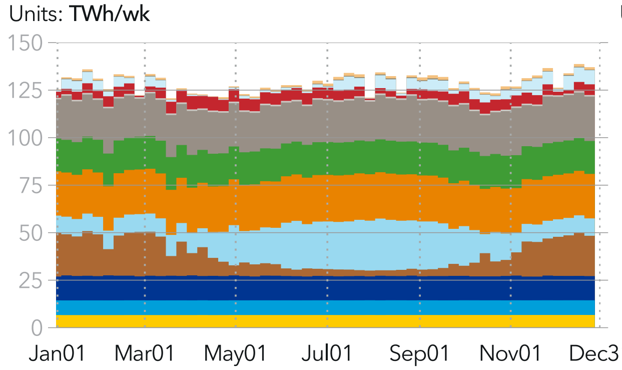


Battery storage
Pumped hydro
EV storage
Floating offshore wind
Fixed offshore wind
Onshore wind
Solar PV
Solar thermal
Oil-fired
Biomass-fired
Gas-fired
Coal-fired
Hydropower
Nuclear

We expand the year 2043 over 52 weeks. All profiles are aggregated over the whole region. As seen below, increased solar-PV generation coincides with increased activity of storage and hydrogen production, flattening the demand. This is due to the high variability of solar PV.

North America electricity demand by segment, 2043

Units: TWh/wk

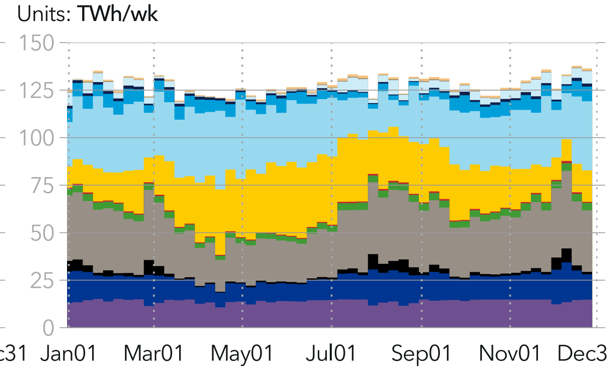


Battery storage
Pumped hydro
EV storage charging
Hydrogen production
Rail, aviation, shipping
Road vehicles
Resid. appl.& lighting
Comm. appl.& lighting
Space cooling
Heating & cooking
Manufacturing
Energy sector own use
Other

T&D losses are allocated to demand.

North America electricity supply by source, 2043

Units: TWh/wk

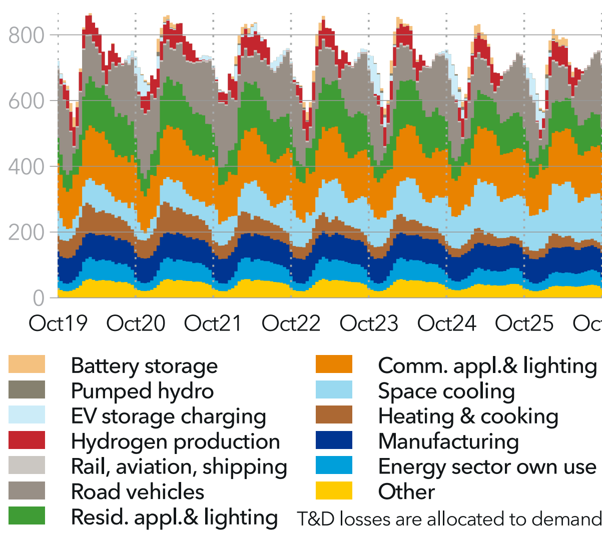


Battery storage
Pumped hydro
EV storage
Floating offshore wind
Fixed offshore wind
Onshore wind
Solar PV
Solar thermal
Oil-fired
Biomass-fired
Gas-fired
Coal-fired
Hydropower
Nuclear

This next chart zooms in on week 43. How storage and hydrogen production plant operators behave is based on price signals, as previously described. Thus, they tend to store energy when vRES output is ample and to release energy when it is not. However, as many operators compete, the result is not optimal with respect to reducing variability.

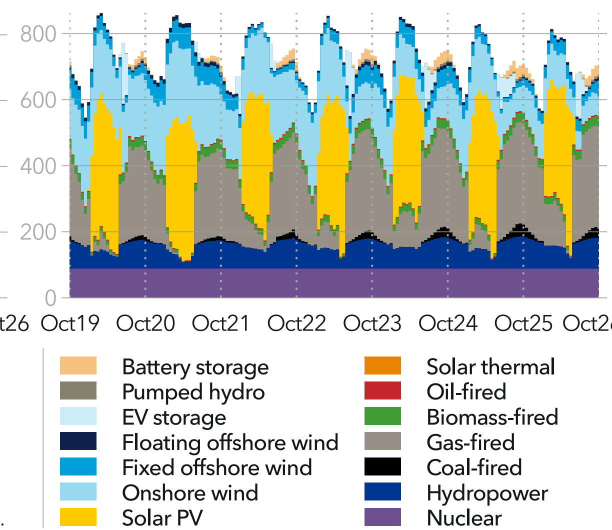
North America electricity demand by segment, week 43, 2043

Units: GWh/h



North America electricity supply by source, week 43, 2043

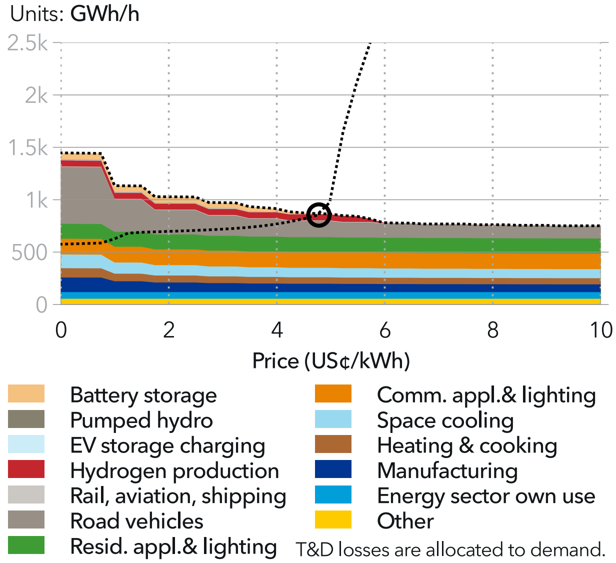
Units: GWh/h



At each hour, the model establishes demand and supply curves, as shown below, demonstrating regional supply and demand at each possible price. The point at which supply and demand curves cross indicates the realized supply, demand, and price.

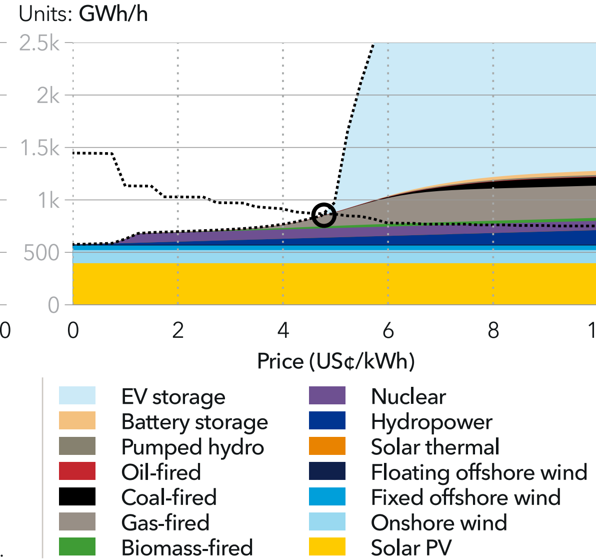
North America electricity demand curve, 23 October 2043, 10:00 CDT

Units: GWh/h



North America electricity supply curve, 23 October 2043, 10:00 CDT

Units: GWh/h



Please note that, unlike other models, our hourly power-dispatch model does not assume a perfect market (where the supply curve is the 'clean' merit order), but instead considers a region-wide market that reflects geographical variations through normal distribution of power-station dispatch prices. For example, the first biomass unit will already start running before the last gas unit. This is because we have used a normal distribution of marginal costs of different power plants, simulating differences in efficiency, grid costs, and local circumstances such as differences in national markets.

Our hourly model ignores any grid constraints, meaning that, within the model, any demand can be met by any generator in the region, regardless of location. This simplistic assumption favours geographically concentrated generation technologies and power-station types that have limited grid connections, particularly vRES and storage. However, neither power stations nor demand are spread homogenously around the world and, in reality, grid constraints can pose problems with delivering generated electricity to consumers. Thus, we are aware that the assumption of no grid constraints does not hold, particularly in regions, such as OECD Pacific, where power systems are geographically diverse or even disconnected. Nevertheless, we have chosen to use this approach to simplify the model.

INVESTMENTS AND RETIREMENTS

The steady pace of electricity demand growth will require continued investment in new power capacity around the world. Demand growth is the first driver, but not the sole driver of power sector investments. A significant portion of new capacity, especially in developed countries, replaces retiring capacity. The most obvious and second driver of power-station retirements is reaching the end of technical lifetime. We reflect this process in our model by reflecting the ages of all existing capacity and using a statistical lifetime distribution to estimate the time of retirements. We use an average lifetime of 40 years for coal-fired power plants, 30 years for oil- and gas-fired power plants, 75 years for nuclear power plants, and 200 years for hydropower stations. In addition, a 23-year lifetime is used for onshore wind turbines, 28 years for fixed offshore wind turbines, and 25 years for floating offshore wind turbines and solar PV panels. Economics is the third driver of capacity retirements. We are starting to see more examples of decommissioning of power stations that are no longer profitable to operate. In some markets, solar and wind have become so cheap that old and polluting coal-fired power plants are utilized less often. To reflect this reality in our modelling, we shorten the lifetime of under-utilized plants from their nominal values. A fourth driver of capacity additions is also linked to solar and wind, but in a different way. As these energy sources are inherently uncontrollable, power systems will require a certain firm capacity (or dependable capacity) so that the demand can be reliably met even at its extremes. In our model, if firm capacity requirements are not met at any point over the course of the simulation, low-CAPEX dispatchable generation capacity (gas-fired and oil-fired) is added.

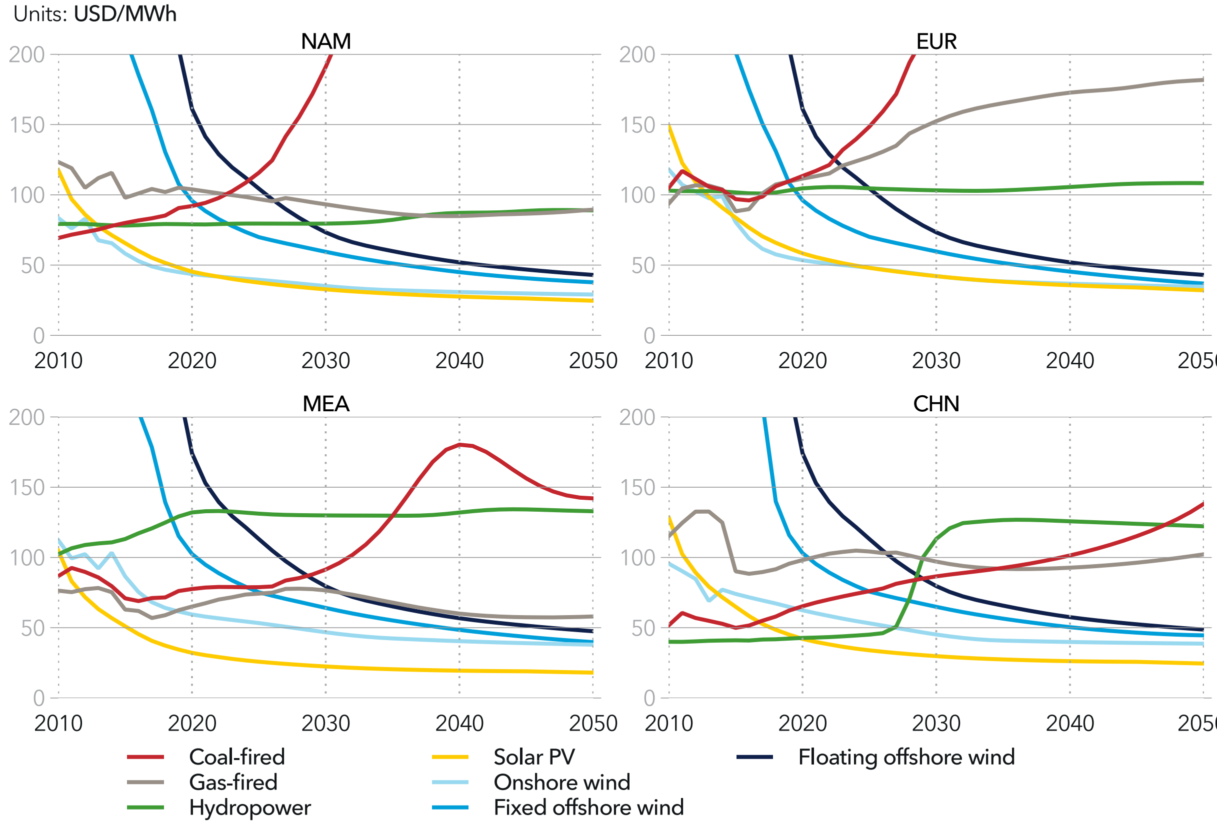
The mix of capacity additions is determined by the profitability of power-station types. Due to geographical, technological, political, and temporal variations, the most profitable option varies significantly even within a region. In order to prevent a 'winner-takes-all' situation, and to represent such local variations within a region, we take a probabilistic approach when we model the capacity additions, where the profitability of a power-station type is assumed to follow a normal distribution. In this way, even if a technology is not the most profitable one, on average, it still retains the chance of being in the capacity-additions mix should the high end of its profitability distribution coincide with the profitability distribution of the leading technology.

The two components of a future power station's expected profitability are its expected cost and anticipated revenue. On the cost side, the industry standard is to calculate the expected levelized cost of electricity (LCOE). It is a useful measure because it reveals the cost of producing a megawatt-hour of electricity over the lifetime of a power station. Figure 3.3 shows the evolution of LCOE of various power-station types for selected regions. The LCOE for coal-fired power stations trends upwards due to declining capacity factors (fewer running hours) as well as the added cost from carbon prices or carbon capture and storage (CCS). Except for in Europe, the LCOE from gas is mostly flat because its lower carbon intensity makes it a cheaper complement to vRES, balancing out the increasing carbon cost with longer running hours. The rise in hydropower costs is linked to lack of resource availability, and is most prominent in China where widespread buildout of capacity already uses cheaply exploitable sites. The decline in the LCOE for vRES is due to learning rates in technology costs. Annex A.4 gives more details about the learning rates. Solar PV and onshore wind already have the lowest LCOE in many regions, and this will continue. Note that cost of equity is part of LCOE formulation. The current discount rate that we use is 7% for the OECD regions, and 8% for all others. However, as fossil-fuel investments are increasingly regarded as riskier, the discount rate of fossil-fuel-fired power stations increases to 10% just before 2030.

FIGURE 3.3

Levelized cost of electricity by technology in four regions

Units: USD/MWh



Shows the regional average LCOE without financial support. For conventional power stations, LCOE is based on the average capacity factor of same type of power stations in operation at the investment year. For solar and wind, the expected capacity factors of future additions are determined seperately.

While the cost differentials between technologies are central to their uptake, the revenue side of the profitability equation is equally important. Except for peaking plants, the revenue has not been a differentiating factor between conventional power stations because long running hours ensured that all power stations received more or less the same average price over the year. Also for variable renewables, power purchase agreements have provided sufficient revenue to early investments. Although such mechanisms are gradually removed, renewables largely remain 'price-takers' in power markets where the electricity price is (mostly) determined by the variable cost of the most expensive generator providing electricity at any given time. That means that, historically, renewables did not have a significant impact on the price and could benefit from high revenue at the times of high demand as their variable costs are practically zero. However, as the shares of solar and wind increase in power systems, the number of hours in a year in which these zero-variable-cost renewables will be sufficient to meet the load will increase, in turn potentially setting the price to zero, or even negative. Consequently, the 'capture price' of renewables (i.e. average price weighted by their generation volume over the year) will decline, as shown in Figure 3.4. To reflect this revenue disadvantage for variable renewables, our profitability formulation uses the average expected capture price over the year of decision making as the expected revenue. Technologies that supply more electricity at times of tight supply and high demand receive a higher price.

VARIABLE RENEWABLES

Solar and wind will dominate power systems in most regions within a few decades. From 2018 to 2050, solar PV capacity will grow 21-fold reaching 10 TW just before 2050, whilst installed wind capacity will increase ten-fold to 4.9 TW for onshore, 1 TW for fixed offshore and 255 GW for floating offshore wind. With improved technologies in solar tracking, bifacial solar panels, larger and taller wind turbines, and with investments in locations with better insolation and wind characteristics becoming financially feasible, the worldwide annual electricity output per unit capacity (capacity factor) will rise. According to our best estimate, solar and wind will provide 46% of the world's electricity in 2040 and 62% in 2050.

FIGURE 3.4

Price distribution over operating hours by technology in Europe

Units: Price relative to year average

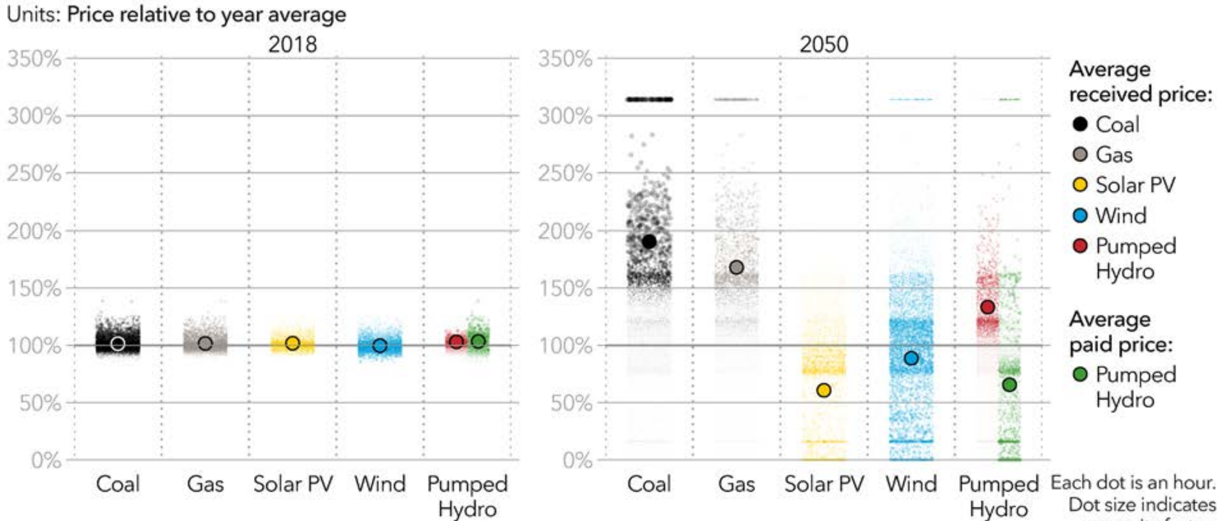


Figure 3.5 shows the progress in renewable energy generation. Solar PV and wind capacity additions in every decade will consistently exceed the previous decade until mid-century. The pace of expansion will be highest for both fixed and floating offshore wind, especially after 2030.

Sections 3.4 and 3.5 give more details on solar PV and wind developments through to 2050.

CONVENTIONAL POWER GENERATION

High renewables penetration will impact the operations of conventional thermal plants. On the one hand, their operating hours decline since they cannot compete with zero-variable-cost solar and wind when there is enough sunshine and wind. On the other hand, as Figure 3.4 shows, the average price received by these technologies increases, because they operate only when solar and wind are unavailable and insufficient to meet demand, which are the hours with a high electricity price. So, over time, thermal generation technologies will transition to become complementary to renewables, rather than providing the base load.

Although we assume a flat trajectory for coal prices, the added cost of carbon (directly or through CCS), along with fierce competition from gas and renewables, will see coal lose its competitiveness in many parts of the world. As Figure 3.6 shows, coal-fired capacity additions until 2030 will be slightly lower than retirements, just enough to keep the capacity flat until around 2030. But rapid retirements afterwards will drop the installed capacity to almost half of present capacity by 2050. The decline in actual generated electricity from coal is even more dramatic. From 2018 to 2050, the electricity output of coal-fired power stations will fall by 75%, implying that the average capacity factor will be halved. Our sensitivity tests show that the decline of coal-fired generation could be delayed by a few years, until the 2030s, should the carbon price be halved or should electrification in transport occur faster, with no additional incentives for renewables. But the long-term impact is not affected significantly.

With relatively low-carbon emissions, higher flexibility to complement variable renewables, and stable prices, natural gas will stay competitive in

FIGURE 3.5

Progress of variable renewable electricity generation by decade

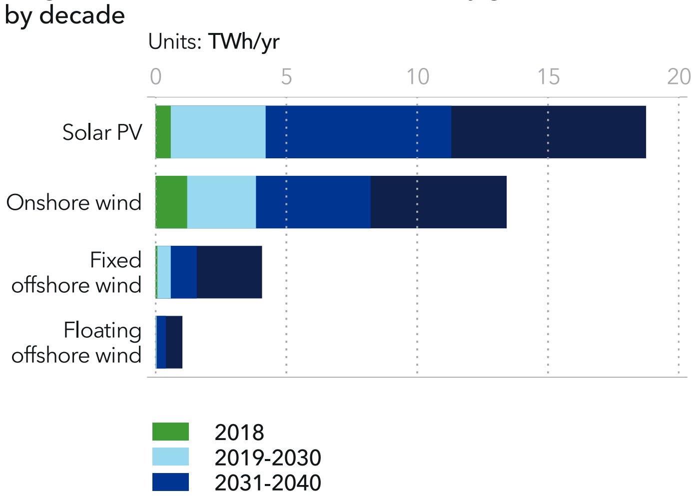
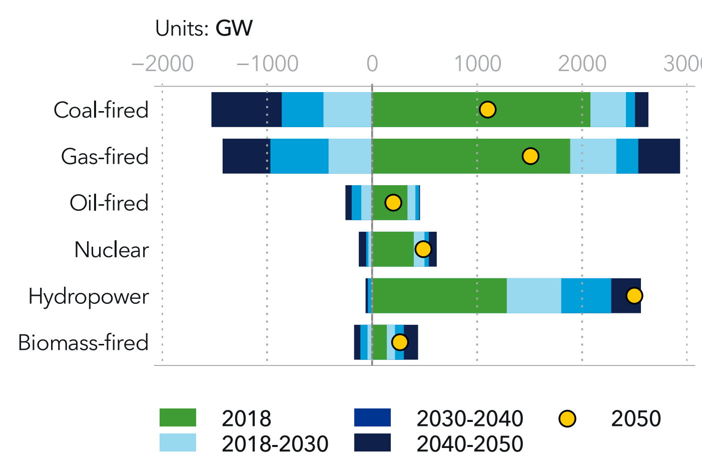


FIGURE 3.6

Change in global conventional capacity by decade



Historical data: GlobalData (2020), Platts (2018) the power sector. Although the installed capacity of gas-fired power stations will decline 20% by 2050 as old capacity is retired, their electricity output will increase by 12%, meaning that the average capacity factor of gas-fired power stations increases (more running hours) from 38% in 2018 to 53% in 2050. Gas-fired power generation is most sensitive to gas prices. 50% higher gas prices would reduce 2050 gas-fired power generation by 33% from our best estimate of 7.1 PWh/yr, cutting its share in the world electricity mix from 12% to 8%. A similar reduction in price would increase the share to 19% at the expense of renewables.

> "At least 9% of annual power-sector carbon emissions will be captured and stored by 2050

We see CCS starting to play a role in the future generation of electricity in the 2030s, then increasing rapidly during the 2040s to the point where approximately 9% of power-sector carbon emissions will be captured by 2050.

Nuclear power capacity will show a small but steady increase until the early 2030s, with new capacity additions largely in Greater China and the Indian Subcontinent. However, nuclear is expensive, and, as older plants in Europe and North America are decommissioned, global electricity generation from nuclear power stations will reduce to below current levels by 2050. In relative terms, nuclear more than halves its share from 10% in 2018 to 4.5% in 2050. The future of nuclear through to 2050 relies mostly on whether the lifetimes of existing power stations are extended through further investment. With the expectation that extensions are relatively likely, we assume a lifetime of 75 years in our base forecast. This is longer than the period regarded as the technical lifetime, so if countries choose not to invest in life-extension measures the decline will be steeper.

With the advantage of having no emissions and providing a reliable supply, we forecast hydropower to grow by 86% until 2050. However, growth in hydropower will be limited by resource constraints, reducing its share in the global electricity mix from 16% in 2018 to 14% in mid-century. The use of waste and biomass for power production will grow, but at a lower rate than it has been.

FLEXIBILITY AND ENERGY STORAGE

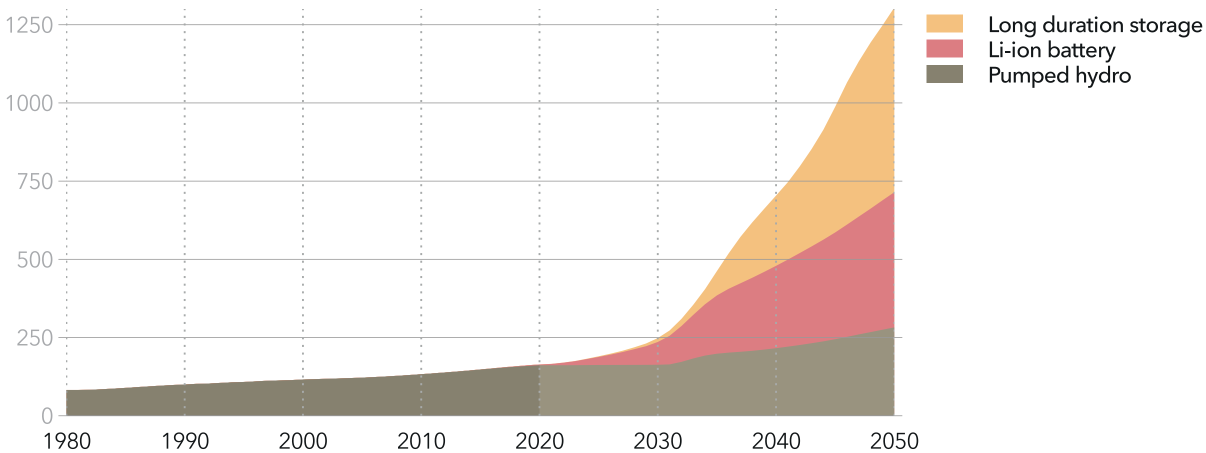
Unlike other energy carriers that can be cheaply stored for prolonged periods, the supply of, and demand for, electricity over the grid must always be balanced. Historically, variability and uncertainty in the power systems were due to changing demand patterns and to failures. To ensure continued reliable electricity provision to consumers, several mechanisms have conventionally been relied upon. They include spinning reserves to correct any frequency deviations at the second or millisecond level; fast-response generators to meet peak demand that occurs for only a few hours every year; and, demand-side management (DNV GL, 2017).

The most important question around the wide penetration of vRES is whether the power system will have sufficient flexibility to meet electricity demand reliably. Balance and stability will be key issues. In a future with high shares of solar and wind, several sources will provide flexibility to the power system. On the supply side, oil- and gas-fired power stations with quick ramp-up / ramp-down rates are already used to match the demand on slightly longer time scales. With the value of flexibility increasing, many other conventional generation technologies are seeking ways to accelerate their ramp rates and reduce their start times. Energy-storage technologies are also increasingly used to allow power generation to be decoupled from power demand in time. On the demand side, some consumers use price signals to shift their load from times with tight supply to periods with abundant and cheap electricity, and

FIGURE 3.7

World utility-scale storage capacity

Units: GW

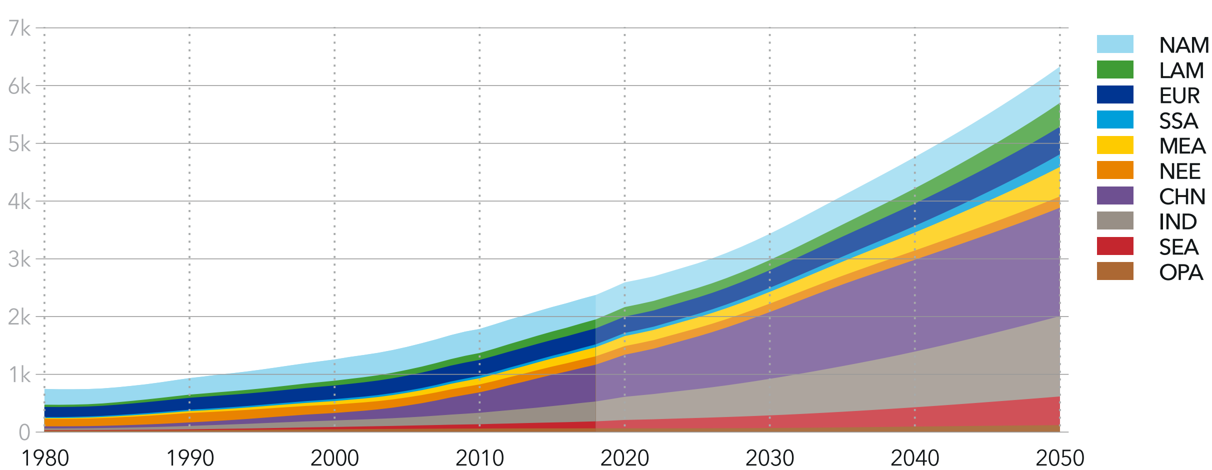


Historical data source: GlobalData (2020), US DOE (2020)

FIGURE 3.8

Power grid capacity by region

Units: TW-km



Historical data source: NRGExpert (2013), Eurelectric (2017), EIA (2013), national sources new technologies and market mechanisms will allow more consumers to provide flexibility in the form of demand response. Converting cheap electricity from vRES to other energy carriers, such as hydrogen, is yet another option providing flexibility.

Storage in today's power system is mostly in the form of pumped hydro. Differences between the received and paid prices for pumped-hydro storage in Figure 3.4 show that increased solar and wind, with a higher chance of mismatch between supply and demand at different times, will create a price arbitrage opportunity. By modelling the storage investments based on profitability from price arbitrage, we forecast a widespread expansion of battery storage. Li-ion batteries will be the first to experience a quick uptake. After the second half of the 2030s, other long-duration storage solutions will enter the market. EVs will also play a central role in flexibility. For one thing, the rapid decline of Li-ion batteries is mainly driven by the EV market. Following past trends, we expect battery prices to decline at a rate of 19% for every doubling of cumulative capacity-additions. In addition, we expect EV charging systems that can feed in to the grid to lead to 10% of all EV storage capacity becoming available to provide grid flexibility at any time.

ELECTRICITY GRIDS

Three factors drive grid investments: greater electricity demand; requirements for new connections for power stations distant from the grid; and, the need to reinforce transmission and distribution systems due to expansion of vRES. We distinguish between different types of grids, including line type (overhead, underground, and underwater), five classes of voltage transmitted through them, and whether the associated current is AC or DC.

The extent of grid expansion will vary between regions (Figure 3.8). Measured in terawatt-kilometres (TW–km), Greater China, the Indian Subcontinent, South East Asia and Middle East and North Africa will experience the largest growth in grid capacity. In 2050, 31% of world's electricity grids will be in Greater China, followed by the Indian Subcontinent with 26%. The share of underground cables in world grids will continue to increase. As long-distance connections become more important, 12% of grid capacity by 2050 will be covered by ultra-high voltage (power lines operating above 800 kV) DC lines. This Outlook's companion publication on Power & Renewables (DNV GL, 2020a) provides further insights on power grids.

> “The most important question around the wide penetration of vRES is whether the power system will have sufficient flexibility to meet electricity demand reliably

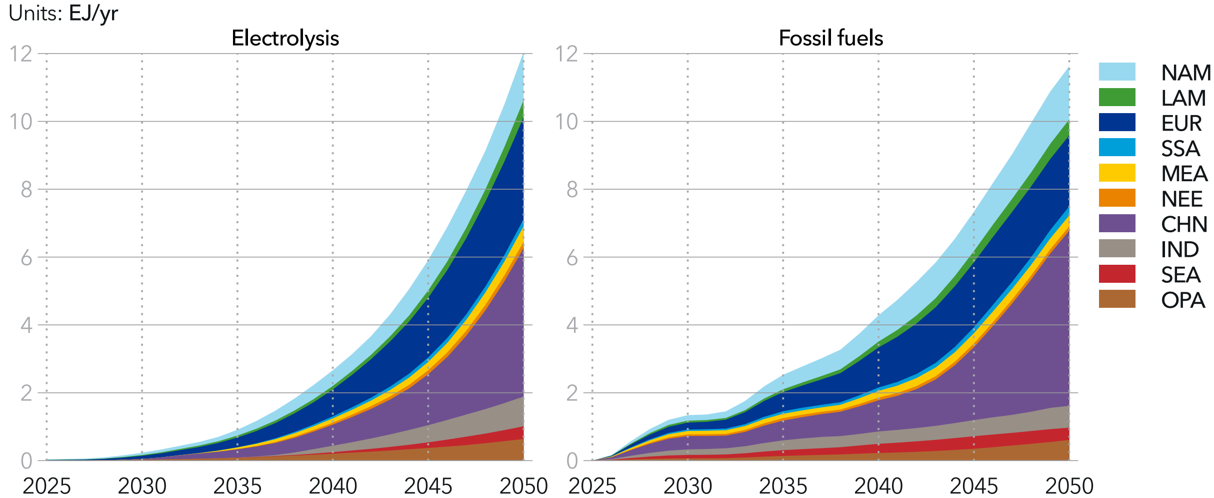
3.2 HYDROGEN

Hydrogen is the simplest element and emits only water when consumed for energy production. This is hydrogen's main strong point. Conversely, only water and energy are needed to produce hydrogen as it does not occur naturally as a gas on earth. Its weakness is that its production using an electrical current requires costly electrolysis equipment and generates substantial energy losses. The main alternative production method via steam methane reforming (SMR), where hydrogen is derived from hydrocarbons has lower overall costs due to low fossil-fuel prices. However, with an increasing carbon price on CO_2 emissions and ongoing process improvement for electrolysis-based hydrogen, this gap is going to decrease. To lower overall process emissions, SMR based on fossil fuels can be combined with CCS technologies. A third route to hydrogen production is based on gasification of coal and biomass. Thus, for energy applications, we see hydrogen as an energy carrier being favourably compared with electricity when hydrogen's cost advantages associated with distribution, handling, and storage are higher than cost disadvantages associated with its production. In contrast to last year's Outlook, we now factor in learning rates for the aforementioned hydrogen production pathways. In a further enhancement of our analysis this year, distribution costs are also considered. For our forecast, two of the competing low- and/or zero-carbon fuel technologies for producing hydrogen are considered – SMR with CCS, and electrolysis. Hydrogen production via the gasification pathway is planned to be integrated into the ETO model next year.

FIGURE 3.9

World hydrogen production from electrolysis and fossil fuels by region

Units: EJ/yr

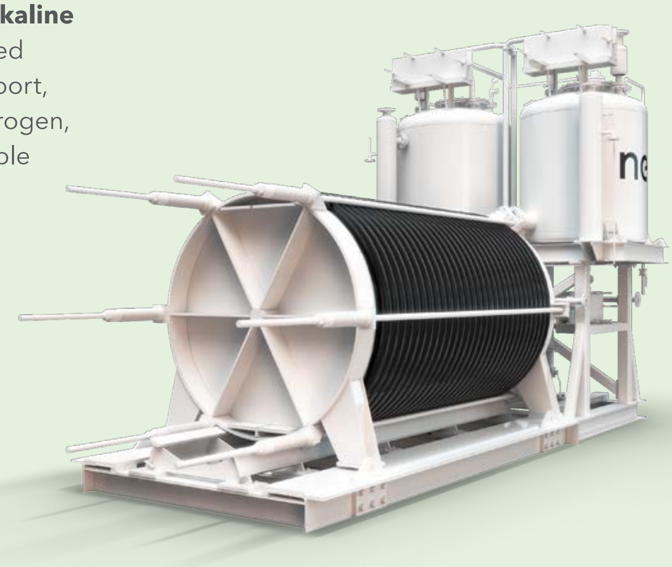


Only includes hydrogen as energy carrier.

Hydrogen production through electrolysis is seen as one of many flexibility options to take advantage of low power prices when production from vRES is plentiful and demand is lacking. This will increasingly be the case. However, there are many takers for such cheap electricity: demand response, pumped hydro, battery-electric vehicles (storage), utility-scale batteries. Consequently, surplus renewable electricity is not expected to be available for significant periods. In fact, it is beneficial for the energy transition that the power price remains at a reasonable level, which is partly associated with the amount of surplus electricity and its demand, otherwise it would cannibalize the profitability of vRES. We forecast that, after 2035, abundant vRES will result in increasing shares of electrolysis-based hydrogen production, as shown in Figure 3.9. Electrolysis-based production will differ significantly by region. A combination of high demand, wide vRES penetration, and decarbonization policies will enable Greater China and Europe together to host 60% of global electrolysis. For example, the European Commission recently unveiled plans to promote renewable hydrogen investments by up to USD 530bn (EUR 470bn) to mid-century (Reuters, 2020). VRES penetration and decarbonization policies will play a crucial part and are incorporated in this analysis with further information detailed in Chapters 3 and 5 respectively. Associated policies in the transport, power and manufacturing sectors will support hydrogen uptake. Regarding transport, CAPEX support is now available for fuel-cell passenger and commercial vehicles in all regions. Considering the total available funding and support for hydrogen uptake, OECD Pacific and Europe stand out. The European Union is even expected to increase its already relatively high budget with the upcoming implementation of the European Green Deal. In power and manufacturing the situation is different. Only a handful of countries offer direct support for hydrogen use in these sectors. This shows that the current policy focus is clearly on hydrogen use in transportation, alongside research, innovation and pilot projects.

The main purpose of using hydrogen in buildings will be to replace natural gas as a fuel for space heating, water heating, and cooking. Until the end of our forecast period, hydrogen use in buildings

Nel Hydrogen's A150 Atmospheric Alkaline Electrolyser. Water electrolysers are used to produce hydrogen for industry, transport, and power-to-x applications. Green hydrogen, produced using electricity from renewable sources, plays an important role in the energy transition. (Image courtesy NEL.)



will be limited. We assume that hydrogen distribution can be achieved by retrofitting current gas grids at minimum cost. Distribution cannot only be by blending natural gas and hydrogen, with up to about 20% hydrogen, in a mixture that can be burned just like natural gas. It will also involve piping pure hydrogen through the network. Only the latter technology will require an additional total upgrade of appliances. In Europe, North America, OECD Pacific and in Greater China, current and planned gas grids are substantial and will easily accommodate the piping of hydrogen. In line with higher carbon prices, hydrogen will be used in the most suitable regions. Nevertheless, hydrogen for heating will represent only 1.3% of energy use in the buildings sector globally, almost equal to coal's 2% share. Regionally, hydrogen will represent about 6% of energy use in the buildings sector in Europe by mid-century, which is the highest regional share, with natural gas still representing a quarter of energy use. In Greater China, hydrogen use in buildings is as low as the global average, whereas natural gas still represents almost 20% of the sector's energy use.

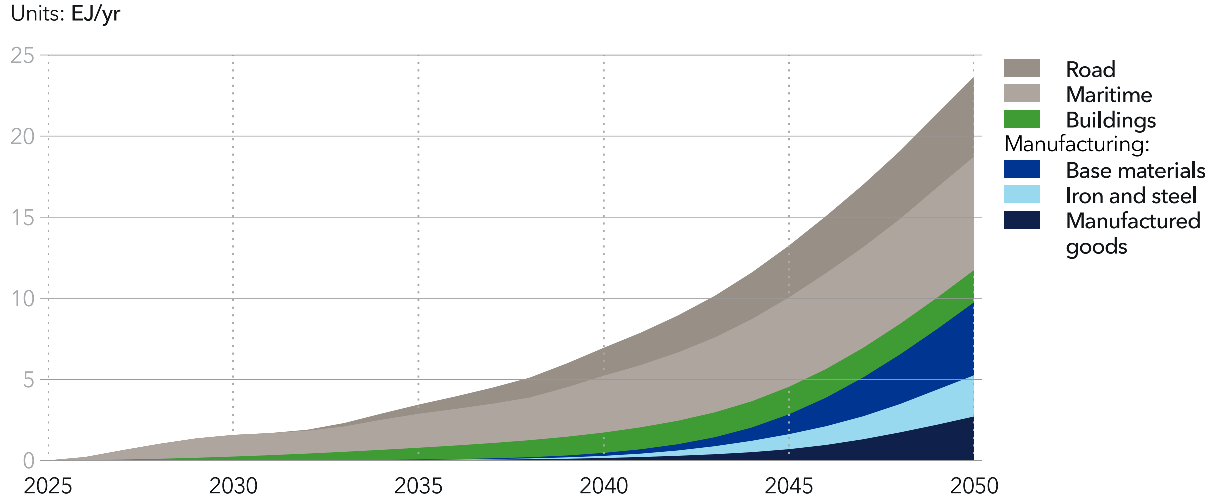
Similarly, we see hydrogen as a potential low- and/or zero-emission energy carrier for heat applications in manufacturing. To compete on cost, this would require carbon prices higher than those envisaged (being USD 80/tCO_2 in 2050 in Europe and USD 60/tCO_2 in Greater China). Still, few installations are expected to emerge before 2050, and these will use about 8% of global hydrogen by then.

In road transport, hydrogen can serve as an energy-storage medium, competing with battery storage in zero-emissions usage. In particular, long-haul, heavy road transport that cannot rely as easily as passenger vehicles on batteries for main energy storage, will turn to fuel-cell solutions, despite these being only half as energy efficient, more complex, and costly. Although this amounts to only 7% of road-transport energy use worldwide, it is more than double the share of biofuels in 2050. Regional fractions vary between 30% in Europe and less than 1% in North East Eurasia and Middle East and North Africa.

FIGURE 3.10

World hydrogen demand by sector

Units: EJ/yr



Only includes hydrogen as energy carrier. Maritime sythetic fuels are counted as hydogen.

In maritime transport, the story is different. As we discuss more thoroughly in chapter 5 and in our Maritime companion report (DNV GL, 2020c), there is no significant battery-electric option for decarbonization, as synthetic fuels, ammonia and hydrogen are the main low- and/or zero-carbon fuel options available. Also implemented in hybrid configurations with diesel and gas-fuelled propulsion, we see these high-cost fuels having significant uptake and providing slightly more than 60% of the maritime fuel mix by 2050, most of which will be synthetic fuels. Note that synthetic fuels are not a separate category in this Outlook, which classifies them under hydrogen because their production shares many similarities. In conclusion, Figure 3.10 shows 41% of global hydrogen demand in 2050 is for manufacturing, 30% for ships, almost 21% for heavy long-range road transport, and 8% for buildings. The significant deviation from last year's results regarding use patterns can be explained by updated policies, figures and trends on the enabling of hydrogen production and utilization in all regions and sectors.

In our analysis, we have tested the sensitivity of global hydrogen demand to 40 different uncertainties, ranging from learning rates, to EV subsidies, to carbon and gas prices. We have chosen to highlight insensitivities to SMR and electrolysis learning rates, (increase and decrease by 50% from base) and carbon price (ranging from 50% to 300% from base), along with the effects of gas prices (increase and decrease by 50% from base). Table 3.1 shows the results.

The carbon price is highly significant for hydrogen uptake. The main effect can be observed in the manufacturing and transport sectors, where policies are tied to carbon prices. Consequently, for higher carbon prices, the assumption is that there is also a stronger decarbonization push favouring hydrogen (see Chapter 5 for more detailed information). As a result, hydrogen use will almost double for a 400% increase in carbon price. Interestingly, variation of natural gas prices will cause only slight variation of hydrogen uptake, in the order of 10%.

In contrast, our analysis indicates that hydrogen uptake is insensitive to SMR and electrolysis learning rates – at least within the boundaries that we have tested. The hydrogen production pathway split between electrolysis and fossil is sensitive to changes in carbon and natural gas prices, but not to SMR and electrolysis learning rates. The share of electrolysis in hydrogen production keeps growing until the carbon price reaches double the level assumed in the base case. Beyond such a doubling, the share of electrolysis declines, though the absolute amount of electrolytically produced hydrogen remains stable at about 24 EJ in energy terms.

TABLE 3.1
Hydrogen demand sensitivities

2050 level values		Parameter uncertainly tested									
		Carbon price				Gas price		SMR learing rate		Electrolysis learning rate	
Sensitivity range	Base	-50%	+50%	+100%	+300%	-50%	+50%	-50%	+50%	-50%	+50%
Hydrogen demand (EJ/yr)	24	13	32	34	43	20	22	24	24	24	24
Share in hydrogen production Electrolysis/SMR(%)	51/49	59/41	62/38	69/31	57/43	58/42	50/50	51/49	51/49	51/49	50/50

3.3 DIRECT HEAT

We define direct heat as the thermal energy produced by power stations for selling to a third party, e.g. district heating, or by industries for their own activities. In practice, such heat is always delivered as hot water or steam. Manufacturing currently uses 42% of direct heat globally, followed by 36% for space heating in residential, commercial and public buildings, and 7% for water heating (Figure 3.11). The historical anomalies seen in this figure are due to switches between fuels and sectors reported in the energy accounts, especially around the time of the disintegration of the Soviet Union.

The Russian Federation alone accounts for 37% of global direct heat demand; North East Eurasia as a whole, 45%; China, 33%; and, Europe 17%, led by Germany.

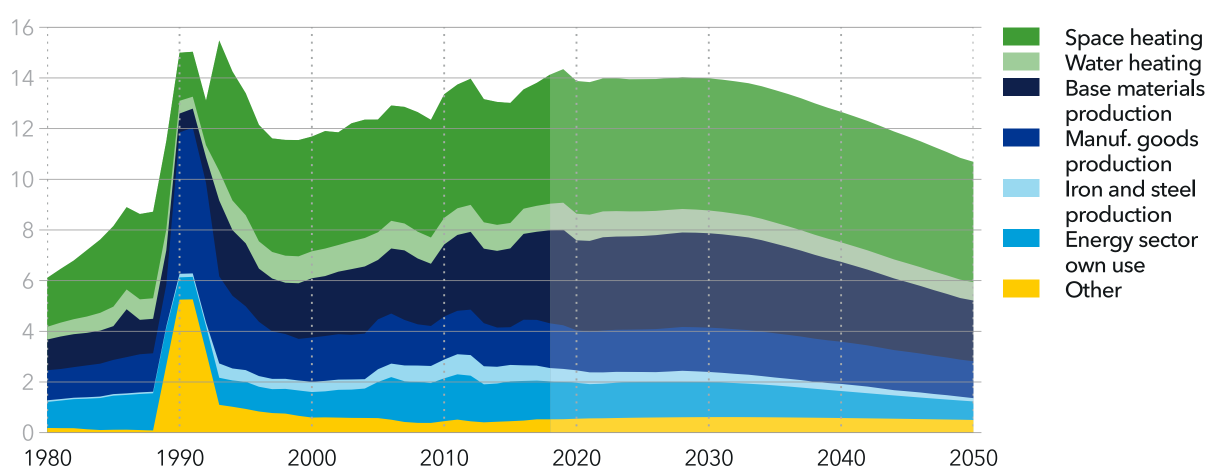
In 2018, coal and gas provided 43% and 46% respectively of global direct heat supply. More than two thirds of this came from CHP plants. As thermal power loses ground to renewables for power supply, and as use of direct heat in manufacturing declines, direct heat demand will fall from 14 EJ/yr in 2018 to 11 EJ/yr in 2050.

By 2030, coal will be replaced by biomass-fired technologies that mostly use municipal and industrial waste as fuel, bringing the share of coal in direct heat demand down to 37%. In 2050, biomass will provide 25% of direct heat, while coal's share will shrink to 10%. Simultaneously, the share of natural gas will increase to 71%. Except for the expansion in China's share, the geographical breakdown will not change significantly.

FIGURE 3.11

World direct heat demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2019)

HYDROGEN IN THE ENERGY SYSTEM

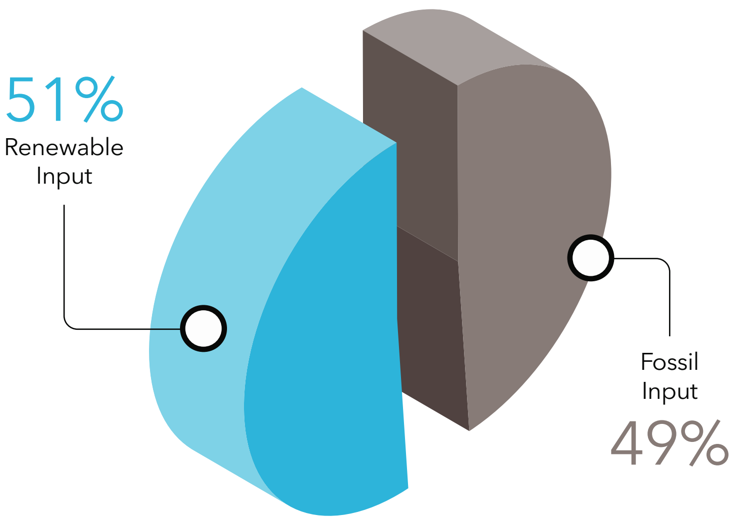
AN ENERGY CARRIER

By the end of the forecast period, we expect renewable sources to account for slightly more than 50% of hydrogen used as an energy carrier. Today, about 95% of the hydrogen produced globally (for all purposes, not only as energy carrier) is from fossil fuels. In contrast, production of hydrogen as an energy carrier will initially come from renewable sources and will later be supplemented by hydrogen from fossil sources.

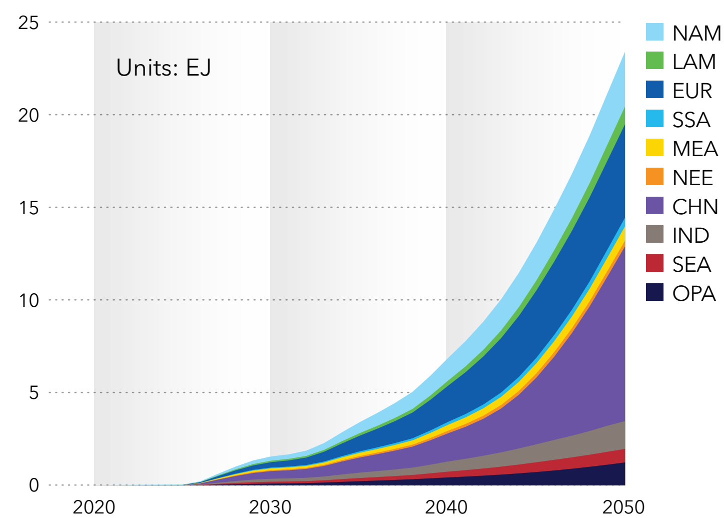
REGIONAL PRODUCTION

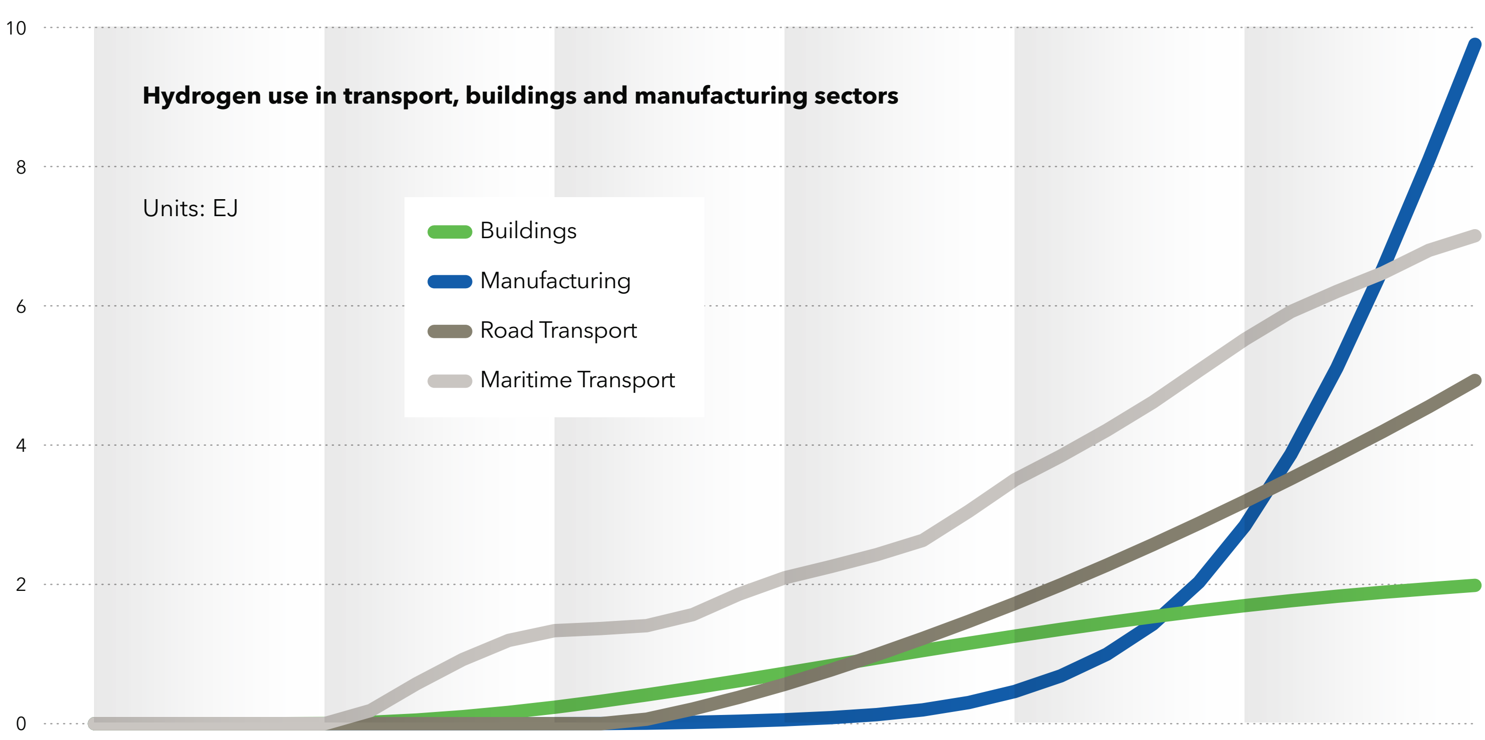
In our forecast period, hydrogen production is dominated by Europe, North America and Greater China, with the latter holding a 40% share of global hydrogen production by 2050. Our forecast indicates a total production of more than 23 EJ per year by 2050. Hydrogen is mainly expected to be used in the transport sector (both maritime and road transport) and in the manufacturing sector. Hydrogen in the building sector will represent a minor share of less than 10% of global use.

Hydrogen production split in 2050



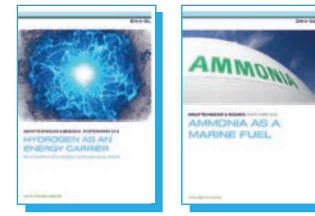
Regional production of hydrogen

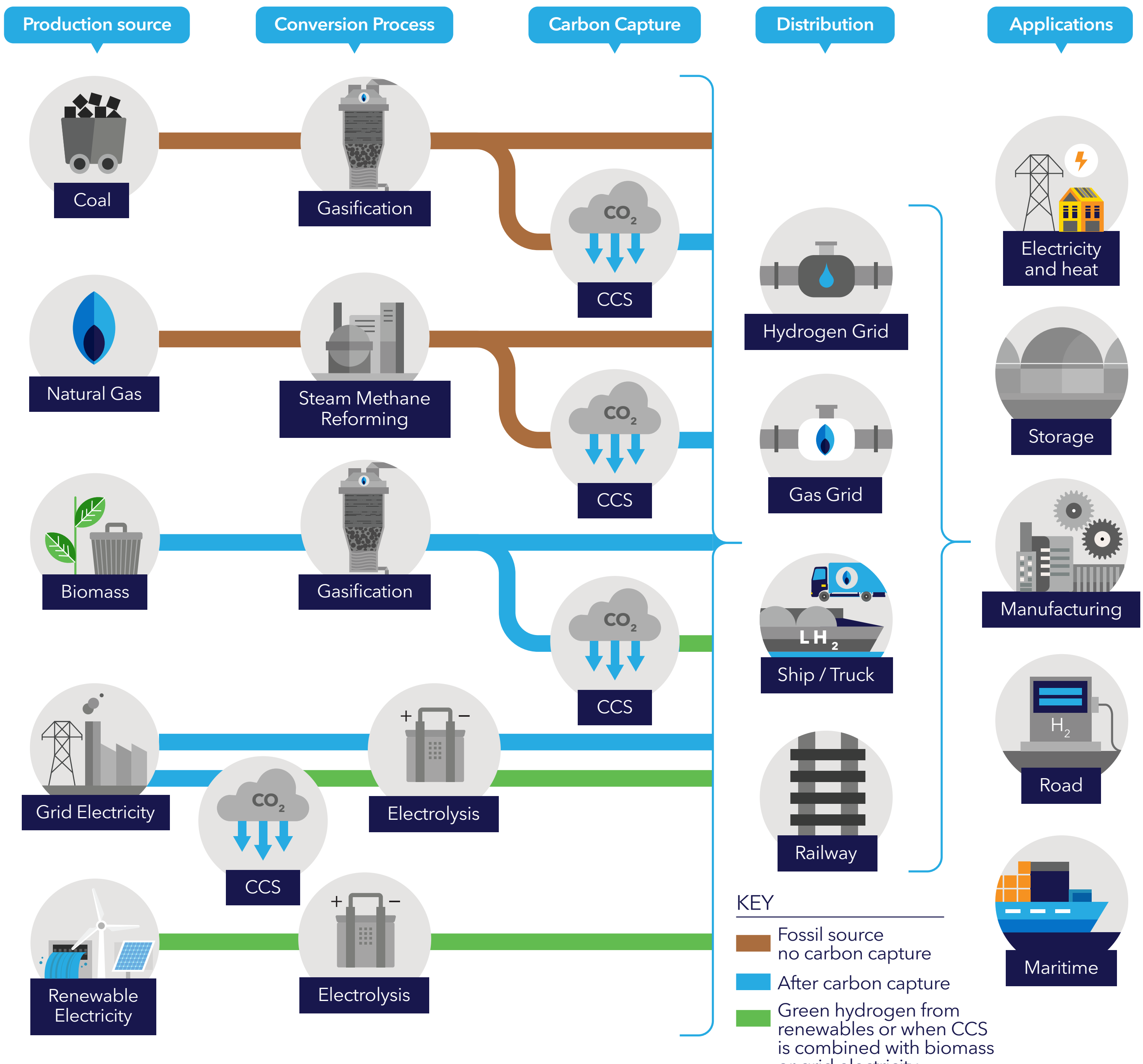




A CHANGING ROLE

Today about 3% of global energy consumption is used to produce hydrogen, for use in oil refining, but mainly to produce ammonia predominantly for the fertilizer industry. Ammonia could, however, become an important marine fuel in the coming decades, as discussed in a recent white paper by DNV GL (*Ammonia as a Marine Fuel*, 2020). Today, only 0.002% of hydrogen is used as an energy carrier – i.e. as a fuel to be converted into other forms of energy to drive physical or chemical processes. (See also DNV GL's research paper, *Hydrogen as an energy carrier,* 2018.) We expect that this will change significantly, with hydrogen reaching an almost 6% share in global final energy demand by 2050. Produced from decarbonized or renewable sources, green hydrogen will become an important energy carrier supporting global emission reduction actions.





3.4 SOLAR PV

Solar PV may be scaled from the smallest rooftop installations to big, utility-scale farms that tend to be located on remote, unproductive land. Smaller installations cannot compete with utility-scale facilities (DNV GL, 2019e) on energy cost, but their advantages of flexibility and security of supply will enable rooftop and micro-grid-sized installations to grow significantly in absolute terms, though their market share will decline.

The main driver for growth is our assumed unit investment cost-learning rate (per capacity doubling) of 28% for the next five years, falling to 18% over the following 20 years. However, the OPEX-learning rate of 9% is expected to remain unchanged until mid-century.

There are, and will continue to be, a host of flexibility options being developed. These include, but are not limited to: financial forward-purchase flexibility arrangements; hydrogen production through electrolysis; shifting of demand to periods with lower costs (e.g. using home boilers as an energy storage option); various forms of energy storage, such as pumped hydro and other hydropower, EVs and bespoke power batteries, and distributing power through a reinforced power grid.

However, despite its cost advantages and flexibility solutions, there is widening recognition (e.g., IEA, 2018a) that proponents of PV overstate their case when using LCOE as an indicator of PV's competitive position in the power-investor community. In our model, we allow for various generation technologies to receive different power prices. Even when applying these flexibility options, solar PV remains the technology that, due to its variability, receives the lowest average power prices. These lower received prices will vary between regions, influenced both by the regional solar-PV share, the competing power mix, and the affordability of flexibility options.

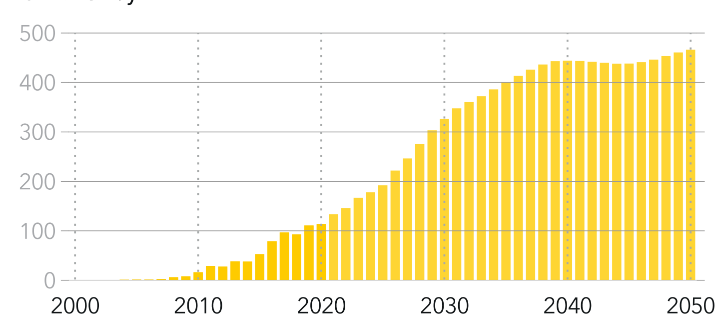
All the same, the lower received prices will not be a showstopper for PV generation in any region. Solar PV generation will grow almost thirty-fold between today and 2050. From being just 2.4% of power generation in 2019, it will supply almost one third of global electricity, 18.7 PWh/yr, by 2050. At that point, solar PV will contribute almost three times the energy supplied by gas-fired generation, or more than both onshore and offshore wind power combined.

PV capacity factors cannot possibly exceed 50%, due to the lack of sun after sunset. Growing through technology improvements, PV capacity factors will improve by almost half from today, reaching 20% in many regions by 2050, still, however, the lowest capacity factor of any

FIGURE 3.12

World solar PV gross capacity additions

Units: GW/yr



Historical data source: IRENA (2020)

power-station type. We see a mixture of approaches, notably lower-cost devices that angle the solar panels better towards the sun, and thereby increase capacity factors. We also foresee bifacial solutions. In nominal terms ,solar PV capacity additions will roughly equal those of all other power-station types combined in the 2040s. This implies that solar capacity additions will grow four-fold from today to 2050, reaching about 470 GW that year, as shown in Figure 3.12.

Figure 3.13 shows installed capacity for all power stations. Compared with its 2018 capacity, solar PV will grow almost 20-fold to reach 10.6 TW/yr in 2050.

As seen in Figure 3.14, regional solar PV capacity is, and will continue to be, dominated by Greater China with its share of global installations staying around 37% for the next 30 years. By 2050, the Indian Subcontinent's share will grow from 7% now to almost 17%. Europe, which had three quarters of global capacity 10 years ago, and 22% today, will have less than 8% in mid-century.

Solar PV has thus far had significant preferential treatment through support to PV manufacturers, developers and consumers encouraged by 'feed-in-tariffs'. Such policy mechanisms will decrease in importance, with subsidy-free solar and market mechanisms increasingly taking over. That said, we predict declining but still significant solar PV capture on the basis of market designs that do not place PV generation at a disadvantage.

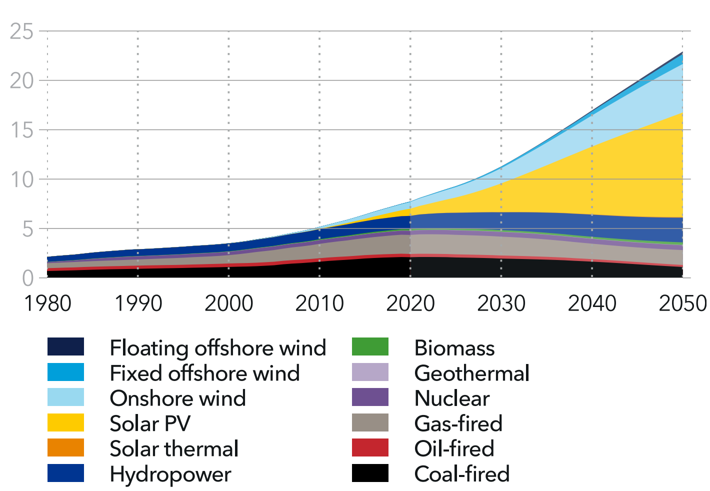
We contend that the stability disadvantages of solar PV for power systems are overstated by some utilities and energy stakeholders. We foresee the continued role of conventional generation, storage and digitalization helping PV; for example, by supporting frequency stabilization once solar PV penetration increases to potentially challenging levels. Shifts in the generation mix, demand, markets and sources of flexibility, will together provide power-system balance and stability.

Because capacity factors will grow at similar rates in all regions, generation dynamics will mimic those of capacity. As an example, Greater China's generation will account for 37% of global generation in 2050. Our Power Supply and Use report (DNV GL, 2020a) contains further details on solar PV, with charts also including a category called

FIGURE 3.13

World power station installed capacity

Units: TW

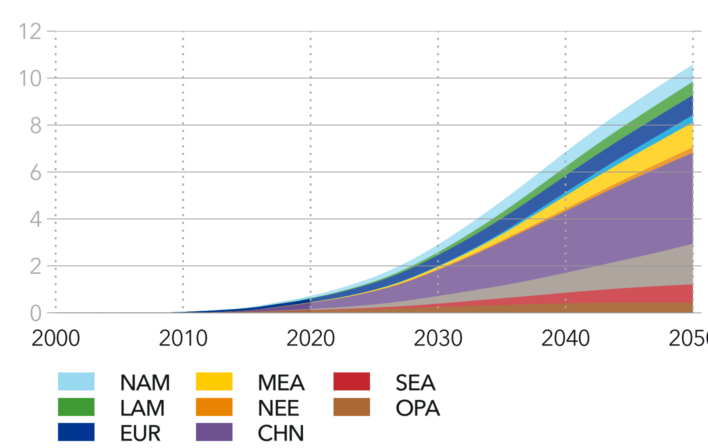


Historical data source: GlobalData (2020), Platts WEPP (2018), IRENA (2020), WNA (2020)

FIGURE 3.14

Installed solar PV capacity by region

Units: TW



Historical data source: IRENA (2020)

'off-grid solar PV', which is applied only to Sub-Saharan Africa and the Indian Subcontinent. Granted, the global energy contribution of off-grid solar PV will be marginal even by 2050. But for the next two decades, inexpensive equipment – solar panels supported by limited battery storage – will provide hundreds of millions of less affluent Africans with access to energy. Such equipment will similarly be critical to the electrification of the road sector in both Sub-Saharan Africa and the Indian Subcontinent, as it allows inexpensive, distributed off-grid EV charging.

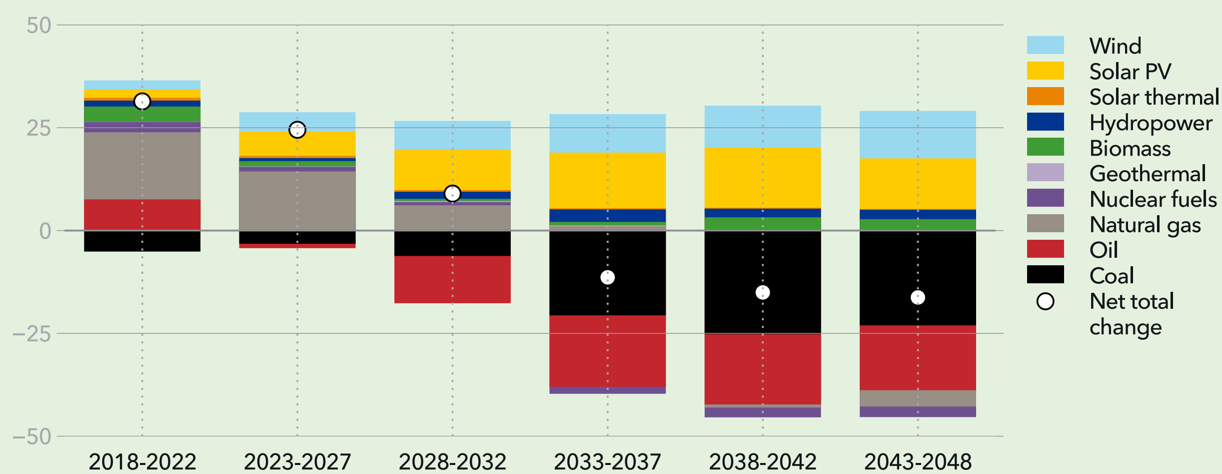
From the sensitivity testing in Table 3.2, we can see that the uptake of solar PV is not significantly affected by electricity or gas prices. Carbon prices do affect PV uptake; but interestingly, the effect plateaus after doubling of carbon prices. As described in sections on the use of natural gas, hydropower, and biomass, combustion fuels compete with each other and hydropower; and our analysis shows that solar PV competes mainly with wind power, and is therefore most sensitive to the assumptions on wind and PV cost-learning rates.

RISE OF RENEWABLES

Today, we are adding net energy to the system each year, meaning that energy demand is still growing. This trend is about to change and by the 2030's we reach a peak in primary energy demand and start using less energy each year indicated by the white dot 'Net total change'. In addition, historically and up to today, most of the energy added to the system has been fossil fuel based. By 2030 this picture completely reverses and from there on all growth in the energy system will be based on renewable energy.

Net change in primary energy supply by source

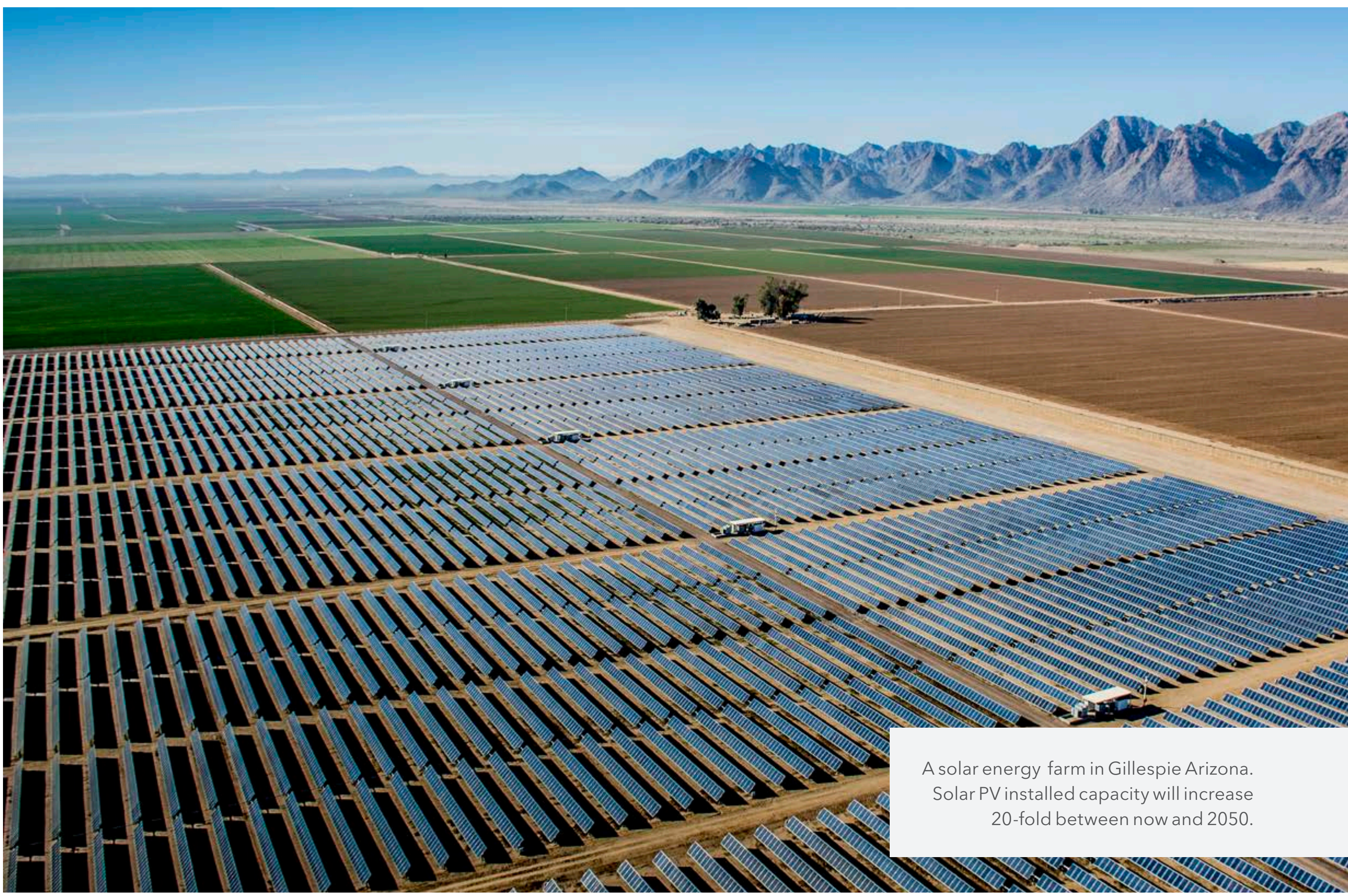
Units: EJ/yr



5-yr average primary energy supply subtracted from the previous 5-yr average. Historical data source: IEA WEB (2019)

TABLE 3.2
Solar PV sensitivities

2050 level values		Parameter uncertainly tested											
		Electricity price		Gas price		Carbon price				PV learning rate		Wind learning rate	
Sensitivity range	Base	-50 %	+50%	-50 %	+50%	-50 %	+50%	+100%	+300%	-50 %	+50%	-50 %	+50%
Solar PV generation (PWh/yr)	18.8	18.9	18.6	18.2	18.5	18.1	19.7	20.2	20.2	17.3	20.0	20.0	16.8



A solar energy farm in Gillespie Arizona. Solar PV installed capacity will increase 20-fold between now and 2050.

3.5 WIND

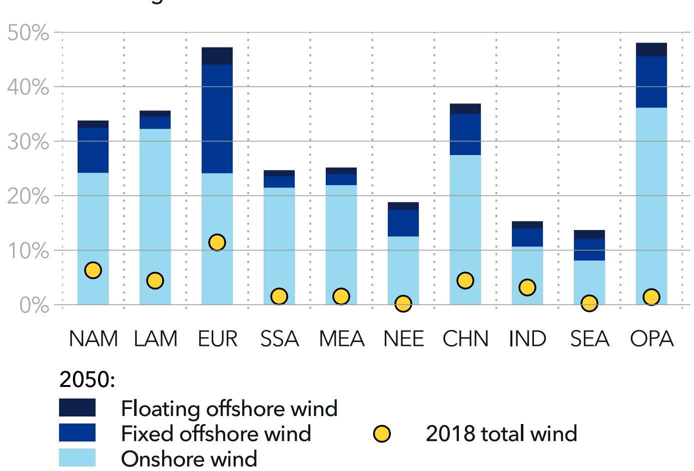
Wind power provided 4.7% of the world's electricity output in 2018. In some regions, like Europe and North America, its share was as high as 11.4% and 6.3% respectively (Figure 3.15). This uptake has been driven by financially supportive policies and growing awareness of the impact of conventional energy sources on the environment and climate. We foresee onshore wind being more cautiously supported in the future in some developed countries where the industry has reached a high maturity level, and where conflicts on wind-turbine location are looming. For offshore wind, we expect strengthened support in countries with limited land areas, bypassing community opposition.

We foresee electricity generation from wind increasing from 1,280 TWh/yr in 2017 to 18,500 TWh/yr in 2050, with Greater China, Europe and North America providing the largest output. After 2030, regions like OECD Pacific, and the Middle East and North Africa, will also see significant growth. By 2050, wind will provide more than 40% of electricity in OECD Pacific and Europe, and more than 30% of electricity in Greater China, Latin America and North America (Figure 3.15). The share of offshore wind in the total wind electricity generation will increase steadily, rising globally from 5.5% in 2018 to 28% in 2050, a fifth of which is floating offshore. In terms of the percentage of regional electricity demand supplied from fixed and floating offshore wind, Europe will remain in the leading position throughout the forecast period.

FIGURE 3.15

Share of wind in electricity generation by region

Units: Percentages



Historical data source: IEA WEB (2019)

In 2018, a 1 MW onshore wind turbine generated on average 2.1 GWh/yr of electricity. In other words, the average utilization, or capacity factor, of all onshore wind turbines in the world was 24%. As wind capacity expands, new wind regimes will be exploited. Although some farms may have lower average wind speeds, new turbine types will allow better performance under varying wind conditions. Such developments along with continued increases in turbine, blade, and tower sizes, will lead to improvements in the capacity factors, bringing the world average for onshore wind turbines to 31% by 2050. For offshore wind turbines, the average capacity factor is already 34%, due to the more favourable wind conditions offshore. We expect this to rise to 51% by 2050.

Figure 3.16 shows where the cost savings will come from. Since onshore wind is the most mature segment, its cost reduction will be limited to 31% over the period 2020 to 2050. The largest reduction in the average LCOE from onshore wind will come from increasing capacity factors and from cheaper turbines. As onshore wind projects move to less favourable locations and to regions with higher costs, there will be a slight increase in the 'other fixed cost' component, which is composed of non-turbine material costs, as well as labour, overhead and tax costs. But its impact will be limited. The reductions in the levelized costs for fixed and floating offshore wind will be 56% and 69% respectively. The majority of their cost savings will be from 'other fixed cost' and operating and maintenance (O&M) cost, as experience of installing and operating offshore wind turbines builds up.

Global wind capacity has been growing steadily since the early installations in the 1980s. Installed capacity reached 729 GW in the beginning of 2020. We forecast 1 TW in 2023, 2 TW in 2031, 4 TW in 2041, and 6.2 TW in 2050, of which 1.3 TW will be offshore (Table 3.3). These developments are thanks to larger turbines, mega-sized projects, and a more dedicated offshore supply-chain. In addition, the 2020s will see floating wind progress to full-scale demonstration projects and on to commercial-scale deployments. We predict that floating offshore wind projects will have 255 GW of installed capacity by 2050.

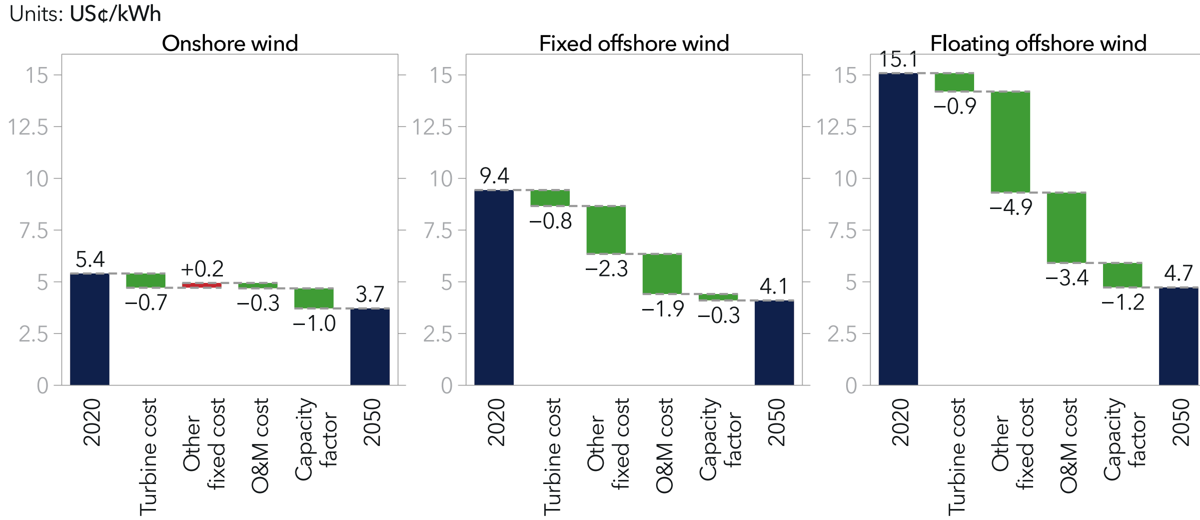
Global wind capacity additions will increase from 64 GW/yr in 2019 towards 370 GW/yr in mid-century, with a brief stagnation period in the early 2020s due to COVID-19. Starting from the mid-2020s, some of the capacity additions will be due to the replacement of early capacity installations that have completed their lifetimes. In the ETOM, we use 23, 28 and 25 years for the lifetime of onshore, fixed offshore and floating offshore wind turbines respectively. Because wind technology is still in its early stages, it is not clear when existing capacity will complete its technical life, nor what will happen afterwards. However, it is likely that wind farms that complete their lifetimes will be repowered with new wind turbines that reflect state-of-the-art technology. This is already happening, with some existing wind farms being repowered even before the end of their technical lifetimes to take advantage of favourable financial conditions.

From Table 3.4, we see that the global primary energy supply from wind is sensitive to many parameters. Although a 50% decline in gas price results in a 10% decline in wind output, a symmetrical

FIGURE 3.16

Drivers of change for the global average levelized cost of wind between 2020 and 2050

Units: US¢/kWh



The share of offshore wind in the total wind electricity generation will increase steadily, rising globally from 5.5% in 2018 to 28% in 2050 gradual increase in gas price does not stimulate further replacements of gas with wind. Halving the carbon price reduces wind output by 5% in 2050, while increasing the carbon price by 50% increases wind output by 5% by mid-century.

The learning rate applied to the decline in wind costs also alters the results. Based on historical trajectories, our best estimate for the learning rate for wind turbines is 16% for every doubling of cumulative additions. We foresee 8% and 30% learning rates for O&M costs of onshore and offshore wind farms respectively. For 'other fixed costs', we project learning rates of 1% for onshore wind, 18% for fixed offshore, and 11% for floating offshore. Raising these learning rates by 50% raises wind output by 11%, while halving the rates reduces output by around 11%. Similar changes in solar PV-learning rates work against wind, indicating significant competition between solar and wind.

TABLE 3.3
Installed wind capacity by region
Units: GW

	2020			2030			2050		
Region	Onshore	Bottom-fixed offshore	Floating offshore	Onshore	Bottom-fixed offshore	Floating offshore	Onshore	Bottom-fixed offshore	Floating offshore
NAM	136	1	0	246	18	1	432	139	21
LAM	35	0	0	88	5	0	371	23	11
EUR	189	25	0	311	54	5	411	240	39
SSA	4	0	0	18	2	0	142	11	6
MEA	14	0	0	46	5	0	358	29	17
NEE	3	0	0	13	5	0	75	26	7
CHN	248	11	0	645	48	3	2 265	355	87
IND	43	0	0	89	8	0	435	83	32
SEA	3	0	0	9	5	1	177	49	19
OPA	15	1	0	80	8	2	248	58	15
World	**690**	**39**	**0**	**1 546**	**159**	**14**	**4 914**	**1 014**	**255**

TABLE 3.4
Wind sensitivities

		Parameter uncertainly tested							
		Natural gas price 50% change		**Carbon price** 50% change		**Solar PV learning rate** 50% change		**Wind learning rate** 50% change	
	Base	**Low**	**Hi**	**Low**	**Hi**	**Low**	**Hi**	**Low**	**Hi**
Wind generation (PWh/yr)	17.5	15.7	18.3	16.7	18.4	18.6	16.4	15.7	19.4

3.6 HYDROPOWER

Hydropower is at a policy crossroads, as planning permission for large dams must be balanced with protection of biodiversity and the livelihoods of residential communities. Although we expect broader environmental concerns to gain primacy in the hydropower debate, we believe that many countries will still want to exploit this formidable source of reliable, renewable power.

In many places, vRES will compete strongly against hydropower, lowering average electricity prices and creating harsh conditions regionally for new hydropower projects. Overall, though, we predict policy continuity for hydropower projects. We expect that, in the decade ahead, large hydro-power developments will still be supported in developing economies due to robust new demand for electricity.

Hydropower will also be increasingly valuable for balancing load and generation, both for short-term, daily variations, and for medium-term seasonal variations. Pumped hydro, which increases water volumes by harnessing surplus solar and wind energy to pump water back up to the reservoir, will become increasingly important. However, this is not suitable for all hydropower production; pumped hydro requires new investments and involves energy losses, so many areas will continue with traditional hydropower, including reservoirs without pumping facilities and run-of-the-river hydro. Compared with wind and solar power, hydropower benefits from being dispatchable and therefore production can be withheld on sunny and windy days. This enables hydropower to receive much higher average prices and ensure profits, despite hydropower being unable to compete with wind and solar on the basis of LCOE.

World hydropower production has doubled over the last 30 years, and Figure 3.17 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 8.6 PWh/year, 14% of the world's electricity, at the end of the forecast period. Greater China, Latin America, and North America are the regions producing most hydropower today. Production in Greater China will continue to grow steeply, with production in Latin America also increasing, while growth in Sub-Saharan Africa occurs later in the forecast period.

How will hydropower fare amid significant power-sector uncertainties? Table 3.5 shows the result of our sensitivity investigations. Our sensitivity analysis results indicate that higher fuel prices, either directly for gas, or indirectly through carbon prices, will benefit hydropower. In contrast, significant changes in the learning-rate assumptions for variable renewables will have only a marginal impact.

> “Hydropower will also be increasingly valuable for balancing load and generation, both for short-term, daily variations, and for medium-term seasonal variations

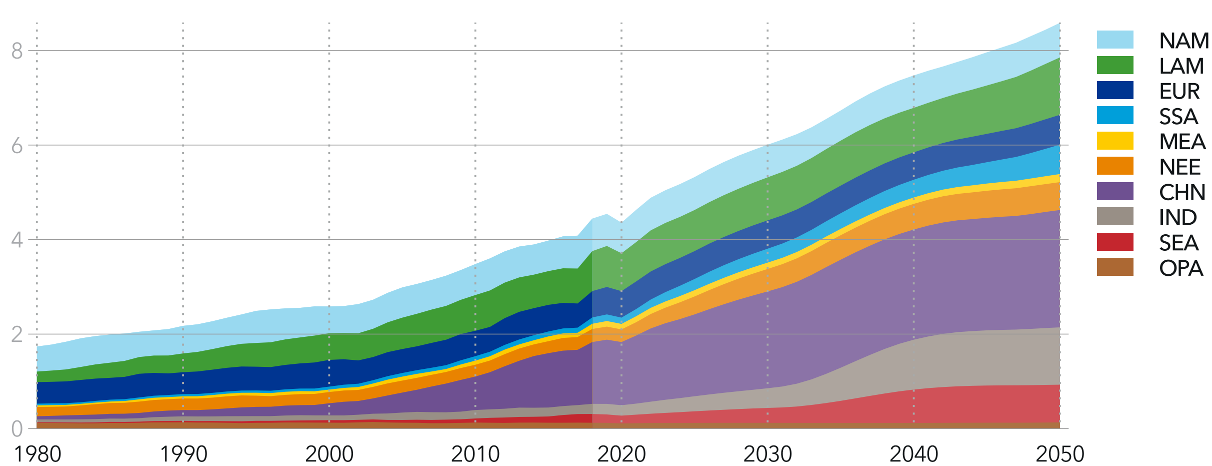
TABLE 3.5
Hydropower sensitivities

2050 level values		Parameter uncertainly tested: Gas price		Carbon price				PV learning rate		Wind learning rate	
Sensitivity range	**Base**	**-50%**	**+50%**	**-50%**	**+50%**	**+100%**	**+300%**	**-50%**	**+50%**	**-50%**	**+50%**
Hydropower primary supply (EJ/yr)	30.9	29.7	31.3	29.9	31.5	31.8	31.9	30.9	31.0	31.8	29.8

FIGURE 3.17

Hydropower generation by region

Units: PWh/yr



Historical data source: IEA WEB (2019)

3.7 NUCLEAR POWER

The fate of nuclear energy will be determined by its cost and by its environmental impact. On the one hand, there is the fact that nuclear energy can provide reliable, carbon-free electricity via large, centralized power stations. In the 1970s and 1980s, when energy security was the top priority for many countries, investment in nuclear had strong appeal. In more recent decades, when controlling carbon emissions moved up the list of priorities, advocates of nuclear energy believed that another Golden Age for nuclear was on the horizon. However, the inability of governments to agree on a long-term, viable solution to the nuclear waste problem, along with rising costs and construction times due to increased safety concerns, have resulted in a less favourable perception of nuclear energy by governments, the public, and investors.

Several factors have been shown to be detrimental for nuclear. These include actual investment costs for nuclear projects consistently exceeding their planned budgets; uncertainties about decommissioning costs; and, increasing competition from renewable energy technologies as a faster-to-market option for meeting the growing energy demand in developing countries. Adding these disadvantages to the safety and environmental risks will reduce the willingness of markets and policymakers to treat relatively expensive nuclear power preferentially, as has often been the case until now.

Nuclear power output globally has grown almost four-fold since 1980, and 2.8 PWh of electricity was produced this way in 2018, with 397 GW of installed capacity. Figure 3.18 shows our forecast that nuclear power will plateau in the 2030s, thereafter falling to 3 PWh/year by mid-century, about 9% above current production. North America, Europe, and North East Eurasia are currently the three most nuclear-dominant regions, and will be joined by Greater China as a major nuclear energy power within a decade. Although several nations – such as Bangladesh, Belarus, Turkey and the UAE – are just starting their pivot to nuclear, the future of nuclear will be determined by retirements. These will mainly occur in North America and Europe, and to a lesser extent in OECD Pacific and North East Eurasia.

Half the world's installed nuclear capacity is over 30 years old, and many reactors are approaching the end of their original design lifetimes. Some countries, such as Spain and Germany, are implementing their decommissioning plans. However, the high cost of decommissioning, and the difficulty of replacing sudden capacity retirements with low-carbon alternatives, have led some governments to consider extending the lifetimes of some old nuclear capacity through upgrades and life-extension measures. While some countries, like France, are revising their nuclear shutdown plans, Japan is working towards bringing its reactors back online, depending on improved safety demonstration, after the Fukushima disaster led to suspension of operations.

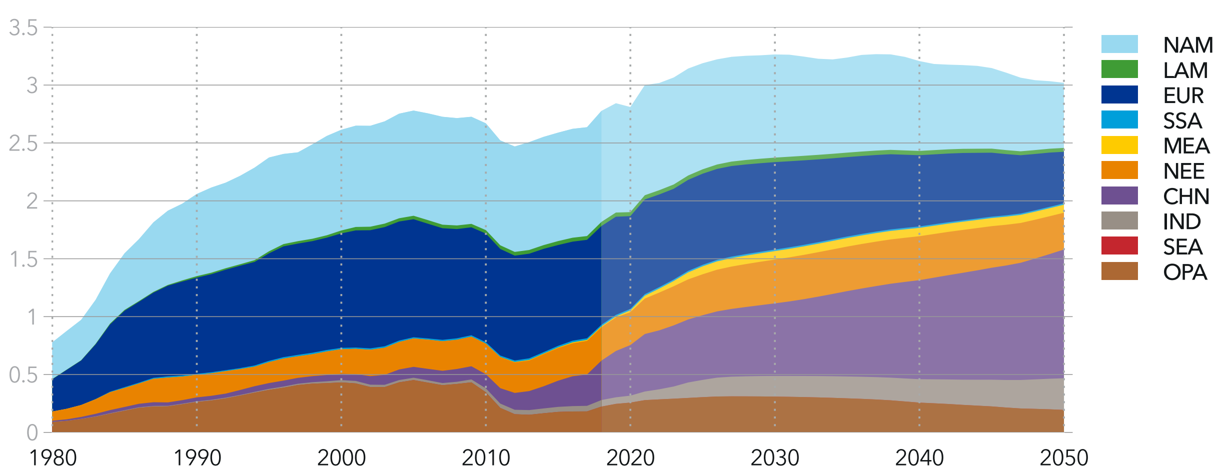
Table 3.6 shows the sensitivity of nuclear power generation to changes in gas price, carbon price and learning rates for solar PV and wind. Our analysis shows that at higher carbon prices, nuclear power generation would be 7% higher in 2050 than in 2018.

TABLE 3.6
Nuclear sensitivities

2050 level values		Parameter uncertainly tested									
		Gas price		Carbon price				PV learning rate		Wind learning rate	
Sensitivity range	Base	-50%	+50%	-50%	+50%	+100%	+300%	-50%	+50%	-50%	+50%
Nuclear electricity generation (EJ/yr)	10.9	9.8	11.2	10.0	11.6	11.7	11.6	11.3	10.5	11.2	10.4

FIGURE 3.18
Nuclear electricity generation by region

Units: PWh/yr



Historical data source: IEA WEB (2019)

3.8 BIOMASS

Biomass, that includes manifold forms such as waste and residues from agriculture and livestock production, wood from forests, energy crops, and aquatic biomass such as algae – is currently the largest source of renewable energy. Its applications are as diverse as its many forms. Wood or charcoal is used for heating and cooking. Biogas produced from waste is used for power production and as fuel and, if further upgraded, as biomethane. Liquid fuels produced from crops, algae, or genetically modified organisms are seen as promising in hard-to-abate sectors such as aviation. So far, we have not differentiated quantitatively between the various biomass forms but have used the gross energy output from its combustion as a metric. We have not modelled the biomass sector's capacity, other than in power generation, where we explicitly follow the building of biomass power capacity.

Global energy demand supplied from biomass has almost doubled since 1980. Figure 3.19 shows biomass for energy use will keep growing until the early 2030s and level off towards the end of our forecast period. The transport and power sectors will be the main contributors to the growth. The overall share of biomass in primary energy supply will retain its share at about 10% until 2050.

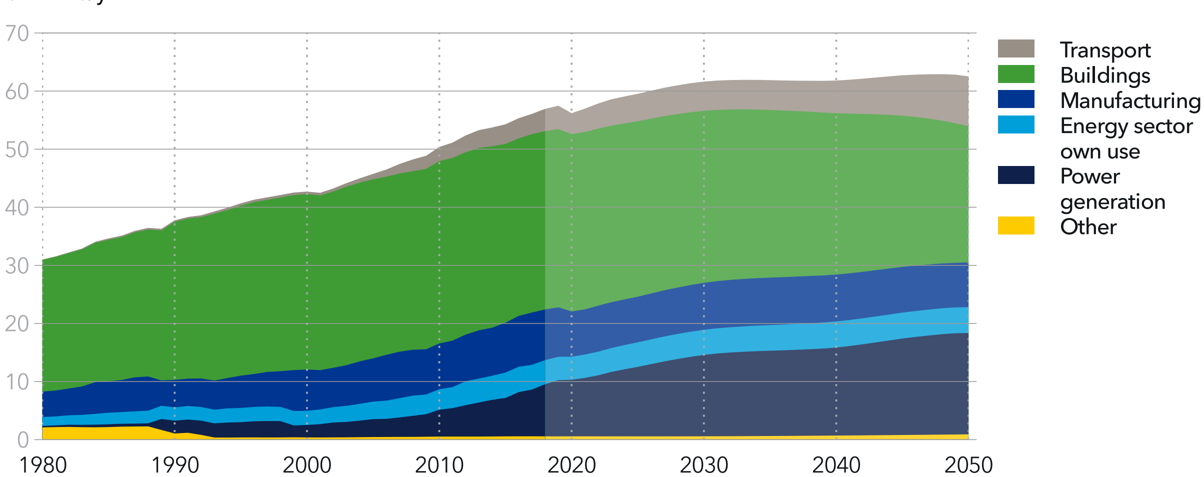
In 2018, biomass contributed 6% of the energy mix in the manufacturing sector, and will retain this share during the forecast period, with large regional variations. In electricity production, biomass usage will double. However, the share is small and will remain stable at around 2% until 2050, again with large regional variations.

As seen in Figure 3.19, the use of biomass in the transport sector, mainly in the form of liquid

FIGURE 3.19

World biomass demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2019)

biofuels with gaseous biofuels being a very small niche, will experience significant growth. With a predicted doubling between 2018 and 2050, biomass will become one of the major energy sources used for transport, especially aviation, where it will account for over 40% of energy use. The major driver for this growth will be decarbonization policies, implemented as regulations such as mandates, carbon pricing, and the limited availability of alternatives such as electrified propulsion technologies. Biomass use for heating buildings will almost disappear, but power stations will increasingly use it (including all forms of waste).

As seen in Figure 3.20, the composition of regional demand will not change dramatically over the forecast period for most regions except Greater China (+60%), Sub-Saharan Africa (+34%) and Middle East and North Africa (+185%), where biomass demand will increase. Although the growth in Middle East and North Africa is the highest, it will still account for a very low share (less than 2%) of total demand for biomass across our 10 regions in 2050. Over the forecast period, Sub-Saharan Africa will maintain its position as the largest user of biomass, increasing its share from 28% to 33%.

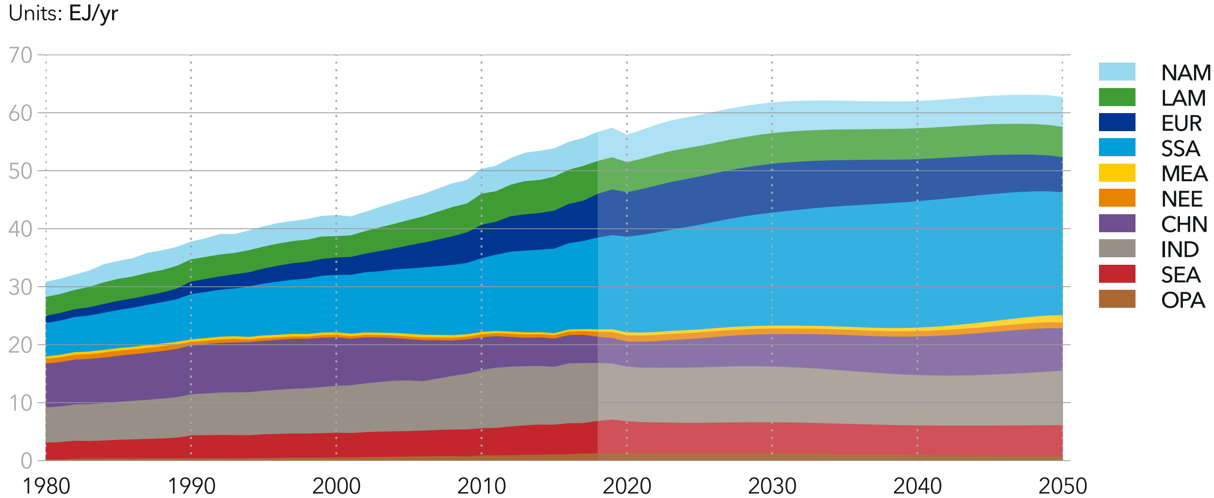
The overall demand for biomass will increase. However, the global biomass composition will change considerably, from the previous traditional forms such as wood or charcoal (for example, in cooking) to greater shares of modern biofuels derived from waste (being used, for example, in aviation). In some regions, traditional biomass is currently the dominant energy source in residential buildings. This direct use will change but will remain a considerable energy source in some regions.

As described in the fact box overleaf, the carbon neutrality of biomass is debated, and it also raises other environmental concerns like biodiversity loss and land-use change. Consequently, policies tend to focus on better use of biomass residues and waste, hitherto left to rot and thereby producing the powerful GHG, methane. Support for such efforts will increase in many regions.

FIGURE 3.20

Biomass demand by region

Units: EJ/yr



Historical data source: IEA WEB (2019)

Table 3.7 shows the sensitivities of our biomass results. Our analysis indicates that high carbon prices will hinder biomass end use. Doubling the carbon price will decrease biomass use by 10%. Similar effects will result from lower prices for fuel competitors of biomass, such as natural gas.

In contrast, biomass use will be only slightly affected by the prices and thus learning rates of vRES. High vRES learning rates have only a negligible effect on biomass uptake, partly because lower vRES prices also promote higher electrification rates.

TABLE 3.7
Biomass sensitivities

2050 level values		Parameter uncertainly tested: Gas price		Carbon price				PV learning rate		Wind learning rate	
Sensitivity range	Base	-50%	+50%	-50%	+50%	+100%	+300%	-50%	+50%	-50%	+50%
Biomass primary energy supply	63	58	66	63	59	57	55	63	63	64	61

CARBON-NEUTRAL BIOMASS?

Combustion of biomass, including biofuels, is considered carbon neutral, and thus no carbon emissions are counted. This is in line with IPCC assumptions that carbon in biomass is eventually absorbed from the atmosphere by photosynthesis, assuming that the burned plants are replaced with new plants.

The shares of different types of biomass used in the future will differ from today, favouring different types of waste. Third and fourth generations of biofuels are likely to be subject to close scrutiny before they are approved for use and labelled as sustainable and carbon neutral. Between now and 2030, while the next generation of biofuel infra-structure is being developed, it is likely that biofuels produced from unsustainable sources will be an important part of the biomass mix.

The time perspective of biomass emissions is important and is a concern. In our forecast, potential additional emissions due, for example, to deforestation to make room for crops for liquid biofuels production are accounted for under agriculture, forestry, and other land-use (AFOLU) emissions. Emissions during transport of biomass are accounted for under transport. We still adhere to the overall view that biomass, including biofuel, is carbon neutral over time. Biomass-based value chains are also being considered as carbon negative, such as the use of organic waste as feedstock for energy production rather than being left to rot, which produced methane. However, we will follow this subject closely and update our calculations should research conclude otherwise.

3.9 OTHER

Other energy sources, such as solar thermal and geothermal, will remain marginal on a global scale towards 2050, both providing less than 1% of world primary energy in mid-century.

In this Outlook, 'solar thermal' refers to both solar water heaters and concentrated solar power stations (CSP). Globally, primary energy supply from solar thermal energy will grow from 1.5 EJ/yr in 2018 to 2.5 EJ in 2050, most of which will be in the buildings sector. As discussed in Section 1.2, we foresee expansion in solar water heaters and other uses of solar thermal energy. But with preference towards solar PV, CSP costs will remain high and only limited uptake will occur. Although CSP plants have the advantage of including energy storage, the combination of solar PV with other storage technologies will be more cost effective.

Geothermal energy from hot springs or low temperature sources has many potential applications, ranging from power generation to heat pumps. As of 2018, geothermal energy provided 3.4 EJ, 0.6% of the world's primary energy supply. Although geothermal energy has the technological potential to increase in some applications, economic factors will limit its expansion to only marginal growth of 0.8% between now and 2050.

POTENTIAL FUTURE ENERGY SOURCES

As presented in the introduction, we base our forecast on continued development of proven technologies, including advances in these technologies. Such improvements, like technological developments in solar PV and wind, are already included in their respective chapters. Our companion reports also go into greater detail on improvements in mainstream technologies that are expected to impact on the energy transition.

Technologies that are not yet proven, and marginal technologies that are not expected to scale, are not included in our forecast.

Ocean energy is one such example. Several technologies for capturing energy from oceans are currently being pursued (OES, 2018), including wave energy (shoreline and open-sea devices); tidal energy (stream and range devices); ocean currents; ocean thermal energy; and, reverse osmosis.

Proof of concept has been demonstrated for these technologies, but none has progressed sufficiently to push the technology cost-learning curve down to a level at which ocean-energy technology can achieve 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 the predictions for our forecast period, they would need to grow at faster rates than those of other renewables, which is unlikely. The technologies are often confined to sites where the conditions are particularly favourable to their operation, making the solution cost effective, but not enough to scale globally. Thus, we estimate that the global contribution from emerging ocean-energy technologies will be very small.

Nuclear fusion is another example. For several decades, nuclear-fusion technologies have been discussed as a potential breakthrough, carbon-free source of nuclear energy. Several promising research projects focusing on smaller fusion systems are currently being piloted. In spite of extensive ambitions, none has progressed very far, and no plant has yet produced more energy than that 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 is therefore confined to traditional fission technologies.

Over the course of the next 30 years, we are likely to see breakthroughs in new technologies. Such advances could occur in the areas mentioned above, or in others, but we do not know which. As this Outlook represents our best estimate of the energy future, it is too speculative to quantify them and include them in our forecast.

VISUALIZING THE ENERGY TRANSITION

GLOBAL FLOWS OF ENERGY CARRIERS, 2018 VERSUS 2050

The Sankey diagrams on the next spread are the snapshots of the global energy flows in 2018 and 2050, revealing the major changes in the energy system over the 32-year forecast period.

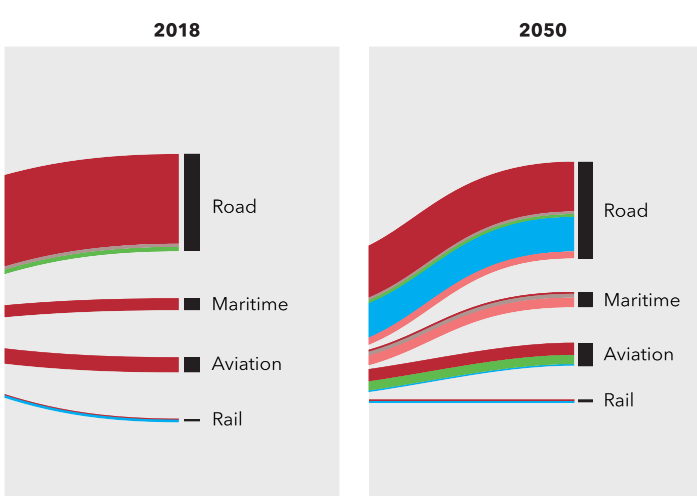
One striking change on the supply side of the picture is the emergence of solar PV and wind at the expense of coal and oil.

Electrification more than doubles through to 2050, which leads to an increase in the overall system efficiency, for two main reasons:

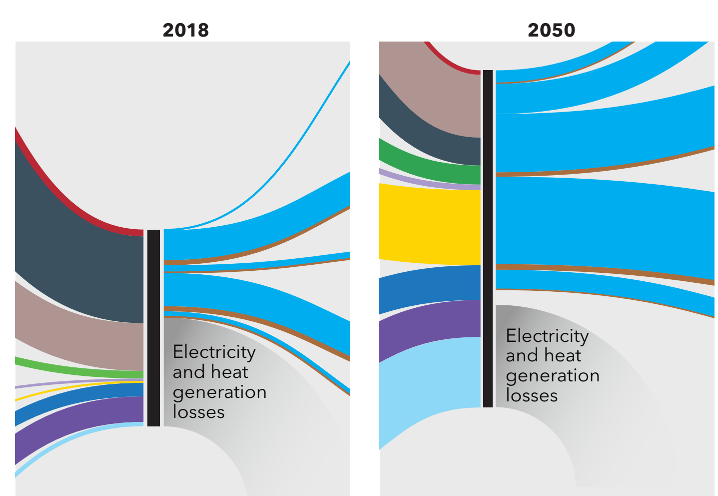
– Electrification of end-uses leads to rising efficiencies, some of which are modest, like switching from gas to electric cooking (which can raise efficiency from 70% to 90%), while other electrification-linked improvements are dramatic. Notable examples are switching to heat pumps for heating, or installing electric powertrains in road vehicles, both of which can lead to efficiency improvements by a factor of three or four. In the Sankey diagram zoom-in below, we can see a slight reduction in total transportation demand accompanied by a diversification of energy carriers. This decrease occurs even though more energy services will be provided (e.g. the world car fleet growing by 66%). By 2050 almost all new cars will be EVs, with motors that virtually eliminate the heat losses of ICE engines.

– Heat losses in current predominantly fossil-fuelled electricity generation are reduced by the transition to renewables. Although renewables convert only a small fraction of solar or wind energy hitting the panels and the turbines to electricity, they are assumed to be 100% efficient as they do not consume any other energy carrier. This means a huge leap in power generation efficiency from the average efficiency of 40% for all fossil-fired power stations around the world. As high-lighted below, electricity generated more than doubles, while losses reduce in absolute terms.

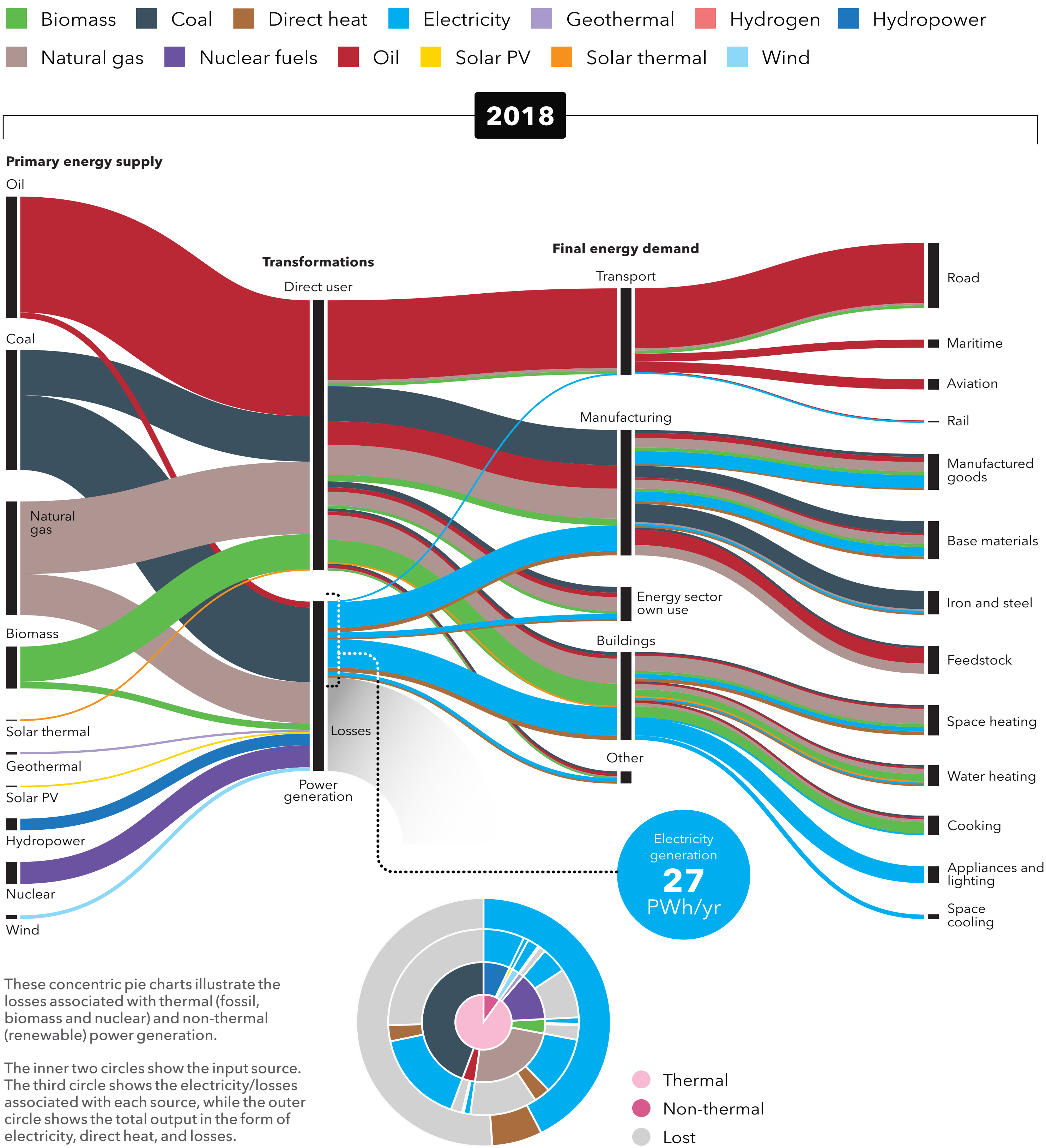
Electrification of end-uses



Heat losses

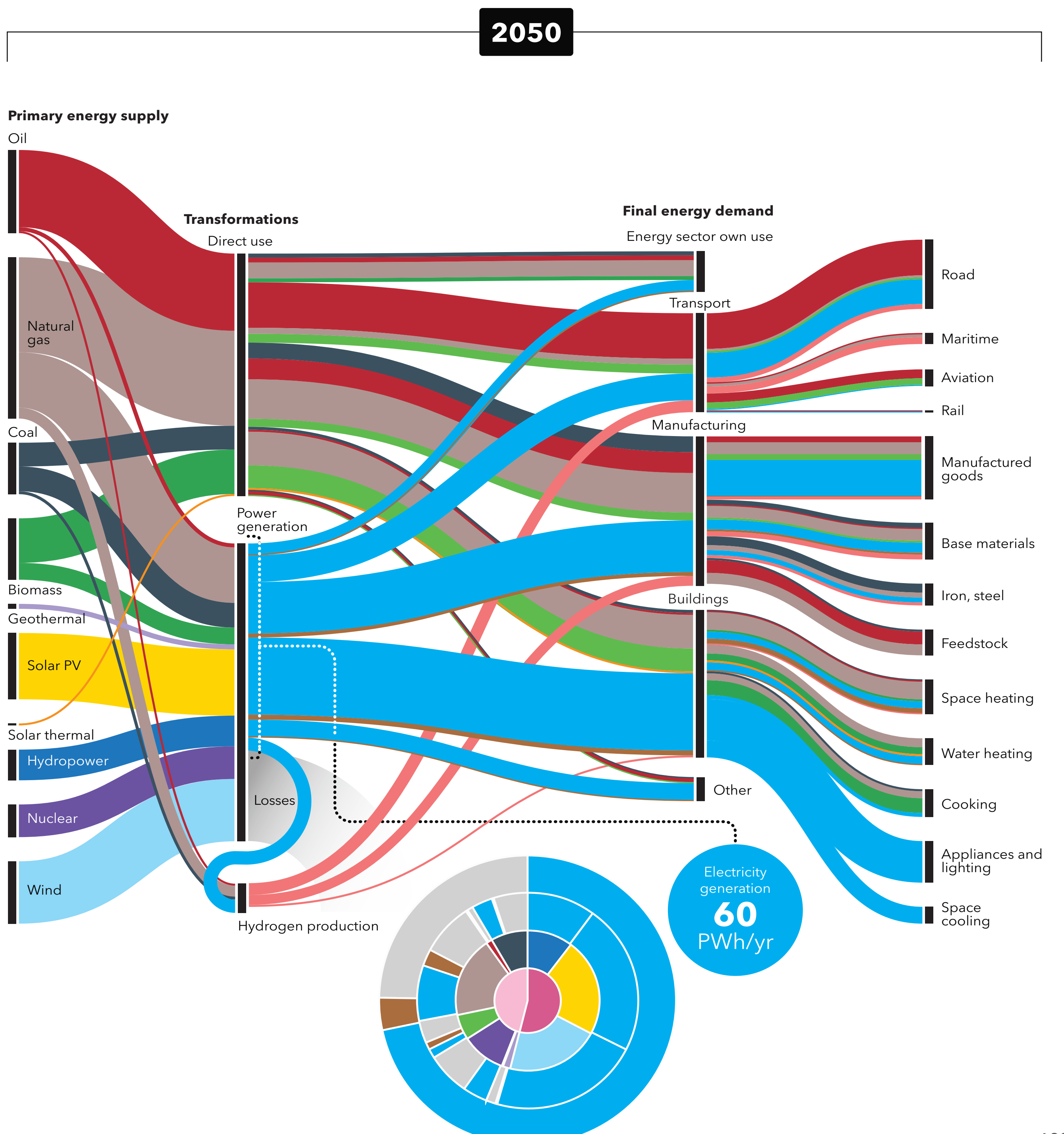


COMPARISON OF ENERGY FLOWS: 2018 AND 2050



These concentric pie charts illustrate the losses associated with thermal (fossil, biomass and nuclear) and non-thermal (renewable) power generation.

The inner two circles show the input source. The third circle shows the electricity/losses associated with each source, while the outer circle shows the total output in the form of electricity, direct heat, and losses.


2050
Primary energy supply
Oil
Natural gas
Coal
Biomass
Geothermal
Solar PV
Solar thermal
Hydropower
Nuclear
Wind
Transformations
Direct use
Power generation
Losses
Hydrogen production
Final energy demand
Energy sector own use
Transport
Manufacturing
Buildings
Other
Road
Maritime
Aviation
Rail
Manufactured goods
Base materials
Iron, steel
Feedstock
Space heating
Water heating
Cooking
Appliances and lighting
Space cooling
Electricity generation
60
PWh/yr

HIGHLIGHTS

Energy efficiency plays a central role in the energy transition – essentially it is our greatest resource in the quest for a sustainable and equitable energy system.

We find that primary energy intensity (i.e. unit of energy per dollar of GDP) declines at an average of 2.3% over the next 30 years. The pace of this deceleration is higher than population and GDP growth, with the implication that from the early 2030s, the world's energy use will start declining.

Acceleration of electrification, and the increasing share of renewables in the power mix, are the main drivers of these rapid energy-intensity improvements. We illustrate the effect and quantity of energy efficiency gains in the main demand sectors – transport, buildings, and manufacturing.

Affordability. Global energy expenditure will increase by only 5% in the next 30 years, rising from USD 4.2trn in 2018 to USD 4.4trn in 2050. This increase is far lower than the doubling of GDP over the same period, and energy expenditure will thus fall as a percentage of world GDP from the present level of 3% to 1.6%. This leaves considerable ‘savings’ on the table that could be used to accelerate the transition and progress towards the ambitions of the Paris Agreement.

We describe and quantify the large shifts in OPEX and CAPEX between fossil and non-fossil sources during our forecast period.

CHAPTER 4

ENERGY EFFICIENCY AND FINANCE

4.1 ENERGY INTENSITY 126

4.2 SECTORAL ENERGY EFFICIENCY 128

4.3 ENERGY EXPENDITURES 130

4.1 ENERGY INTENSITY

Increased efficiency of the energy system is a key feature of the energy transition. Efficiency is in effect our greatest resource. It should be the top priority for authorities and other stakeholders in the industry.

Energy efficiency can be measured in several ways. For example, Lovins (2018) writes about 'efficiency' in the engineering sense (ratio of energy output to energy input, or of effect to effort) rather than from an economic perspective. Lovins further describes various categories of efficiency – e.g. extraction, distribution, end-use, and 'system efficiency. We broadly follow this approach, looking at the primary energy intensity of the global economy and thereafter the sectoral energy efficiencies of the various demand sectors.

Primary energy intensity
Primary energy intensity is measured as primary energy consumption per unit of GDP; the lower the number, the less energy intensive the economy in question is. Globally, energy intensity has been reducing by 1.7%/yr on average for the last two decades. This decline has not been smooth but has spiked along the way. The COVID-19 pandemic has introduced further short-term spikes with varying fluctuations in both energy consumption and GDP. The large reduction in energy intensity in recent years has been driven mainly by developments in China, where sustained economic expansion has seen energy use per unit of output reduce considerably. This was achieved through concrete energy-efficiency actions, such as legislation on energy-efficiency standards and products; and, mandatory energy-efficiency improvement targets (Zhu et al., 2017). These policy actions boosted the decline in energy intensity typically associated with the growth of the tertiary ('services') share of an economy.

Over our forecast period, in which we foresee a doubling (101%) of global GDP and a 6% reduction in overall primary energy consumption, energy intensity will be more than halved from 4.5 MJ/USD in 2018 to 2.1 MJ/USD in 2050. Irrespective of short-term impacts of the pandemic, energy intensity will continue to decline faster than in the past, by 2.3%/yr on average over the next 30 years.

Electrification
Acceleration of electrification, and the increased share of renewables in the power mix, are the main drivers of more rapid energy-intensity improvements in the future. In a rapidly electrifying energy system, efficiency is greater due to smaller energy losses, meaning less energy is needed to produce the same services. As renewables' share of electricity rises, energy intensity benefits from smaller heat losses during power generation. The typical thermal efficiency for utility-scale electrical generators is some 30 to 40% for coal and oil-fired plants, and up to 60% for combined-cycle gas-fired plants. Solar and wind generation are 100% efficient. A discussion on calculating primary energy can be found in Chapter 2.

Based on our results, the third measure of the UN Sustainable Development Goal #7 – to double the rate of improvement in energy efficiency – will not be met. Our forecast of an improvement of 2.0%/yr from 2015 to 2030 is higher than, but not double, the historical 1.6%/yr seen between 2000 and 2015.

Although regional changes in energy intensity can be measured, the results are often flawed, as they do not consider trade. Hence, regional decoupling of energy consumption and economic activity fails to account for manufacturing being largely outsourced from Europe and North America to China and other Asian nations over the last few decades. We therefore choose not to focus on regional energy-intensity forecasts.

FIGURE 4.1

World energy intensity

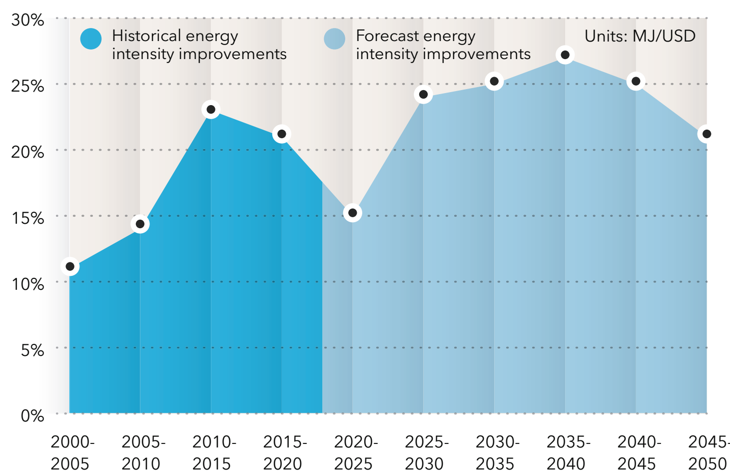
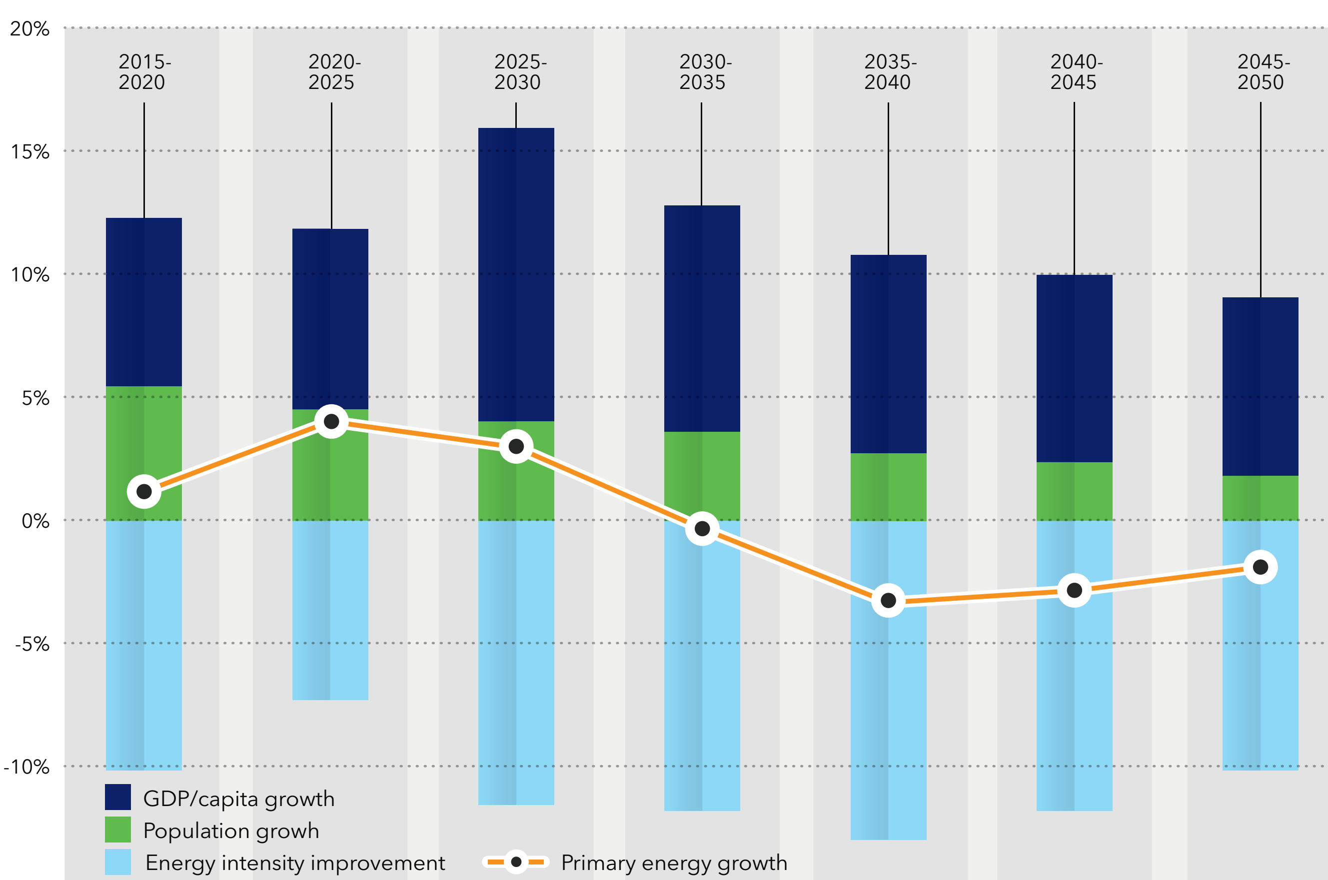


Figure 4.1: The graph shows the forecast annual rate of energy intensity improvement globally (i.e. the rate at which primary energy consumption per unit of GDP falls). There is steep growth in the coming decade, and sustained improvement rates through to the early 2040s, and thereafter tapering slightly – as one would expect with an energy system which by then will be heavily electrified.

Figure 4.2: The development of energy intensity can be plotted together with the growth of population and GDP/person, as shown below in 5-year intervals between now and 2050. After 2030, the reduction in energy intensity is stronger than the combined growth of population and GDP/person, and hence, growth in the global primary energy supply is negative once primary energy supply peaks in the early 2030s.

FIGURE 4.2

Primary energy growth as a function of Population, GDP/capita and Energy intensity improvement



4.2 SECTORAL ENERGY EFFICIENCY

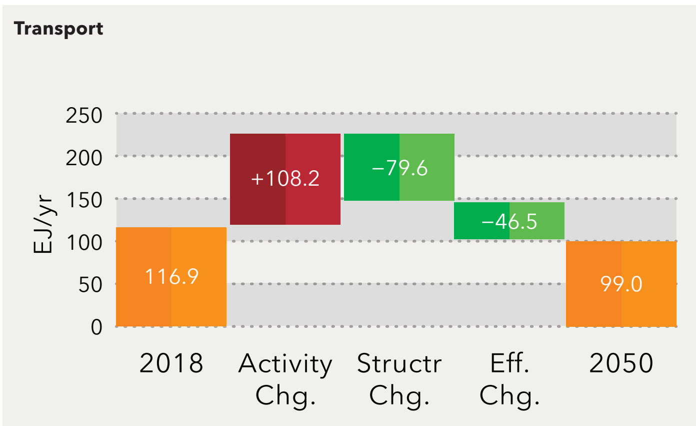
The demand for energy services – e.g. for transporting passengers and goods, heating and cooling buildings, or producing consumer goods – grows as a function of population and economic activity. Technology, process and efficiency improvements will typically counter some of this growth, sometimes even leading to reduced energy demand despite a growth in energy services. Such improvements come in many forms:

- Activity improvements: Some improvements reduce activity levels and/or contribute to slower rates of activity increase. These include increased recycling of materials, with lower demand for virgin feedstock; improved insulation of buildings; and, the impact of climate change on heating demand.
- Efficiency improvements: In the various energy demand sectors, several efficiency improvements continuously drive down energy use per service delivered. Examples include more-effective engines or improved hull hydrodynamics and vehicle aerodynamics.
- Structural shift of technologies: Occasionally, services are better delivered through the switching of one technology to another. Examples are replacement of a combustion engine with an electric motor to power a vehicle, or abandoning traditional solid biomass for cooking in favour of gas or electric stoves. Such technology shifts can lead to huge reductions in energy use – in extreme cases by a factor of 10 or more. These changes are often termed efficiency improvements, which is correct in the sense that they improve the efficiency of the process. However, the underlying service itself does not change; the improvement is due to the use of a new technology. Structural shifts normally always reduce energy use.
- Structural change in service delivered: Sometimes, there are structural changes in the service delivered, such as bigger cars or a greater degree of space sharing (i.e. housing occupancy). These shifts may counter technology-led improvements and lead to higher energy use; in other cases, they might reduce energy use.
- Structural changes between regions: When looking at global numbers, we sometimes have structural changes from regional shifts; for example, in the offshoring or nearshoring of manufactured goods production. Such structural changes might also lead to both higher and lower energy use.

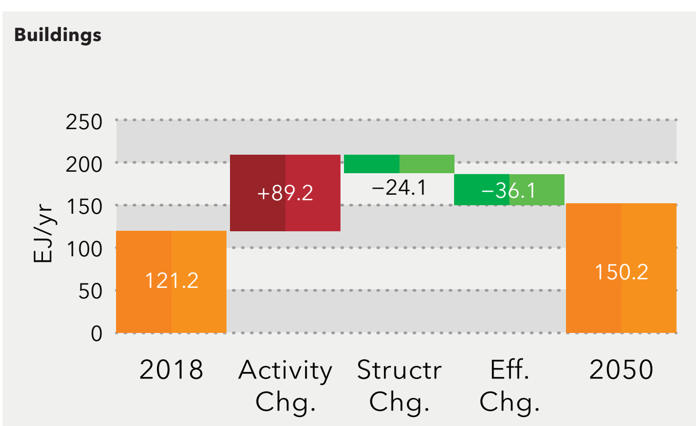
Efficiency improvements reduce both energy use and costs. The 'cheaper and/or better' mantra has always been the main driver for technology innovation. But sometimes this is not enough, and policy interventions in the form of efficiency and performance standards (e.g., technical retrofits, building codes, fuel efficiency) play an important role, as detailed in Chapter 5. We observe that in countries with mandatory efficiency policies, energy use or emissions grow little. This trend reverses where there is rollback of such regulation – currently in the US, for example. Policy frameworks help to direct investment towards energy-efficiency initiatives that otherwise tend to be overlooked by investors for several reasons, one of which is that direct returns are often difficult to quantify and allocate across complex supply chains.

In our view, there is enough technology and policy momentum for efficiency improvements generally to grow across all sectors. However, to illustrate the importance of what is already included, we find that without any energy-efficiency improvements, global energy demand would increase by 65% towards 2050, in sharp contrast to the almost flat development that we forecast. This is illustrated opposite for the main demand sectors.

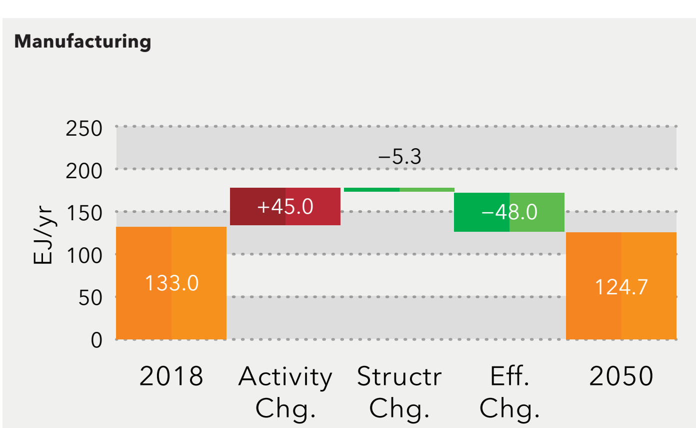
FIGURE 4.3



This subsector is dominated by road transport, with vehicle kilometres (km) doubling over the next 30 years (shown as the '**activity change**'). In 2050, more than 75% of all passenger km and more than half of all cargo km will be driven with EVs, and this **structural change** drives energy use down dramatically. Bigger cars contribute in other direction, but much less. **Efficiency gains** in combustion engines are gradual, but less important than the shift to EVs. Aviation activity doubles, but significant efficiency improvements counter most of the growth.



Activity-wise, world total building floor area doubles in our forecast period, but the increase in energy services in buildings varies considerably, from cooling which grows six-fold to heating which increases by only 15%. Changes in heating, water heating and cooking technologies contribute to the **structural** improvements, while **efficiency gains** are largest in cooling, lighting and appliances.



The anticipated **activity** changes for this subsector are that the production of manufactured goods increases by 70%, base material by 27%, while iron and steel production declines slightly. **Structural** changes even out and are mostly related to regional shifts in production, while (mainly electrification-related) **efficiency gains** in the various manufacturing segments and particularly in iron and steelmaking are significant and reduce energy use more than the overall activity increase.

4.3 ENERGY EXPENDITURES

Affordability is the acid test of the energy-transition that we forecast. Will the annual cost of the future energy system that we see unfolding be higher than today? If so, less costly energy futures than those that we forecast could perhaps crowd out our projections.

The 'good news' on affordability is that since world GDP will more than double by 2050, and energy expenditures remain virtually flat, we project a near halving – from 3% to 1.6% – by mid-century in the share of world GDP devoted to energy expenditures. Major expansions in high capital-cost renewables and electricity networks are accommodated within current global energy budgets. Hence, we conclude that the energy transition we are forecasting is indeed affordable, and that a strengthening of ambitions and emission reductions for compliance with the Paris Agreement, is entirely feasible within energy's current share of global GDP. The rest of this section explains in detail how we arrive at these conclusions.

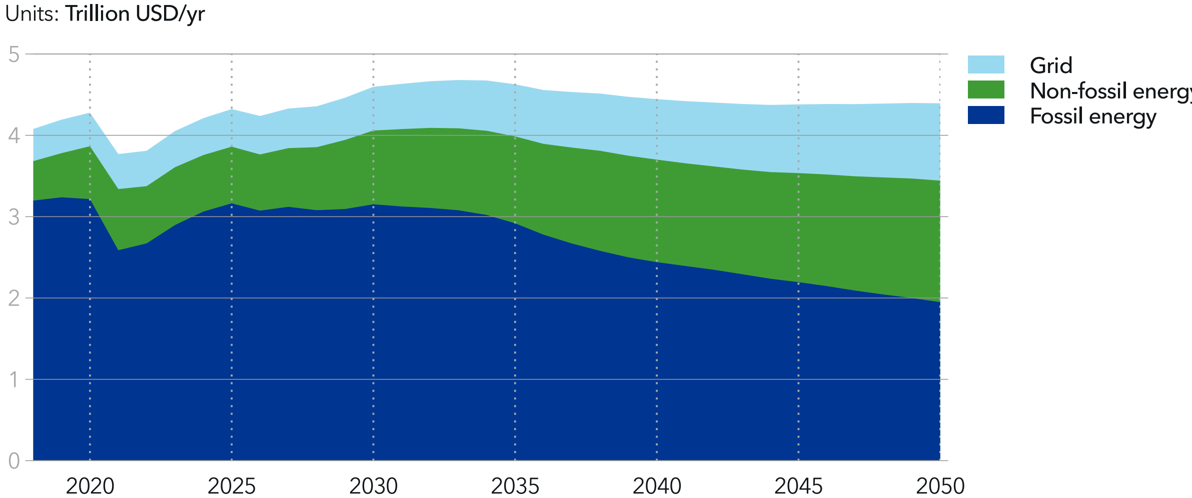
Defining expenditure
Contrary to other modelling frameworks, such as the IEA's TIMES and the EU's PRIMES, our approach does not ensure the global optimality of solutions. However, in many sectors – such as power production, upstream oil and gas, and energy use in manufacturing – we use a merit-order cost-based algorithm established on the basis of production costs in its energy sectors (power, oil, and gas), to drive the selection of energy sources / production technologies over each other through time.

What should be defined as 'energy expenditures' is open to debate. We have chosen to use a strict definition, and have therefore included only fossil-fuel extraction, and refinement such as

FIGURE 4.4

World energy expenditures by source

Units: Trillion USD/yr



liquefaction, regasification, refineries, and conversion to hydrogen and electricity. Similarly, all costs in the power sector, including power grids, are incorporated, including also installation and operation of renewable energy plants. We have excluded oil and gas pipeline costs, as well as any energy-efficiency measures.

What should actually be considered to constitute a subsidy would deserve a chapter in its own right, and we have decided against this. Even the modelled subsidies that we report in this Outlook are seen as support that benefit consumers and are not counted as energy expenditures.

Although the simulated decision makers in our model discount their expected future cash flows, in this chapter we report annual sectoral outlays in terms of CAPEX and OPEX.

Using this definition, we show in Figure 4.4 that the global energy expenditure will increase by only 5%, rising from USD 4.2trn in 2018 to USD 4.4trn in 2050. The fossil-energy share will decline by almost half of today's 77%, dropping to 44% by mid-century.

> “There will be a near halving – from 3% to 1.6% - by mid-century in the share of world GDP devoted to energy expenditures

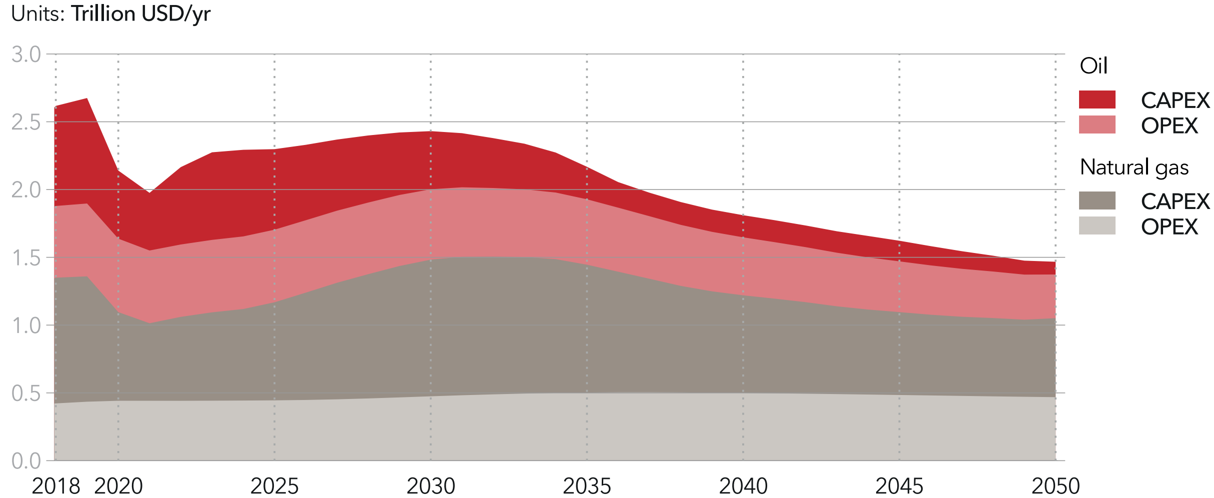
CAPEX and OPEX

Most of the upstream fossil-fuel expenditure will disappear due to oil CAPEX falling by a factor of nine from today to mid-century as seen in Figure 4.5. Neither oil OPEX, nor gas CAPEX will decline by more than a quarter to 2050, and gas OPEX will remain at the same level.

FIGURE 4.5

World upstream oil and gas expenditures

Units: Trillion USD/yr



On the power-system side, grid expenditures will grow even more strongly than power supply, representing one third of global-energy outlays in 2050. Strong growth in electricity demand, and high penetration of vRES, will require expansions in transmission and distribution grids. Moreover, old power cables will need replacing near the end of their technical lifetimes, thereby increasing the required level of investments. World grid expenditures will more than double from about USD 400bn to over USD 900bn in 2050 (Figure 4.6).

> "World grid expenditures will more than double from about USD 400bn today to over USD 900bn in 2050

The increase in electricity demand is driving the majority of the expenditure growth. Additional expenditure will be needed to create connections to new power stations, especially offshore and onshore wind farms and utility-scale solar power plants. vRES-related grid reinforcement will make up about 17% of total expenditure.

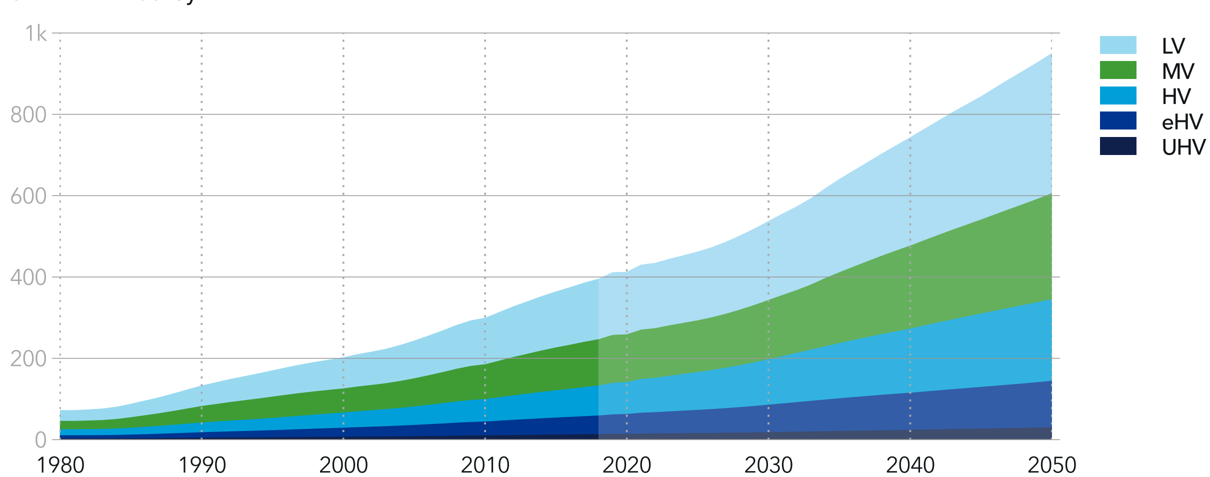
Low-voltage grids will be the largest expenditure category in 2050, accounting for almost a third of the grid funding. Considering grid costs differently (by AC or DC), we see a doubling in the share of DC expenditure from 17% now to 33% by mid-century. With respect to location, there will be changes. Underground and underwater installations will grow faster: undersea expenditures, currently a small niche, will grow from less than USD 1.5bn today to USD 23bn in 2050, or 2.5% of global grid expenditures at that time.

The grid-cost numbers include all costs. Globally, grid OPEX will more than double (+110%) from today's level to reach USD 241bn in 2050, while grid CAPEX rises 130% to USD 726bn to account for a sixth (16%) of global energy expenditures

FIGURE 4.6

World grid expenditure by voltage class

Units: Billion USD/yr



that year. Note that doubling (+105%) power production by 2050, while the share of vRES in generation rises 10-fold to account for almost two thirds of generation in mid-century, requires only slightly more than doubling grid expenditures.

Investments in Greater China will account for 28% of all grid-related CAPEX in 2050. The rest will be distributed among the Indian Subcontinent (18%), South East Asia (11%), North America (10%), Europe (9%), and other regions (24%).

Power-sector investments also include those made in power plants and generation. As shown in Figure 4.7, CAPEX in non-fossil plants will more than triple, reaching USD 1trn globally in 2050.

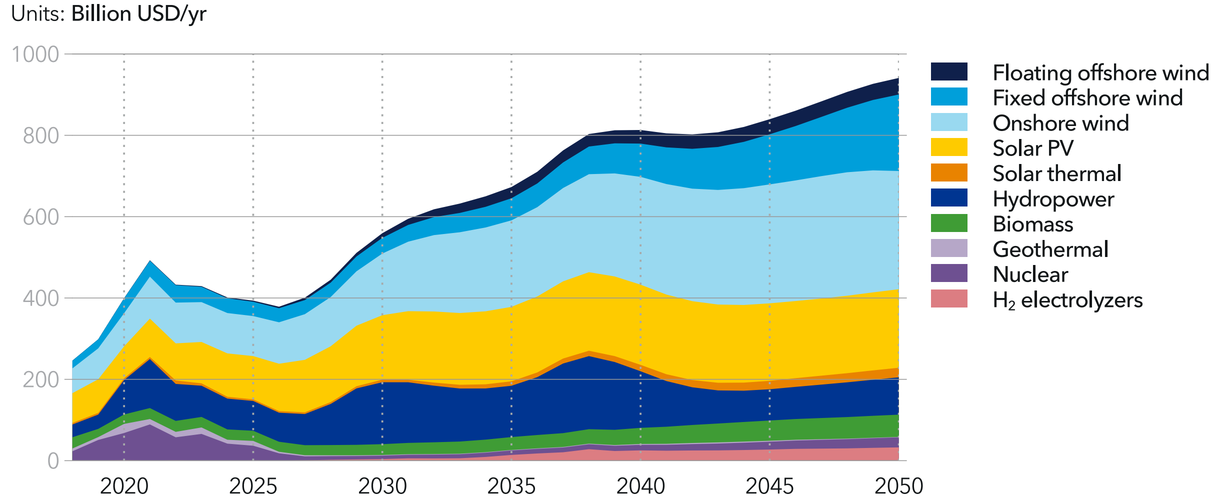
vRES power plants typically require much less maintenance and operating care than traditional non-fossil nuclear and hydropower plants. Thus, even with the majority of power coming from vRES plants in 2050, their share of OPEX will not exceed a quarter of OPEX at that time. Neverthe-less, the tripling of global non-fossil power generation capacity will lead to OPEX more than doubling, as seen in Figure 4.8.

> “CAPEX in non-fossil plants more than triples, reaching USD 1trn globally in 2050

FIGURE 4.7

World non-fossil power CAPEX

Units: Billion USD/yr



Gas production will grow strongly over the next decade. Gas consumption will increasingly take place overseas from upstream production. This logistical mismatch will be met by a combination of new LNG liquefaction plants on the production side, gas carriers for ocean transport, and regasification at the consumption end. Figure 4.9 shows the dramatic rise in LNG CAPEX for liquefaction and regasification to solve this logistical challenge, including a quintupling before 2025.

A declining percentage of GDP

As shown in Figure 4.4, world energy expenditures will shift from fossil to non-fossil sources, and the sum will increase by only 5%, rising from USD 4.2trn in 2018 to USD 4.4trn in 2050. Figure 4.10 shows that the share of GDP devoted to energy expenditure will halve, dropping from its current level of 3% to 1.6% by mid-century.

While world GDP will more than double by 2050, the share of GDP devoted to energy expenditure will halve, and as such prompts a thought experiment: If the world decided that the current fraction were to stay constant, that would create a war chest to fight climate change that would amount to, on average, almost 2 trn USD each year, reaching close to USD 60trn by 2050. That would still be less than 0.8% of global GDP to 2050. As noted in our study (DNV GL, 2020g), that sum would cover the needs of a faster energy transition, one compliant with the Paris Agreement

> "If the current fraction of GDP devoted to energy expenditures were to remain constant ... the war chest would fill up with USD 2trn each year - enough to pay for a transition compliant with the Paris Agreement

FIGURE 4.8

World non-fossil power OPEX

Units: Billion USD/yr

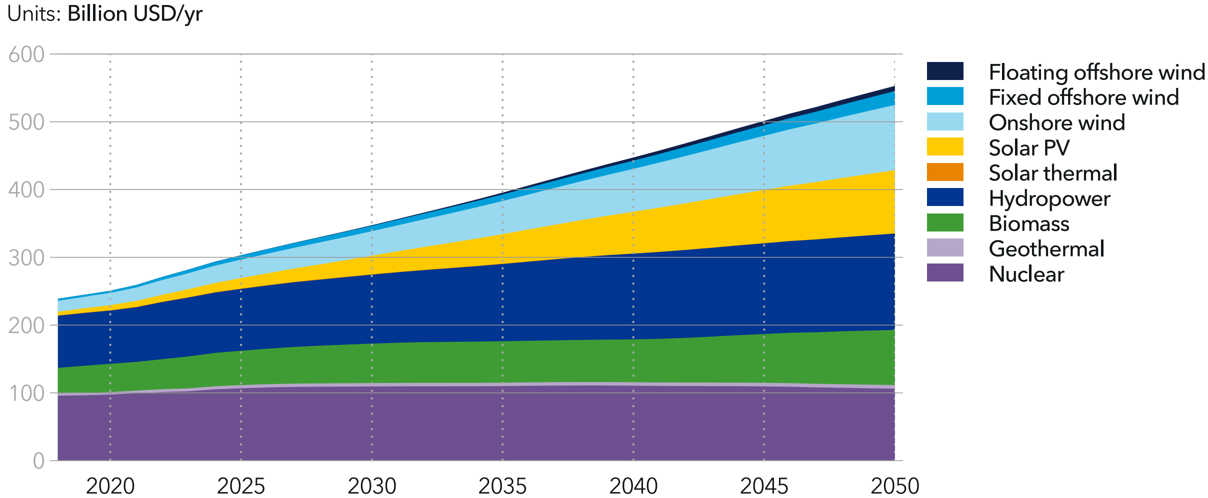


FIGURE 4.9

World LNG CAPEX and OPEX

Units: Billion USD/yr

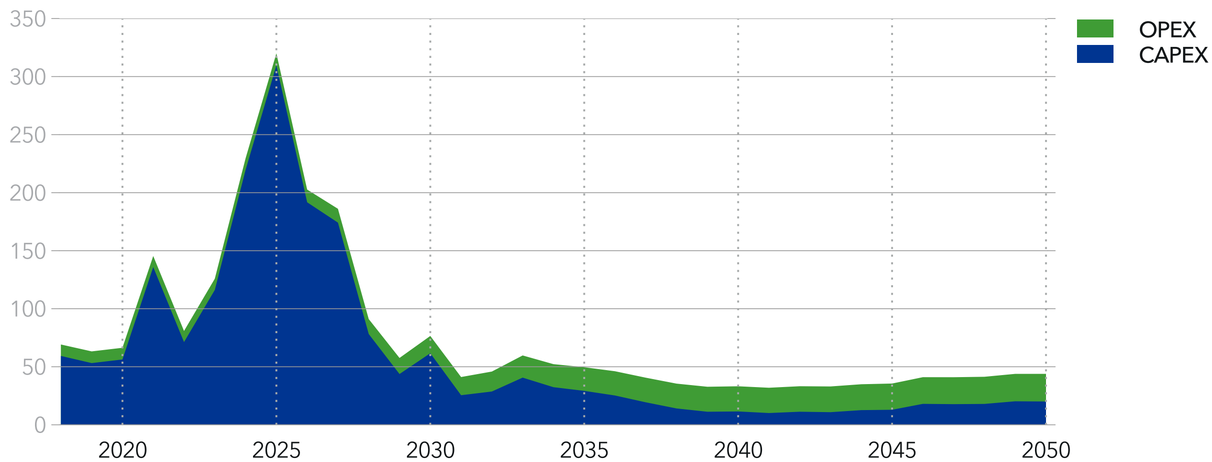
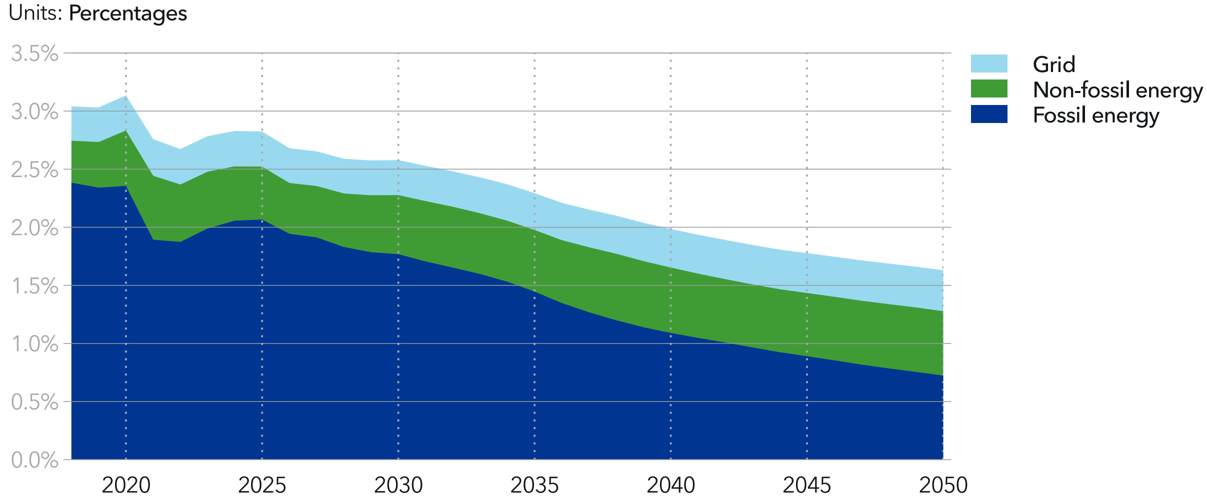


FIGURE 4.10

World energy expenditure as a fraction of world GDP

Units: Percentages



HIGHLIGHTS

This chapter explores the role of policy in the energy transition and describes 11 **policy considerations directly factored into our Outlook.**

The present energy transition is unlike previous transitions in the sense that it is **mission orientated** – motivated by climate change concerns (framed by global agreements like the Paris Agreement and the SDGs) and the need to protect planetary boundary conditions, not least biodiversity (as described in the IPBES report).

We discuss a series of **drivers** of, and **barriers** to, the energy transition. These create uncertainty over the speed of the transition. However, mission-oriented policy, along with rapid developments in technology and costs, suggests that change will hold sway over continuity. We highlight key **dilemmas** for policymakers, along with our view on **policymaking 'toolboxes'** that optimize the advancement of low-carbon energy.

We address specific sectoral challenges and policy options including **sector coupling, power systems and renewable energy integration** and **hard-to-abate sectors.**

COVID-19 has introduced additional policy uncertainty to the transition, not least with the profile of stimulus packages introduced by governments around the world.

CHAPTER

5

POLICY AND THE ENERGY TRANSITION

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5.1 INTRODUCTION – GOVERNANCE MATTERS

This chapter explores the role of policy in the energy transition and highlights policy considerations that we have specifically factored into our forecast.

The nature and pace of the energy transition will vary regionally and by country, depending on natural resource endowments, sectors, and geography, as well as on local circumstances and socioeconomic realities. Regardless of the starting point, policy will play a pivotal role in how existing energy infrastructure is adapted and how new energy technologies and systems evolve. Policy influences, and is in turn influenced by, market forces. Many energy subsectors will face shrinking consumer demand (influenced inter alia by climate concerns), competition from cleaner fuels, as well as swings from investors and insurers backing away from some energy options and placing their bets on others.

MISSION-ORIENTATED TRANSITION

With these shifts underway, the 2020s is a watershed decade given the timeframe for reaching overarching global goals by 2030. Time is of the essence, and 2020 has been dubbed the super year (UNEP, 2019a) for action on climate and the environment, follow-up and review of the Sustainable Development Goals (SDGs), and for reaching decisions on post-2020 global frameworks.

The energy transition will become increasingly mission-oriented, in line with the UN 2030 Development Agenda and the Paris Agreement, as government action and policies on climate, energy, and technology target structural energy-system changes that address planetary, economic, and human development risks. The use of near-term policy action to fulfil long-term goals is unprecedented and differentiates the current energy transition from previous ones that have very largely been driven by market forces. DNV GL's energy transition forecast therefore anticipates an intensification of efforts to promote energy system change and anticipates that opportunities in sustainability-related innovation, low-carbon sectors, and technologies advancing decarbonization, will hold primacy.

For these reasons, we have assessed key plans, especially ambitions like the Nationally Determined Contributions (NDCs) process and the EU's Green Deal initiative. We expect energy-policy measures to 'roll-over' government cycles, and to be revamped periodically in response both to progress in emissions' reduction and the impact of the energy transition on welfare, employment, and industrial development.

COVID-19 – A WINDOW OF OPPORTUNITY?

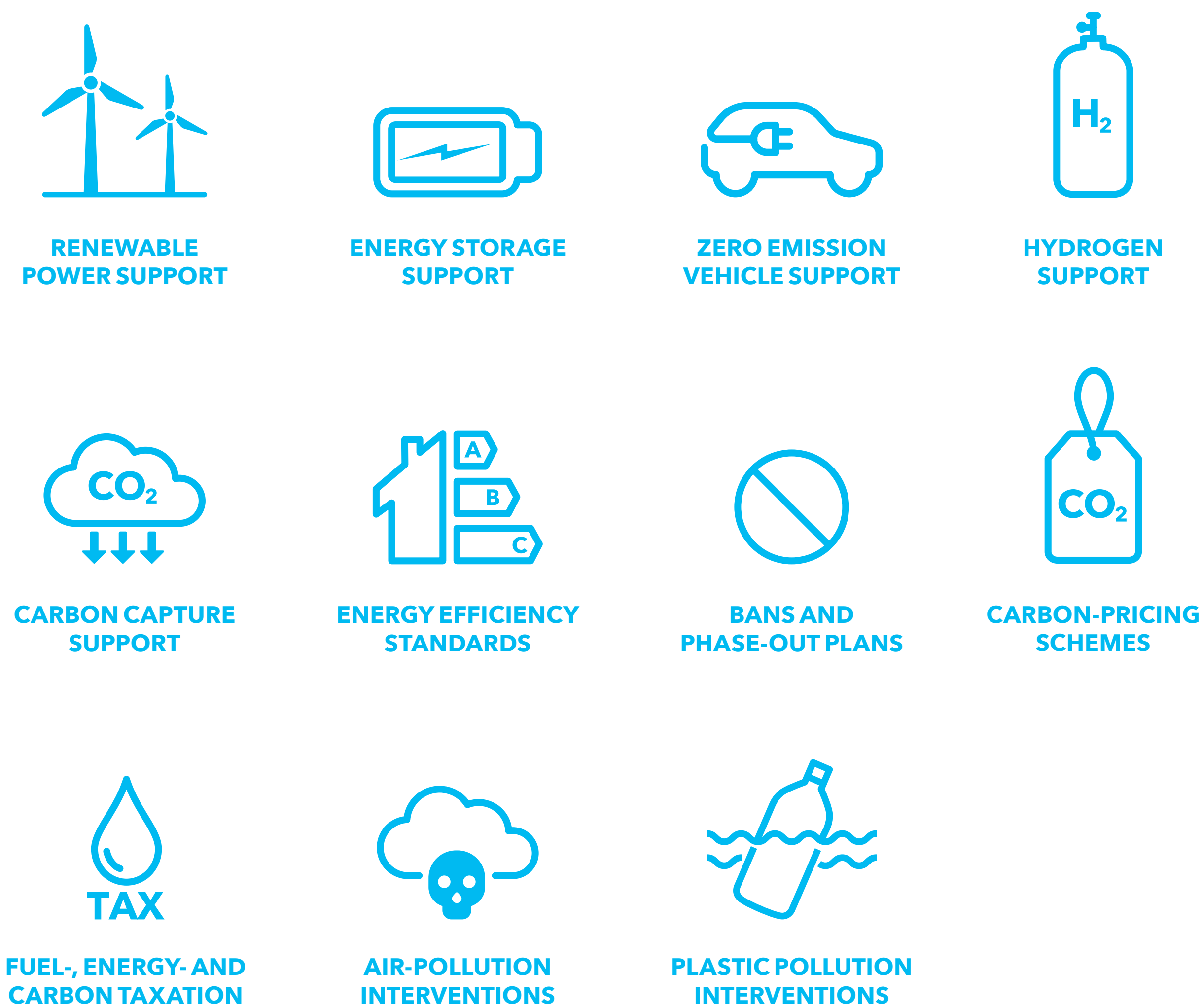
The most immediate policy considerations are those linked to the COVID-19 pandemic. As stated by former UN climate negotiation chief, Christiana Figueres (FT, 2020): "The most consequential question looming over us right now is not whether we can address the COVID-19 crisis and climate change at the same time, but rather whether we can afford not to do so." Our analysis explores the contrary motion that has been set in play by the pandemic: that it delays attention to the climate agenda (e.g., through the postponement of COP 26 to 2021, and potential reduction in investments in new and risky climate-friendly technologies, amplied by likely risk aversion amongst investors in the short- to medium term);

but, at the same time, reveals the importance of multilateral co-operation. In some countries, stimulus packages may emphasize job recovery in the fossil-fuel sector, whereas in others, policy responses are seeking to converge recovery measures with decarbonization efforts, air-pollution measures, and other objectives. There are signs now of both directions being pursued.

The pandemic is also likely to lead to long-term behavioural changes (e.g., normalizing remote working) and may permanently affect some key energy-intensive industries, such as aviation. As we explain in Chapter 1 of this Outlook, the overall short-term effect is likely to be dramatic, but the course of the energy transition is unlikely to be delayed in the longer term.

FIGURE 5.1

Policy factors included in our Outlook



5.2 GLOBAL AGREEMENTS FRAMING THE TRANSITION

Three important global agreements and reports frame the energy transition, all established as part of the UN system. The energy transition that we forecast takes these priorities into account against the backdrop of the key barriers and drivers presented in the pages that follow.

IPCC AND THE PARIS AGREEMENT

The Intergovernmental Panel on Climate Change (IPCC) is the UN body dedicated to providing objective scientific information on human-induced climate change, impact risk, and response options. At regular intervals it summarizes the latest science in comprehensive assessment reports; the previous report, AR5, was published in 2014 (IPCC, 2014a,b), and AR6 is expected in 2022.

Every year, the UNFCCC arranges the COP events, and, at COP 21 in Paris in 2015, 193 countries agreed on what is now simply referred to as the 'Paris Agreement'. The sum of what the individual countries promised to do in their pledges (the Nationally Determined Contributions - NDCs) is, collectively, far from sufficient to meet the target of keeping 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. According to the annual Emissions Gap Report by the UN Environment programme, the world is heading for 3 to 4°C warming (UNEP, 2019b). This year the NDCs are to be renewed, and the intention of the Agreement is that they are strengthened; however, that is occurring to only a limited degree, and possibly behind schedule with attention on COVID-19, and less on climate.

In our forecast, we have placed weight on the NDCs since they represent the stated intentions (conditional and unconditional commitments, the latter without outside support) of sovereign nations. As such, NDC ambitions guide the policy factors incorporated in the analysis. Nevertheless, we do not envisage that all countries will deliver exactly on their pledges; some will overfulfil them, others will fall short. How the regions perform in delivering on aggregate regional pledges is discussed in Chapter 6 on Regional Transitions.

THE IPBES BIODIVERSITY REPORT

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is an organization that was established to improve the interface between science and policy on issues of biodiversity and ecosystem services. In 2019, its first Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) was released. No international agreements have yet been established on the basis of this report.

The IPBES report is important for the energy transition as it underlines that the transition is taking place in a complicated context, with both competing and correlating priorities. For many challenges (e.g., acidification of the oceans) climate and biodiversity priorities go hand in hand. For other challenges (e.g., biofuels, reforestation, or renewable energy installations), there can be conflicting interests.

THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The 17 SDGs, which were adopted by the UN and 193 nations in September 2015, describe the future that humanity wishes to achieve by 2030. This Outlook does not specifically address the SDGs, but there are many interdependencies between SDG achievement and the energy future, particularly SDG #7 (Affordable and clean energy) and #13 (Climate action). There is ever-growing recognition of the need to balance priorities and trade-offs between the goals, such as those between economic growth and biodiversity protection, and between water and land use for food production and for energy activities. Low energy demand and accellerated energy efficiency have been shown to have the most pronounced synergies and the lowest number of trade-offs with respect to the SDGs (IPCC, 2018).

RATCHETING UP THE NDC AMBITIONS

The Paris Agreement's central aim of keeping the global temperature rise "well below 2°C" is only given effect by the individual climate ambitions from each country – the so called Nationally Determined Contributions (NDCs). NDCs describe a country's climate plan for reducing emissions, considering its domestic capabilities and circumstances.

Every five years, each country must prepare and communicate its NDC with increasing ambition levels. Together, they represent the collective effort of the 189 parties that, per today, have ratified the Agreement. However, looking at total emissions in line with current pledges, the IPCC's Special Report on 1.5°C (IPCC, 2018) expects global warming of 3 to 4°C, meaning that new NDCs have to be far more ambitious, i.e., they need "ratcheting up". The prospect of 'a raising of ambitions' is ambiguous. UNEP and other research organizations concluded in a recent report "The Production Gap Report" (SEI et al., 2019), that countries' planned fossil-fuel production surpasses those production levels that are consistent with the implementation of stated NDCs. This suggests that, in addition to current NDCs having insufficient ambition levels to begin with, there is also minimal policy attention on curbing fossil-fuel production, thereby hindering collective efforts to meet the Paris Agreement goal.

To monitor progress, the Paris Agreement includes a "Global Stocktake", allowing for a global review of climate-policy pledges, including financial commitments and country's mitigation achievements. With the Paris Agreement dating back to 2015, the year 2020 is where new or updated NDCs and GHG-reduction plans should be communicated by each country. To date, only 9 countries have done so, while 7 countries have confirmed they will not update their NDC or they have re-submitted their old targets; these countries include large emitters like USA, Australia, Russia, Japan, and Indonesia.

Our forecast is not steered by pledges to the Paris Agreement, although we let those ambitions guide the policy factors incorporated in the analysis. As shown in Chapter 6, we compare forecast energy-related emissions with aggregated region pledges for emissions reduction. Our forecast suggests that most regions are on a development track to meet 'old' pledges, indicating that most NDCs have targets that are too weak and lack ambition. Furthermore, this indicates that in most regions, the official pledges are not forcing politicians to tighten their policies.

THE 17 SUSTAINABLE DEVOLOPMENT GOALS

5.3 DRIVERS AND BARRIERS

DRIVERS

1. A PLANET PUSHED BEYOND ITS LIMITS

The body of scientific evidence, like the IPCC's Special Report on 1.5°C (IPCC, 2018) and IPBES Global Biodiversity Assessment (IPBES, 2019), paints an alarming picture of environmental degradation, adding to climate risks and air-pollution concerns, the latter probably also exacerbating vulnerability to COVID-19. Global warming, degrading ecosystems, and the potential for pandemics are closely interconnected and create a cocktail of risks. They are manifestations of a planet that has been pushed beyond its carrying capacity due to the exponential pressures of human activity; they provide a glimpse of our vulnerabilities and of climate damages to come. Ongoing crises will, ultimately, make society understand the urgency and will force changes in behaviours, priorities, and policies, to solve related problems.

2. ENERGY SECURITY

Renewable energy and battery technologies strengthen local energy security by exploiting distributed and domestic resources. Renewables diversify the energy mix and enable substitution of imported fossil energy, reducing both reliance on foreign suppliers and exposure to external market forces, as well as positively affecting the trade balance. COVID-19 stimulus packages contain measures supportive of clean energy and energy efficiency, also contributing to securing supply and boosting economic resilience.

3. GLOBAL-GOVERNANCE AGREEMENTS

The Paris Agreement, the SDGs, and the Convention on Biological Diversity all encourage nations to work in the same direction, towards shared targets on decarbonization and the energy transition. Ratifiers have laws addressing climate change, low-carbon transition, and nature-preserving solutions. They also promote clean-technology uptake, obliging businesses to act, drive, or assist. The pressure on politicians to act responsibly has already risen from a civil youth movement (e.g., the Global Climate Strike). This is now being amplified by a broader cross-generational push for judicious COVID-19 recovery spending that keeps the climate-neutral economy and energy transition in focus.

4. INFLUENTIAL SUB-NATIONAL GOVERNMENTS AND CORPORATIONS

Cities are pivotal in accelerating commitments to the energy transition, both because humanity is rapidly urbanizing (UN, 2019) and because cities must adapt to cascades of climate impacts more rapidly than rural areas (DNV GL, 2019b). State and city-level policymakers are moving to improve urban-air quality, reduce carbon footprints, create jobs, and build resilience against climate and power disruptions. They spearhead the deployment of clean-transport options, are imposing restrictions on ICEVs , and are promoting renewables-based heating and cooling. Global networks, such as the Global Covenant of Mayors, support diffusion of best practices. Corporations are primarily urban based and, motivated by reporting requirements, responsible sourcing, and the reliability of energy supply, are expanding renewable-energy power-purchase agreements (PPAs). Companies are prompting the energy transition with carbon neutrality ambitions and advocacy for a price on carbon.

5. COSTS ON DIVERGING PATHS

Cost curves of extractive hydrocarbons and renewables will cross and diverge. Solar and wind have reached cost parity and are already the cheapest new-electricity options in most regions, and set to improve further. Global markets are accelerating the spread of new technologies, with a self-reinforcing cycle of falling costs through further deployment. ‘Plus-storage’ projects are also reaching parity as battery costs plunge. Oil and gas industry cost reductions, digitalization gains, unconventionals, and continued subsidies will delay the divergence. However, hydrocarbons face pressures from the pandemic-induced downturn in tandem with rising extraction costs (deep sea, Arctic), carbon prices, and the unpredictability of returns due to the structural decline in oil demand.

6. INVESTORS EYEING CLIMATE RISKS

The cost of climate risk is moving up the financial world’s agenda. The recommendations from the Taskforce on Climate-related Financial Disclosures (TCFD) are streamlining energy and carbon reporting, and providing transparent market information on climate-related financial risks. Collectively, supporters of the TCFD are in control of assets worth USD 138trn (Carney, 2020). Climate risk will be priced and climate innovation rewarded, accelerating, in turn, the environmental, social, and governance (ESG) trend that already rewards investments with lower cost of capital (MSCI, 2020). COVID-19 and record-low fossil-fuel prices put further focus on the transition risks, and green stimuli in the wake of the crisis could further accelerate this trend.

7. TECHNOLOGICAL PROGRESS

The energy transition is riding a wave of technological developments, ranging from remote working platforms taking off during COVID-19, to improvements in materials and developments in batteries, additive manufacturing and new industrial digital technology. An array of factors is enabling change in all sectors of the energy system and impacting costs and efficiencies, i.e., decoupling energy use from growth in emissions, economy and populations. The deep embedding of IT in industrial technology and energy systems backs the coordination of energy supply-and-demand sectors in real time. This enables new ways to integrate renewables into the system and to optimize resources across borders and energy carriers.

8. NEW MARKET AND BUSINESS MODELS

With technological progress, and supportive policy, markets and business models are transforming to match the operating characteristics of new technologies. Sector coupling forms new linkages between actors in traditionally siloed sectors. New service-based models, enabled by digital technologies, are mounting, such as urban 'mobility-as-a-service' offerings include electric vehicles (EVs), bicycles, and scooters. Pay-as-you-go companies are offering access to energy services in areas with poor access. Also, oil and gas companies announce a transitioning of business models to become providers of electricity and low-carbon fuel, and with commitments to decarbonize.

BARRIERS

1. POLICY UNPREDICTABILITY

Electorate priorities and political cycles are short term. Changes in governments, with ensuing flip-flopping energy policies or regulatory procedures, introduce uncertainty and undermine investor confidence. Although clean-energy technologies are becoming less dependent on government support, decarbonization projects face continued transition risks related to policy making and implementation. Only five countries (New Zealand, Sweden, France, the UK and Scotland) have climate laws for net-zero emissions by mid-century (WEF, 2019).

2. CONFLICTING SDG PRIORITIES

Actions on SDG #8 on sustained economic growth and other human development-related SDGs collide with the more environment-related SDGs, such as climate (SDG #13), biodiversity on land (SDG #15) and sea protection (SDG #14). In developing coal-based resources to improve energy access (SDG #7), nations accelerate climate change, air pollution, and ocean acidification, hence counteracting other goals. SDG #15, which is concerned with protecting life on land, halting deforestation, and reducing biodiversity loss, also risks being negatively impacted by renewable-energy expansions.

3. SUBSIDIES AND LACK OF EXTERNALITY PRICING

Direct subsidies – of consumption and production – as well as inadequate pricing of fossil fuels distort competition between energy technologies. A political misstep is that fossil-fuel subsidies outmatch support to renewables by a factor of four (IRENA et al., 2018). Despite pledges to tackle climate change, an estimate of implied global fossil-fuel support, inclusive of financial impacts of negative externalities, such as cost of global-warming impacts and air pollution, is USD 5.2trn, or 6.5 % of world GDP (IMF, 2019).

4. LOBBYING FOR THE STATUS QUO

Incumbent industries are pressurizing national policy makers to throttle back change, avoid the retirement of uneconomic assets, and prevent new entrants. COVID-19-related stimulus packages could favour existing sectors due to their present economic importance and job preservation. Forbes (2019) reports that the world's five largest publicly owned oil and gas companies spend approximately USD 200m annually on lobbying to control, delay, or block climate-motivated policies. Contributions from industry tilt elected officials towards rolling back environmental rules and creating a regulatory and economic environment that favours the fossil-fuel industry over a clean-energy future.

5. LOCK-IN INERTIA

The energy transition depends on adequate infrastructure, e.g., on using existing grids to move renewable electricity beyond local use, and on using gas-pipeline infrastructure to transport hydrogen that has been produced by electrolysis using excess renewable power or from dedicated renewable facilities. But existing infrastructure also creates a 'lock-in' advantage for the fossil-fuel industry, for which it was originally designed. Inertia is amplified by vested interests, both industrial and unionized labour, that prefer the status quo. Policy and economics on the ground reflect the scale and legacy of technological systems – e.g. early write-offs are undesirable for long-life assets.

6. SOCIETAL PUSHBACK

As we have seen in Brazil and the US, voter anger over socioeconomic issues can lead to the election of climate-sceptic leaders opposed to climate-change action. Opposition can escalate when decarbonization policies hit the wallet without proper handling of distributional effects (e.g., gilets jaunes protesters in France). Carbon capture and storage (CCS) initiatives and renewables are subject to local protests on various grounds, including conflicting land-use interests, landscape impacts, or NIMBY-ism (not-in-my-backyard), where people generally favour clean energy, but not in their community. Such opposition routinely leads to delays, scale down, and/or cancellation of projects.

7. INNOVATION GAPS

Many decarbonization technologies exist but have yet to reach commercial readiness. Critical competence and technology development gaps still need to be addressed and much more investment in R&D is needed; for example, in battery-density improvements that will allow electricity to play a greater role in more sectors. Aviation has few renewable alternatives to oil and is, in general, hard to electrify. In shipping, the widespread implementation of alternative fuels and other efficiency measures faces barriers such as costs, fuel availability, space-requirement challenges, and high-cost machinery. CCS and hydrogen value chains are still very much in need of investment and innovation to scale.

8. MARKET DESIGNS NEED ADAPTATION TO NEW CHALLENGES

Scaling new technologies and their business models requires adequate governance. Market designs are tailored for a different era, when centralized thermal-electricity generation provided significant economies of scale. Rigidity in natural gas nomination processes and lack of co-optimization of power and gas grids contribute to inflexibility within current market designs and undermine the benefits of load-following generation. New market designs with volatile pricing are needed to manage volatility in supply, to integrate flexible resources, to obtain a higher share of variable renewables in electricity mixes, and to encourage sector coupling.

5.4 POLICYMAKER DILEMMAS

Although the trends manifest in the drivers and barriers are often beyond the control of any single organization or government, there are issues that merit consideration by all policymakers when navigating the energy transition. Some choices facing policymakers may be clear-cut, but others involve highly complex tradeoffs and require comprehensive planning and pro-active policy strategies. As we see it, there are at least ten dilemmas which, if they can be resolved by policymakers, will greatly impact future energy-sector developments, and hence the energy transition.

HUMAN HEALTH AND ECONOMIC WELFARE

The COVID-19 pandemic has thrown the health problems associated with poor air quality into sharp relief, and growing citizen dissent on air quality should be expected. Currently, 90% of the world's population breathe polluted air (WHO, 2018), and the Lancet Commission on pollution and health estimates the welfare losses from environmental pollution to be 6.2% of global GDP/year (Landrigan et al., 2017). With satellites (European Space Agency, 2019) and air-quality monitoring technology, such as Google's Street View car fleet equipped with sensors measuring street-by-street air quality (Google, 2019) developing rapidly, emission sources can be comprehensively observed on a near-daily basis. This, in turn, enables accountability in clean-air policies to control public-health hazards from point sources and traffic-related pollutants.

PHASE-IN/PHASE-OUT

The energy transition destabilizes technological systems through regulatory interventions and market drivers by phasing out 'old assets', that may or may not have reached the end of their technical lifetimes. Discontinuation as an integral part of energy policies is emerging, with examples from UK's transformation from coal to renewables and natural gas, or German Energiewende's nuclear and coal phase-out, while simultaneously supporting technological change and the uptake of alternatives.

TACKLING MULTIPLE GLOBAL CRISES AT ONCE

Global warming, degrading ecosystems, air pollution, and the potential for pandemics (such as COVID-19) are closely interconnected challenges. The scale of losses – human, economic, environmental – stemming from these global crises is ever more frequently observed. Lessons learned are part of government responsibility for acting on behalf of present and future generations.
In many cases, prevention is proving to be less costly than cure.

COVID-19 STIMULUS PACKAGES

The COVID-19 pandemic has revitalized the role of the state in the economy and public services to meet the needs of people. Economic systems are now being reshaped by governments' largest-in-history economic-recovery stimulus packages. Intelligent application, mindful of – and propelling solutions to global challenges, is crucial as it concerns long-lived energy assets that will impact the air, environment, and climate for decades to come. Through public spending it is possible to supercharge initiatives that were needed, but scarcely acknowledged, before COVID-19, such as in infrastructure, public health, and land restoration.

CARBON-INTENSIVE DEVELOPMENT TRILEMMA

Balancing policies for energy security, energy equity (accessible and affordable), and environmental sustainability is a well-known 'trilemma'. Some developing regions see coal as the default

Smoggy air over Mumbai skyline. Globally, 7 million people die prematurely every year from air pollution - both household and outdoor (WHO, 2018).

option, with carbon-intensive economic expansions. Ironically, in some cases these are assisted by cheap loans from countries that are themselves on a path towards technology renewal and emissions' reductions, yet benefit from selling off outmoded technology and knowhow. There are ample reasons to rethink policy and asset risk allocation, such that fuel costs and technology risks are carried by owners and operators of fossil assets, rather than by offtakers and consumers. In addition, development assistance can be prompted to align with climate goals and clean-energy pathways.

JOB CREATION AND DESTRUCTION

Energy-resource shifts create systemwide impacts on entire supply chains (e.g., from mining to heat and power production), and the associated socioeconomic implications need to be addressed. Some jobs are jeopardized, while others are created. The upskilling and reskilling of labour forces is at the core of energy shifts and requires transition planning. Enabling a 'a just transition' is a prerequisite for achieving policy targets; transition initiatives will fail in the absence of sustained support from a majority of voters.

STRANDED ASSETS

Both countries and incumbent fossil-fuel players have an interest in full exploitation of domestic resources, but it serves any economy well to keep an eye on the fundamentals of energy demand and supply. The oil price has already shown its sensitivity to demand; price wars indicate that players are trying to win a bigger slice of a shrinking market as a result of the structural downturn of the fossil-fuel industry due to cheaper renewable technologies and more stringent government policies. Policymakers are challenged to consider the risk of investing in assets that are likely to be stranded by the transition (WEF, 2020).

POSITIONING FOR GREEN COMPETITIVENESS

Growing first and cleaning up later is a potentially costly approach. It is likely to result in missed industrial opportunities, given the intensified technological competition in a marketplace moving from 'black to green', where energy savings and environmental-protection technologies are at the core of value creation. Studies show that well-designed environmental policy does not hurt the economy (IBRD, 2019). Furthermore, enhancing industrial upgrading and green transformation are key for policymakers to unlock innovation and for positioning in the growing global clean-tech market.

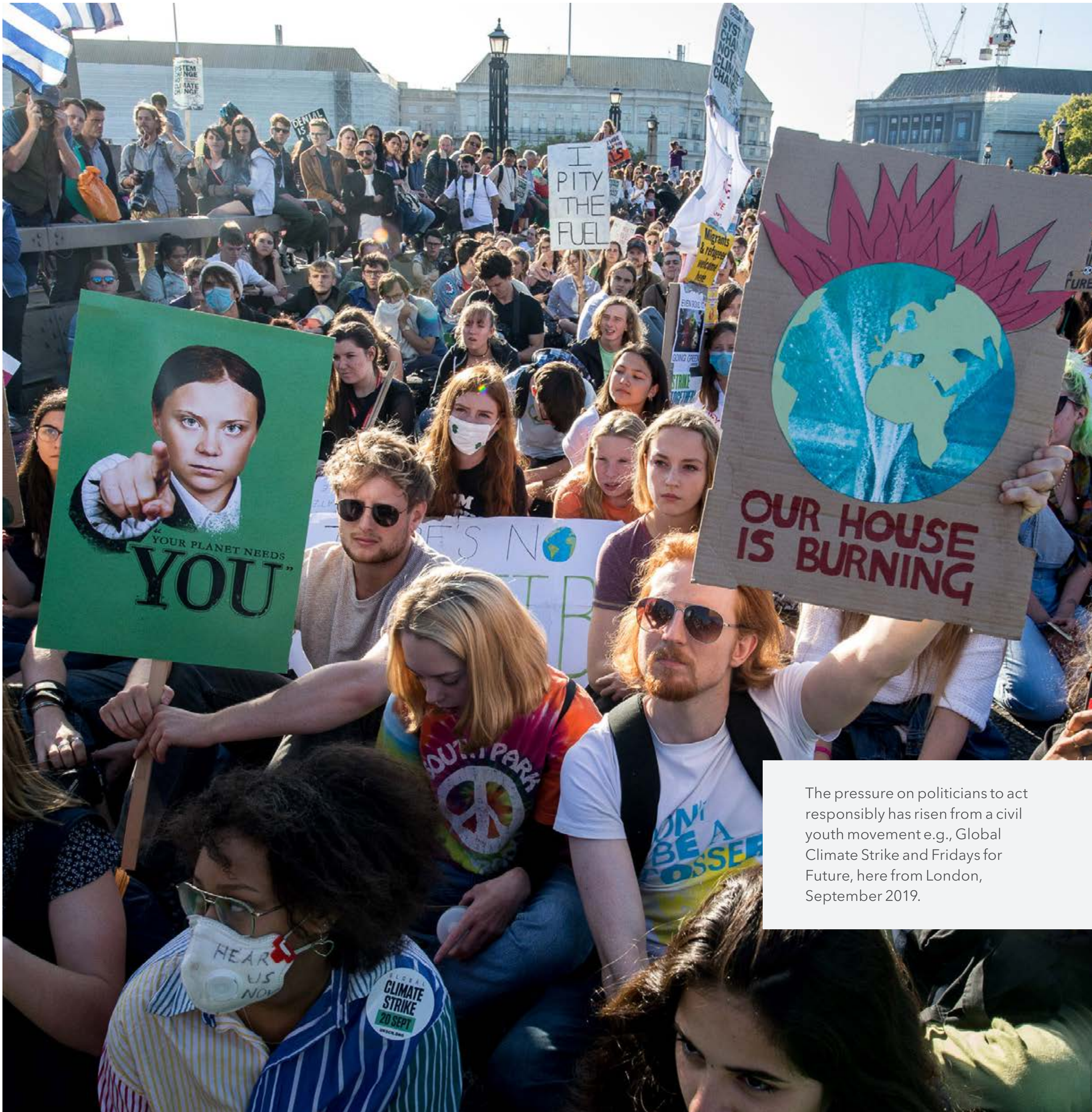
CLIMATE TRADE ADJUSTMENTS

Comprehensive carbon-reduction strategies are ineffective if they result in economic activity with high emissions relocating to regions with fewer carbon regulations. The import and export of carbon footprints are becoming central trade issues and speak for efficiency and emission-reduction measures globally - if countries wish to remain relevant as trade partners. Escalation on carbon border-tax adjustments is part of the European Green Deal to reduce trade-related emissions, avoid carbon leakage and to protect European industry from unfair competition.

INTERNATIONAL COOPERATION

Trade wars, inward-looking policies, and retreat from global economic integration narrow policymakers' room to navigate the energy transition. Global connectivity helps the spread of technologies, supports cost-learning rates, and can unlock synergies as the energy landscape is transformed. With electrification, strategic value will be found in tightly integrated infrastructures to balance capacity, overcome geographical mismatch in energy production, and ensure/adapt the transport of energy (e.g., natural-gas infrastructure to transport hydrogen).

> “Enhancing industrial upgrading and green transformation are key for policymakers to unlock innovation and positioning in the clean-tech market



The pressure on politicians to act responsibly has risen from a civil youth movement e.g., Global Climate Strike and Fridays for Future, here from London, September 2019.

5.5 POLICIES ADVANCING THE ENERGY TRANSITION

From past energy transitions, we know that government and industry players can effect fundamental changes by leveraging technology and stimulating pathbreaking entrepreneurship. The energy transition is an all-encompassing undertaking, with sweeping implications for energy players and business models, owing to the innovative and emergent technical characteristics of the future energy system.

Clean energy and related technologies have reached cost-parity with fossil energy, notably renewables in power generation, and are progressively driving the energy transition, allowing for market-driven global uptake. To meet energy needs, policymakers have affordable, proven, clean energy options, and hence a broader technology-opportunity space at hand – especially for electricity provision. For technologies in harder-to-abate sectors, solutions still need development and acceleration. As we concluded in last year's ETO, it is policy that struggles to deliver the full spread and potential of technology. Many regulatory frameworks are aligned with neither SDG nor Paris Agreement ambition levels and are seldom translated into real policy. In addition, technology options are not fully spurred for implementation across energy sectors.

Hence, policy needs to catch up, and will remain important for speed, scope, and scale-up. This is especially true for those parts of the energy system that are outside the power sector, where policy is not only far-less mature, but also less ambitious as seen in tracking and status reports (REN21, 2020).

Governments will use both 'carrots and sticks' to prompt changes. There is no silver bullet. Rather, a suite of policies is shaping the energy transition. The use of a policy toolbox, ranging from requirements (command & control) to technology-push and market-pull mechanisms and economic instruments, has already been proven effective in several technology areas (solar, wind, bioethanol, EVs, batteries) with a dynamic triggering of technology and cost learning curves (see Annex A.4). We see policy mechanisms playing distinct roles linked to the technological-maturity level, to stimulate commercial readiness and to shape the practices of incumbent companies.

The mix of policy options affects both energy demand and the supply side, and policies fall under three main categories: technology support, market activation, and economic signals, which require coordination as interacting closely in driving technical change. These categories are also incorporated in the ETO forecast, as described in detail in Section 5.7. For each of these policy suites, we suggest an associated policy toolbox.

STIMULATING TECHNOLOGY DEVELOPMENT

Technology-push policies foster innovation through funding of research and development of technology alternatives, hence stimulating the interaction between R&D, production, and learning-by-doing. Investment support stimulates technological advances, in particular with immature technologies, far from commercialization and with high unit costs. Funding for initial projects, nascent industries, and industrial-scale demonstration helps to prove performance, trigger cost-learning rates, and generate stakeholder alignment. Systems-design thinking and a more flexible approach will be required to support trial-and-error experimentation and to ensure that regulated entities recover some of their spending.

Policy toolbox:

– Energy-technology roadmaps and plans for long-term energy system development matched with technology priorities, such as seen in the

COVID-19 RECOVERY PACKAGES

The COVID-19 crisis has now amplified policy uncertainty. The profile of the economic recovery packages that governments are implementing around the world has the potential to either speed up or to slow down the transition to a decarbonized energy system. The last six months have shown many examples of both, and as we write in our COVID-19 section in Chapter 1, at present, the stimulus packages appear, in sum, to give equal support to the fossil and non-fossil sides of the energy mix.

Using our ETO model, we tested whether the impacts of such policies will be lasting or temporary. These tests include increasing the support for EV purchases or putting additional funding into – or removing funding from – renewable energy or CCS over the next five years.

We see that EV sales in 2040 would be 12% higher than our base case level if governments granted additional funding to scrap vehicles at double the base-case rate and mandate the replacement of those scrapped vehicles by EVs over the next five years. Furthermore, annual offshore wind-capacity installations in 2040 would be 12% higher than in our base case if the retirement rate of all fossil-fired power stations is doubled through to 2025, and an additional support reducing the levelized cost by 10% is provided to renewables. For onshore wind and solar PV, the impact is much lower. The main reason for the difference is the self-reinforcing reduction in technology costs we get with additional funding, which is strongest for less-mature technologies. These results support the idea that the stimulus packages implemented in the near term have long-lasting consequences.

Our tests also show that an increase in the support for fossil-fuels may delay uptake of new technologies that will replace them. However, the long-term impact of such policies will be low as market forces will override the support given to these technologies.

The world's first floating wind farm, Hywind Scotland at Buchan Deep. Image courtesy Equinor/ Øyvind Gravås/Woldcam

Strategic Energy Technology (SET) plan defining energy-related research and the innovation agenda in Europe on selected technology areas (European Union, 2019).

- R&D investments with project support and public infrastructure spanning the spectrum from power grids and high-speed rail to digitalization and to recharging or hydrogen-refuelling infrastructure. CCS and carbon-free hydrogen production will also require massive learning and scale up. Germany, South Korea and Japan's hydrogen programmes suggest the need for government support in the scale of USD 370 to 620 million per year (300 to 500 million Euros).

- Technology requirements – such as building codes and product/technology standards – set minimum requirements on, e.g., energy efficiency, fuel economy, and emissions limits (vehicles and power plants). The pursuit of clean air is mounting worldwide. This is exemplified by China's Action Plan for Winning the Blue-Sky War and efforts to cap coal use, India's National Clean Air programme with emission-control standards on coal-power plants, and South Korea's countermeasures after declaring air pollution a 'social disaster'.
  - China's 5-year plans and the EU's Energy Efficiency Directive are programmes targeting productivity gains in buildings, transport, and industry sectors. The EU's 'energy-efficiency first' principle requires that all new policy actions first consider whether an objective is achievable through energy efficiency.

MARKET ACTIVATION

Market-pull policies promote market deployment of solutions and accelerate uptake to help viable technologies achieve a decline in unit costs. This happens through learning-by-using and feedback for further technology development, industrial efficiencies, ongoing market-focused R&D, and economies of scale. Lower costs have a self-reinforcing effect ensuring more sales, which, in turn, trigger lower costs and more buildout, etc. This pattern has been observed from early efforts among pioneers in bioethanol, solar, wind, and, lately, in batteries and EVs. As an example, Norwegian EV purchase incentives have resulted in high EV adoption (fraction of EVs in the passenger vehicle fleet surpassed 10% during spring 2020), which, in turn, helped to push down global battery prices to lower than they would have been otherwise (DNV GL, 2020e), thus increasing global BEV uptake and reducing carbon emissions.

Policy toolbox:

- Economic instruments such as tax reductions, subsidies for EV purchases and charge points, battery storage, low-emission choices in heating and cooling, feed-in tariffs for renewable power, and other influences on energy prices, are in play to stimulate market uptake.

- Renewable energy auctions for contracts to develop power-generation capacity and successfully boost developments, as seen in Latin America where around 80% of the current renewable-energy capacity is built with public tenders and auction schemes.

- Market requirements such as binding targets on renewable-energy use/portfolio standards, green 'public' procurement prioritizing lower energy/carbon content, and biofuel blending mandates in, e.g., road transport and aviation, are policy mechanisms that promote the deployment of technology alternatives over others.

- Bans on polluting technologies such as phasing out diesel and petrol (ICE) cars, with 17 nations so far, mostly European, announcing bans, has now also elevated into an EU-wide discussion on a potential ban in 2035 or 2040. The Powering Past Coal Alliance counts 33 national, and 27 sub-national, governments committed to phasing out coal power in line with the Paris Agreement (OECD 2030, RoW 2050). These bans send a clear policy signal, but only represent around 5% of global coal-fired power capacity, as the ten countries with the largest capacities have not made phase-out commitments to date.

- Enabling policy such as consumer information and energy labels rank appliances and products according to energy consumption. For example, the Energy Star programmes originating in the US have spread globally, providing energy-efficiency information on, e.g., consumer electronics and lighting products. In the future, publically transparent and standard labelling of information about product attributes is likely to expand into other areas of energy use, including the use of water. Education, technical training and job retraining programmes, are other key enablers.

ECONOMIC SIGNALS TO FIX MARKET DISTORTIONS

The pace of the energy transition will be influenced by the political feasibility of dealing with barriers to the uptake of clean technologies. Inadequate carbon pricing and persistent fossil-fuel subsidies, as well as the lack of internalization of negative externalities, are market distortions that delay the energy transition. In some countries, carbon prices are, in fact, negative, owing to high financial support for hydrocarbons. Fossil-fuel subsidies drain public budgets and are distortive, in that they lower the cost of production and/or the price paid by energy consumers.

Fixing these market distortions has cross-sector relevance for creating a global level playing field for products and industries, and for closing the cost differential between 'black and green' technologies. In sectors less prone to electrification, where emissions are harder to abate and technologies are less mature, in the absence of robust carbon pricing it will be especially difficult to see rapid technology uptake, such as CCS and lower-carbon fuels in shipping and aviation.

Policy toolbox:

- Pricing carbon and other negative externalities (e.g., air pollution, environmental damage) provides a clear market signal. A carbon-pricing scheme can impose a tax on emissions or set a

G20 leaders at the Pittsburgh Summit pledged to phase out and rationalize inefficient fossil-fuel subsidies.

cap on emissions while allowing trading to achieve the most cost-effective reduction.

– Phase-out of fossil-fuel subsidies to reform energy pricing, accompanied by supportive measures to mitigate impacts on vulnerable groups. Current low fossil-fuel prices provide an opportune time for reform.

– Revision of government funding and export credit guarantees to consider, e.g., climate risk.

Both subsidy savings and carbon-pricing revenue can be channelled into a shift to low-carbon alternatives and energy efficiency, and support a rise in NDC ambition levels (as discussed in our sidebar on Ratcheting up NDC Ambitions). How savings/revenue are spent will be key to political feasibility and public acceptability. Canada created a Just Transition Taskforce in 2018, and revenue from its CO_2 tax will be recycled and returned to the population ('People's payout') on a per capita basis, to build public acceptance when the average tax burden remains unchanged (Carattini et al., 2019). California's Emissions Trading System (ETS) compensates all households with a 'Climate Credit' on utility bills, and some ETS revenue goes to a greenhouse gas (GHG) Reduction Fund for low-carbon technologies and mitigation.

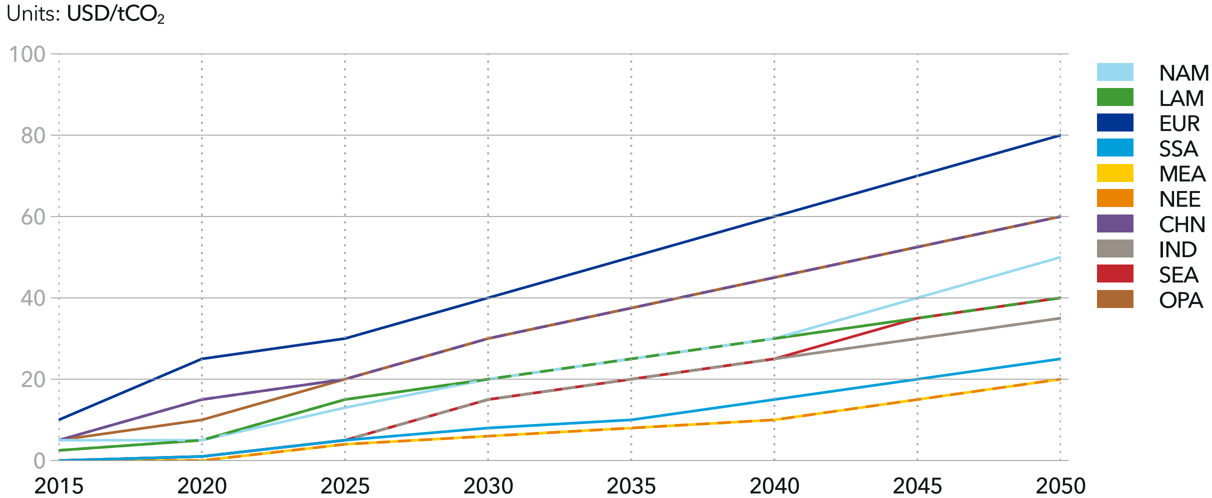
The adoption of carbon-pricing systems and associated revenues is expected to grow, both in prices and coverage. This is mainly to meet climate targets, avoid carbon border-tax adjustments, as well as to access climate finance and international trade in mitigation (article 6 of the Paris Agreement). In our forecast, the modelling includes our best estimate of future carbon-price levels, reflected as a cost for fossil fuels. Regional carbon-price trajectories are shown in Figure 5.2.

Fossil-fuel subsidies in the extraction sectors are incorporated in cost projections – and reform of subsidies and other preferential treatments will evolve slowly, given predominant policy focus on job preservation. On consumption subsidies, we incorporate these as part of fuel and energy taxation (section 5.7). Demand-side subsidies will perpetuate; however, we see tax levels increasing to reflect air-pollution prevention, efforts to limit congestion and emissions, set by the regions covered in our forecast.

FIGURE 5.2

Carbon price by region

Units: USD/tCO_2



CARBON PRICING AND FOSSIL-FUEL SUBSIDIES

DEVELOPMENTS IN CARBON PRICING:

According to the World Bank's Carbon Pricing Dashboard, 2020 initiatives cover 12 Gt of equivalent carbon dioxide (CO_2e), representing 22.3% of global GHG emissions. As of April 1, 2020, approximately 46 national and 32 subnational jurisdictions had placed, or planned to place, a price on carbon. Schemes are implemented across the world, including in New Zealand, South Korea, Canada, South Africa, Argentina, and many others. The EU ETS and supplementing national taxation among member states make Europe a front runner in carbon pricing. The domestic ETS in China, initially on the power sector, starts trade in 2020 and covers 26% of national emissions.

Carbon price-levels are far from uniform and remain insufficient, as 51% of emissions covered are priced below USD 10/tCO_2e, while Sweden and Switzerland's carbon taxes are notable exceptions, at USD 129 and USD 96/tCO_2e, respectively (World Bank, 2020). The High-level Commission on Carbon Prices (2017) concluded that the explicit carbon-price level consistent with achieving the Paris temperature target must be at least USD 40-80/tCO_2 by 2020 and USD 50-100/tCO_2 by 2030. The OECD's assessment of effective carbon rates, considering both taxes and emissions trading schemes across 42 OECD and G20 countries, shows that only about 10% of global emissions are priced at a level consistent with the 2°C target (OECD, 2018).

FOSSIL-FUEL SUBSIDIZATION – STILL HIGH:

Estimates of the global value of fossil-fuel subsidies vary according to definitions. Irrespective of definitions, it is clear that action fails to match long-standing pledges to phase out fossil-fuel subsidies. The United Nations Environment Programme (UNEP) – monitoring progress under SDG #12 on sustainable consumption and production patterns and its 12.c target/indicator: to rationalize inefficient fossil fuel subsidies – refers to an estimate of around USD 425bn annually in fossil-fuel subsidies (UNEP, 2019c). This estimate does not consider negative externality costs.

The low fossil-fuel-price environment represents an opportunity for pricing reforms on petroleum products and removing subsidies, such as seen with efforts in Indonesia and India. Recent announcements have come from Nigeria, with its long tradition of controlling fuel prices and payments to its national oil company; but previous attempts have seen modest results. Syria has announced a reduction in its vehicle-fuel subsidies, by removing from its ration system (offering subsidized fuel) the owners of more than one car and users of vehicles with powerful engines (Associated Press, 2020a). Egypt also aims to cut government-subsidy spending by 47% to USD 1.8bn in its 2020/21 budget (Associated Press, 2020b).

THE EUROPEAN GREEN DEAL

The EU sets a strong example of putting the policy toolbox to work in executing its energy and climate policy. It is steering the transition through comprehensive plans and supportive measures, providing, in turn, a long-term planning horizon for business. This is most recently seen in the European Green Deal, the Sustainable Finance Action Plan and Taxonomy, and the COVID-19 Recovery Plan, of which the highlights are presented in greater detail below.

The new European Green Deal aims to transform the EU into a sustainable economy, while accelerating its decarbonization trajectory. It represents a considerable increase in ambition from existing policies, namely:

- Reduce GHG emissions in 2030 by at least 50% and towards 55% from 1990 levels (existing policies aim for 40% reduction from 1990 levels).
- Net-zero GHG emissions by 2050 (existing policies aim for at least 80% reduction from 1990 levels).

EUs net-zero target looks very ambitious, and is unlikely to be met owing to cost, the political difficulty of implementing a high carbon price and supply chains (aviation, maritime) beyond the EUs control.

The deal provides an unprecedented roadmap for coordinated regional climate action and will require a large number of new policies and technical details to be drafted. It brands the new Commission with a clear green profile; but to turn plans into action requires approval and support from all member states and Parliament.

NATIONAL ENERGY AND CLIMATE PLANS

Besides increased GHG-emission targets, the Green Deal distinguishes itself from previous climate policies through its increased coordination and cooperation efforts across countries, to align national efforts with European targets. Every EU Member State must deliver a National Energy and Climate Plan (NECP) for the period 2021 to 2030, outlining plans on energy efficiency, renewables, GHG emissions reductions, and interconnections, research, and innovation. The draft plans submitted by every country by the end of 2018 showed shortcomings in reaching Europe's targets of 32% renewables by 2030, its 32.5% energy efficiency target, and a 50-55% GHG reduction target. After recommendations from the EU Commission (EC), all countries (with the exception of Germany, Ireland, and Luxembourg) have now submitted final plans and the combined assessment is ongoing.

THE EU TAXONOMY - A MAJOR CONTRIBUTION TO SUSTAINABLE FINANCE

The EC estimates that EUR 520-575bn must be invested annually in the energy system to meet the 2050 net-zero goals (around 2.8% of EU's GDP). This is where the EU taxonomy comes in: a comprehensive set of technical screening criteria (performance thresholds) to define whether economic activities support a transition in line with the Green Deal and therefore can be labelled "green". The taxonomy is a major development in sustainable finance, increases transparency in a rapidly evolving green finance market, and will have wide-ranging implications for investors and debt-issuers working in the EU and beyond.

COVID-19 RECOVERY FUND – TURNING AN IMMENSE CHALLENGE INTO AN OPPORTUNITY

The willingness of states to use full force regarding COVID-19 stimulus packages provides a very large opportunity for the EU's proposed EUR 750bn recovery fund to support its Green Deal and put the Sustainable Finance Taxonomy into practice. Climate action already plays a role in all EU programmes, with a target of 25% of all expenditure contributing to climate objectives, and the EU's decisions on COVID-19 recovery will decide on the region's front-runner position in the global energy transition.

Ursula von der Leyen, President of the European Commission, presents #EUGreenDeal, December 2019: "The European Green Deal is our new growth strategy. It will help us cut emissions while creating jobs."

© European Union 2019 / Source: EC – Audiovisual Service / Photo: Jennifer Jacquemart.

FIGURE 5.3

The European Green Deal vision

BECOME climate-neutral by 2050

PROTECT human life, animals and plants, by cutting pollution

HELP companies become world leaders in clean products and technologies

HELP ensure a just and inclusive transition

5.6 SECTOR CHALLENGES AND POLICY OPTIONS

From our review of sector challenges, a picture emerges of future energy policies that increasingly focus on, and are supportive of, systemic innovation, as driven by the technical characteristics of the energy systems. Sector coupling is expected to play a pivotal role in overcoming challenges in hard-to-abate sectors and renewable-energy system integration, and has its own challenges that are addressed first. These sector challenges are addressed in more detail in the companion publications on Power Supply and Use, Oil and Gas, and Maritime Forecast to 2050 (DNV GL 2020a,b,c)

SECTOR COUPLING

The challenge:
'Sector coupling' (or sectoral integration) will be a core strategy in decarbonization of the energy sector and involves the increased integration of energy end use and supply sectors. The key driver behind sector coupling is the reduction in the cost of electricity production from renewable sources, lowering the overall costs of the energy transition by enabling electrification (directly or indirectly) of more areas of the economy – i.e., energy consuming sectors in transport, buildings, and industry.

Surplus electricity generates a need for storage and transport of energy/infrastructure, and creates business cases for renewable and low-carbon gases. Exactly which gases will be used in the future is uncertain, but the changing technical characteristics of the future energy system are already indicating a business landscape response in which industry boundaries are becoming blurred. For example, electricity companies are innovating to become alternative-fuel production companies, and also vice versa, with oil and gas companies becoming providers of electricity and low-carbon fuel. Power-to-x (the conversion of electricity into heat, gaseous or liquid energy carriers) has the potential to decouple power from the electricity sector, enabling use in other sectors.

Sector coupling involves an increasing level of integration of different energy carriers. However, it has the arduous challenge of connecting the electricity sector to gas, fuel, and heat sectors, in terms of both markets and infrastructure; this requires strategic decision making at national and regional levels.

The likely policy response:

– Research into system coordination and integrated energy-infrastructure planning and operation.

– Regulation for interoperability and functioning markets between countries and regions, also with changes to market design, charging arrangements. Harmonization of sector subsidies, taxation-levels and addressing externalities, to level the playing field.

– Infrastructure regulation shifting from natural gas to a variety of different (low-carbon and renewable) gases, also with clarity on access to infrastructure, quality standards, and safety measures.

– Stimulating technology development with R&D and financial support to renewable and low-carbon gas technologies, pilots, or demonstration projects for innovation across value chains and in order to mature production and achieve industrial scale.

– Market activation with support to appliance switchovers, development of hydrogen-distribution infrastructure (new/upgrades and conversions). Overall removal of barriers to electrification, e.g., addressing economic differences in fuels prices and equipment costs (electric compared to non-electric).

POWER SYSTEMS AND RENEWABLE ENERGY INTEGRATION

The challenge:
Electricity is becoming the central energy carrier and is increasingly sourced from low-cost renewable-energy sources. New electricity demand, for example from the electrification of transport and industry, is also connected to the expanding power system. With high shares of variable renewable power and new types of variable demand, challenges arise in managing technical, regulatory, and market impacts on power systems. Stronger transmission and distribution systems, and increased power system flexibility will all be required. Flexibility will have to come from both physical assets (i.e., batteries or fast-ramp-up natural gas plants), but will also be derived from markets for flexibility and the use of information technology to optimize power supply and demand through demand response, including cloud-based EV-to-grid solutions. Future electricity systems will be more complex, with shifts in the generation mix, demand, and sources of flexibility. Surplus

ENGV and Nel Hydrogen partnered project at ATCO facility in Jandakot, Australia, converts solar excess-capacity into hydrogen, using Nel's advanced PEM water electrolysis technology. ©Nel Hydrogen production at given times will need to find productive use instead of being curtailed and underlines the importance of sector coupling. Financing renewable projects will remain challenging owing to regulatory risk in areas with unstable regulatory frameworks, especially in developing economies.

The likely policy response:

- Market activation through feed-in tariff payments (with adjustment for falling costs) will remain important in less-developed renewable markets. However, they are expected to be increasingly replaced by renewable portfolio standards for qualifying renewable technologies, coupled with competitive auctions or merchant trade as markets mature. Provisions on guaranteed grid access and long-term purchase agreements will remain important.

- Lending and investing of government-sponsored development finance institutions are expected to increase their incorporation of sustainability criteria. Export credit agencies are exploring routes to make renewable projects more "bankable", by, for example, guaranteeing payment obligations under PPAs entered into by industrial companies, removing the counterparty payment risk.

- Fast-tracking and eliminating unnecessary 'soft costs' from lengthy planning, permitting, and contracting on new projects, will remain important.

- R&D will focus on energy-storage systems for different time durations and sizes.

- Evolving performance-based regulation to tailor utility revenue-models to the achievement of policy goals, such as in energy efficiency, reducing carbon intensity; as well as power system balance and stability, etc.

- Development of market designs to adapt power-market rules to a changing resource and demand mix.

- Economic signals with strong and rising carbon prices and a cap on emissions, will provide emitters with an incentive to cut emissions, in turn improving the business case for renewable-power projects.

HARD-TO ABATE SECTORS

The challenge:
All sectors will face continued pressure to reduce carbon emissions, but in certain demand sectors, like heavy industry, maritime transport, and aviation, alternatives to fossil fuels are less readily available or not practical. In maritime, alternative fuels and power sources vary greatly for different ship segments, as do their technical applicability and commercial viability. Direct electrification is expected to play a minor role, beyond the short-sea segment. However, power-to-x, with X in this case being liquids such as hydrogen used directly in its compressed or liquefied form, or used as a basis for different electrofuels (diesel, methane, methanol or ammonia), is expected to play a major role.

A global offsetting scheme is the near-term mechanism for capping growth in carbon emissions in international aviation, under the International Civil Aviation Organization (ICAO)'s CORSIA scheme. Longer-term emission cuts will increasingly require continued improvements in fuel efficiency and low-carbon aviation fuels to achieve carbon-neutral growth to 2050 (from a 2019 baseline) as offsets face more scrutiny and become more expensive. However, production capacity of sufficient feedstock and industrial processing at affordable prices are key to the deployment of sustainable aviation fuel (SAF) at commercial scale, and will require significant infrastructure investment and enabling government policy.

In manufacturing, most energy-intensive industries require large quantities of heat. Options to provide low-carbon heat include fuel switching from fossil-fuel sources to green or blue hydrogen, biomass, or concentrated solar power and electrification (power-to-x). However, few, if any, of

The cement industry emits approximately 8% of global CO_2 emissions. CCS is the main and most effective decarbonization option.

these options for decarbonizing industrial heat production are well developed or available at scale. Also, there are emissions from industrial processes that are not derived from fuel combustion alone. For example, the vast emissions from the cement industry come mainly from the limestone calcination in addition to emissions from fuel combustion to heat cement kilns. Replacing limestone or clinker with other minerals, could help reduce these process emissions. But the main and most effective decarbonization option is to apply CCS to the exhaust gases of cement kilns to prevent both CO_2 emissions resulting from fuel combustion and the calcination process. Strong policy incentives will be required to encourage a shift away from installed plants and equipment (i.e. fossil-fuelled boilers, many of which have a life expectancy of approximately 40 years) towards investment in technology alternatives which are at early stages of maturity.

The likely policy response:

– Stimulating technology development by roadmaps evaluating the short- and long-term potential for alternative fuels and propulsion technology (aviation, maritime), as well as frameworks for development and commercialization.

– R&D funding for industrial heat decarbonization, (pilot) project investments, and processing decarbonization options.

– Support to CCS upscaling and deployment; renewable and low-carbon gases and power-to-x projects.

– Support for the conversion of process technology from fossil fuel-based technology to electricity-based technology ("phase in-phase out"); changes to existing equipment and switching to alternative combustion-based fuels.

– Technology requirements on industry-specific emission limits, energy-efficiency targets and equipment standards, materials efficiency and circularity, the latter to replace primary production with more recycling of materials.

– Market activation through economic incentives to support upgrades and equipment expenditures. Caps on use of fossil fuels and mandatory targets requiring the use of low-carbon technologies are also expected. Development of risk-sharing arrangements, leveraging government funding to obtain private sector funding.

– Economic signals such as rising carbon prices will provide emitters with an incentive to cut emissions, but are likely to prove insufficient for alternatives to become economically viable; hence the need for other policy mechanisms. Carbon tariffs (carbon border-tax adjustments) are expected to address concerns regarding international competitiveness.

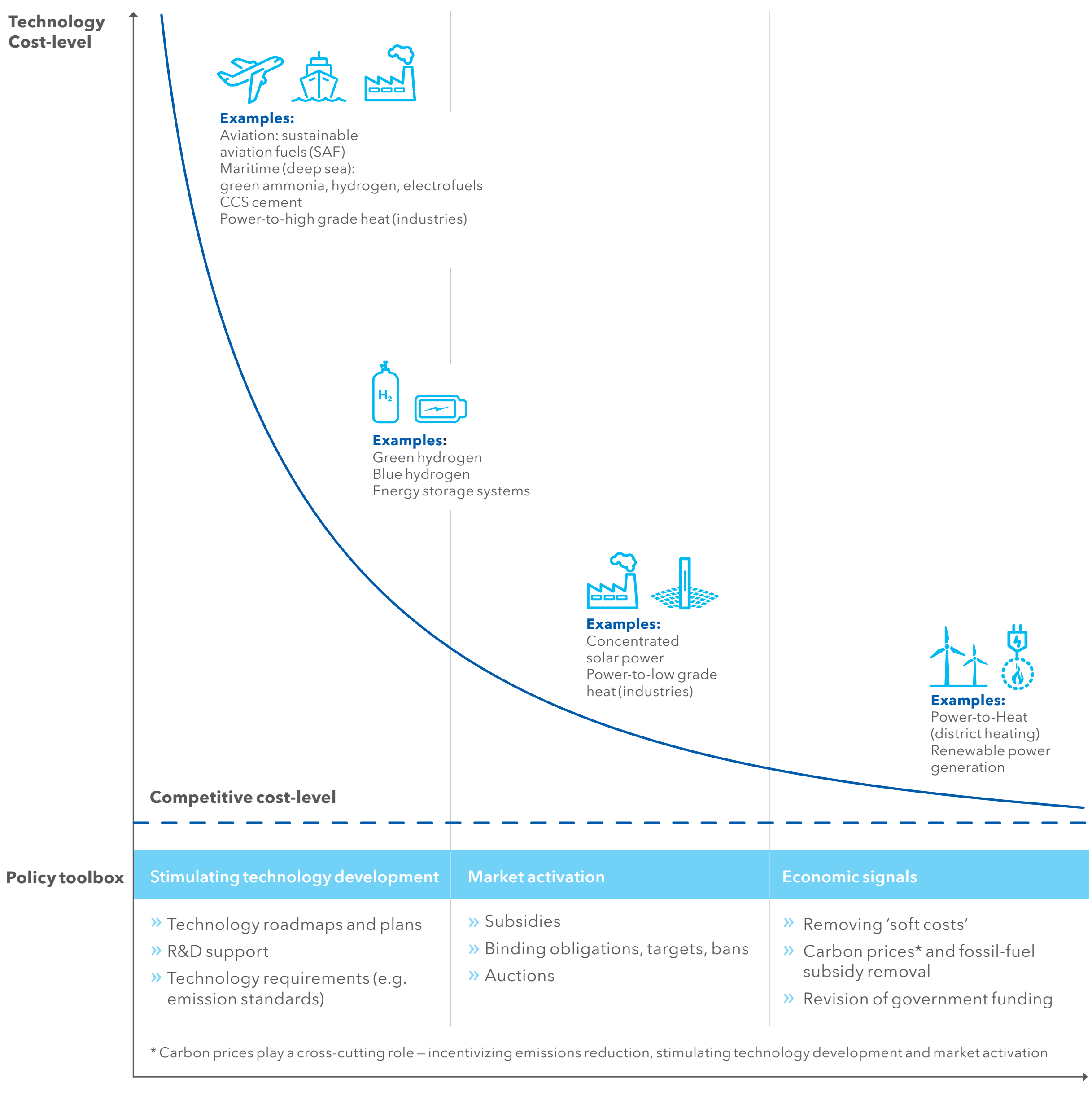
POLICY CHOICES AND TECHNOLOGY LEARNING CURVES

The three sector challenges evidence different phases of cost competitiveness and technological maturity, and as seen in the likely policy response, in turn require different policy mechanisms to stimulate innovation, trigger investment flows and set technology/cost evolution towards maturity in motion (see Annex A.4 for details on technology learning curves).

Figure 5.4 is inspired by the work of Harvey et al. (2018, p. 17) and illustrates the (simplified) predominant policy focus; but now also linking the specific sector challenges to the relevant policy toolbox, as presented in Section 5.5. In reality, policy combinations are expected for technologies and individual applications, such as combinations of R&D and market deployment support, combined with technology and efficiency requirements for continuous technological improvement. Economic signals, such as carbon prices are important across energy sectors (i.e. an incentive to cut emissions); but being most cost-effective in triggering technology substitution when sectors are price sensitive and there are low-carbon alternatives at near-competitive prices. The whole spectrum of policy options will be in play to tackle the highlighted sector challenges, and to mature technological solutions and their supply chains.

FIGURE 5.4

Policy toolbox and the technology-sector learning curve



5.7 POLICY FACTORS IN OUR FORECAST

Our forecast factors in policy measures spanning the entire policy toolbox discussed in Section 5.5. Policy considerations therefore influence our Outlook in various ways: a) supporting technology and activating markets that close the profitability gap for renewable energy technologies competing with existing technologies; b) restricting the use of inefficient or polluting products/technologies by means of technology requirement or standards; or c) providing economic signals - for example, a price incentive to reduce carbon-intensive behaviours. Country-level data are translated into expected policy impacts, then weighted and aggregated to produce regional figures for inclusion in our analysis. Here, we present a snapshot of policy factors in the analysis.

1. **Renewable power support**
   - To reflect historical and expected future support for biomass, solar and wind power, we assume that these technologies receive a subsidy calculated as a fraction of the gap between the expected profitability of renewables (expected received price – levelized cost of energy) and the profitability of the most profitable conventional technology in the same region.
   - The subsidy varies by technology and in terms of a region's willingness/ability to implement support.
   - The subsidy is removed as the profitability gap is closed.

2. **Energy-storage support (batteries)**
   - Existing and planned policy support is translated to an average support as percentage of battery unit costs for battery-storage technologies.
   - A 'willingness/ability' factor is included to reflect regional differences in ability and willingness to implement support.
   - Support levels increase with the share of variable renewables in the regional electricity generation, incentivizing investment in flexibility.

3. **Zero-Emission vehicle support**
   - We reflect an average regional EV support for both battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs), based on existing support at the country level.
   - We account for subsidies, tax exemptions, and reduced import duties, and translate this to an average CAPEX support per region per vehicle type.
   - We account for exemptions for parking costs, time savings (taxi lanes), toll roads, and vehicle taxes, which translates to an average OPEX support per region.
   - We assume a slight initial growth and a decline in preferential treatment from the current levels thereafter. The support is capped by the EV-cost disadvantage.

- Country-level targets for public fast-charging infrastructure (> 22kW) roll-out have been mapped to identify EV-uptake barriers. As charging infrastructure expands over the next decade, it is likely to do so increasingly on market terms and associated grid-infrastructure buildout will follow without any constraints.

4. Hydrogen support

- Existing policies that directly support hydrogen deployment for specific applications mostly target transportation. These policies are accounted for under "Zero-Emission Vehicle support".
- Hydrogen support in transport, manufacturing, and buildings is estimated on the basis of total annual government funding available for hydrogen research, development, and deployment (pilot projects, support for large-scale infrastructure, and industry projects).
- For commercial road vehicles and buildings, the speed of hydrogen uptake is determined by the speed of increase in carbon price, a hydrogen-policy factor, and by an indicator for the availability and quality of gas distribution infrastructure.

5. Carbon Capture and Storage

- The historical CCS implementations, as reported by the Global CCS Institute (2019), are fully incorporated, as well as their future project pipeline of plants and storage to 2030. These projects and non-enhanced oil recovery (EOR) applications receive investment and operational government support.
- Regional carbon prices determine the uptake of CCS in power and manufacturing.
- CCS of hydrogen production is assumed to be fully supported as needed.

6. Standards for energy efficiency

- Standards and regulation (existing and planned) for energy use and efficiency improvements in buildings, transport, and industry sectors are incorporated.
- Buildings: Standards for insulation thickness and energy use for appliances and lighting are used as guides while setting the input assumptions. However, the effects of policies are not quantified explicitly.
- Vehicles: Efficiency and emissions standards per region are incorporated and translated into normalised test-cycle values (New European Driving Cycle, NEDC). An adjustment factor per region is applied to derive real-world fuel consumption from the theoretical NEDC values. The fuel-efficiency trajectories towards 2050 follow the trends determined by these real-world-adjusted standards, adjusted for the EV uptake.
- Shipping: IMO 2050 carbon emissions fully implemented (IMO, 2018).

7. Bans and phase-out plans

- Bans on ICE cars are not incorporated in the forecast, but model results are compared with the announced bans.
- Phase-out plans on nuclear power of Germany and Spain plus regular shutdowns from Sweden, the US, France, are incorporated. For coal-fired power generation, our forecast references the phase-out plans of the following countries: Germany, Austria, Belgium, Finland, France, Greece, Hungary, Ireland, Italy, Netherlands, Portugal, Slovakia, Sweden, UK, Canada, Israel, Mexico and New Zealand.

8. Carbon-pricing schemes

- Our trajectories to 2050 consider hybrid pricing (cap-and-trade schemes and carbon taxation); both national and regional schemes, implemented or announced, have been subject to carbon-pricing expert commentaries/workshops.
- Our carbon-price trajectories (Figure 5.2) are reflected as costs for fossil fuels in the power and manufacturing sectors, as they generally participate in the same regional and/or sectoral carbon-pricing schemes.

9. Fuel-, energy- and carbon taxation

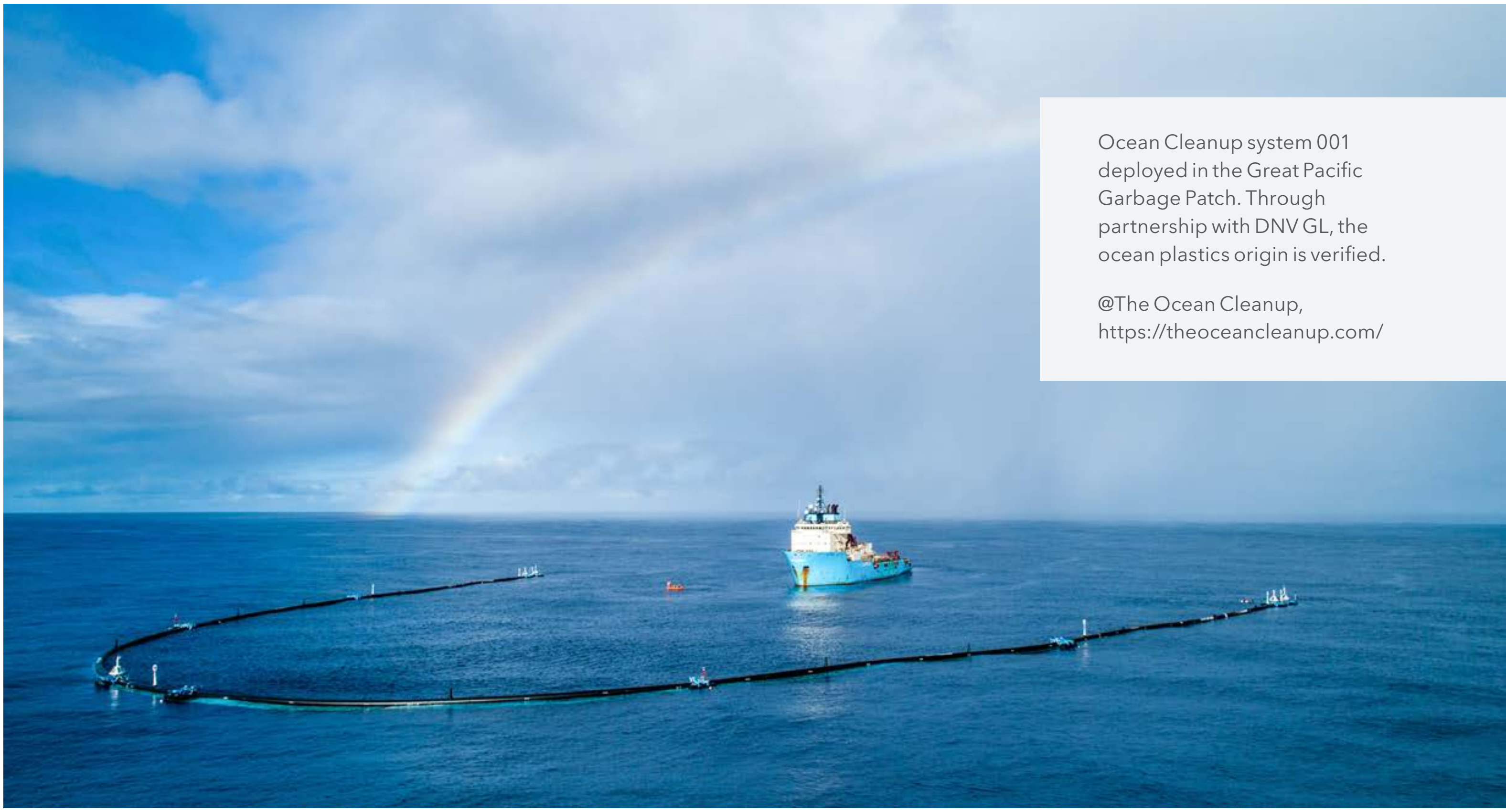
- Fossil fuels used in road transport are taxed at the consumer level, labelled as fuel or carbon taxes.
- Effective fossil-carbon rates per country are incorporated for road transport. These range from negative (indicating subsidies) in the MEA region, to positive (indicating taxation) in the other regions, with EUR seeing the highest taxation, doubling the price of diesel and gasoline for consumers.
- We assume that these taxes will increase in line with the region's carbon-price regime, growing at a quarter of the carbon-price growth rate.
- No change in energy tax rates are incorporated for the other sectors (maritime, aviation, industry, electricity generation).
- Biofuel use in transport will only grow because of mandated blend rates, as fuels e.g., ethanol and biodiesel will remain non-competitive on cost. Current biofuel-blend mandates will strengthen.

10. Air-pollution interventions

- Policy interventions are reflected by an air-pollution cost proxy that transfers costs of control measures to an operating cost per kWh, incorporated in power and manufacturing sectors.
- A regionally dependent ramp-up rate is used, going from 0 to 100% implementation of the operating cost over a certain period, indicating that regulations will be gradually enforced on more and more pollutants and plants.

11. Plastic pollution interventions

- Policy intervention on plastics, such as mandated recycling, trade restrictions, and extended producer responsibilities, are incorporated in the form of future year-on-year increasing recycling rates.



Ocean Cleanup system 001 deployed in the Great Pacific Garbage Patch. Through partnership with DNV GL, the ocean plastics origin is verified.

@The Ocean Cleanup, https://theoceancleanup.com/

HIGHLIGHTS

The energy transition unfolds differently in the various regions, and its speed and scale are influenced by a number of factors. These include: geographical and resource issues; legacy technological systems; stages of economic development; governmental strategies, priorities, and policies; and people and electorate preferences.

Thus, every region has a different starting point and a different trajectory – from OECD countries and post-industrial progress to emerging and fast-growing economies, to regions entering an era of development.

Our ETO model generates insights and captures this granularity, and, in the following sections, the regional story for each of the 10 regions is told, including:

- **Regional characteristics and the current position**
- **Pointers to the future**
- **The regional transition explained and illustrated with reference to transition indicators**
- **Emissions profile and forecast**
- **A forecast case example of a prominent feature of the regional transition**

CHAPTER

6

REGIONAL TRANSITIONS

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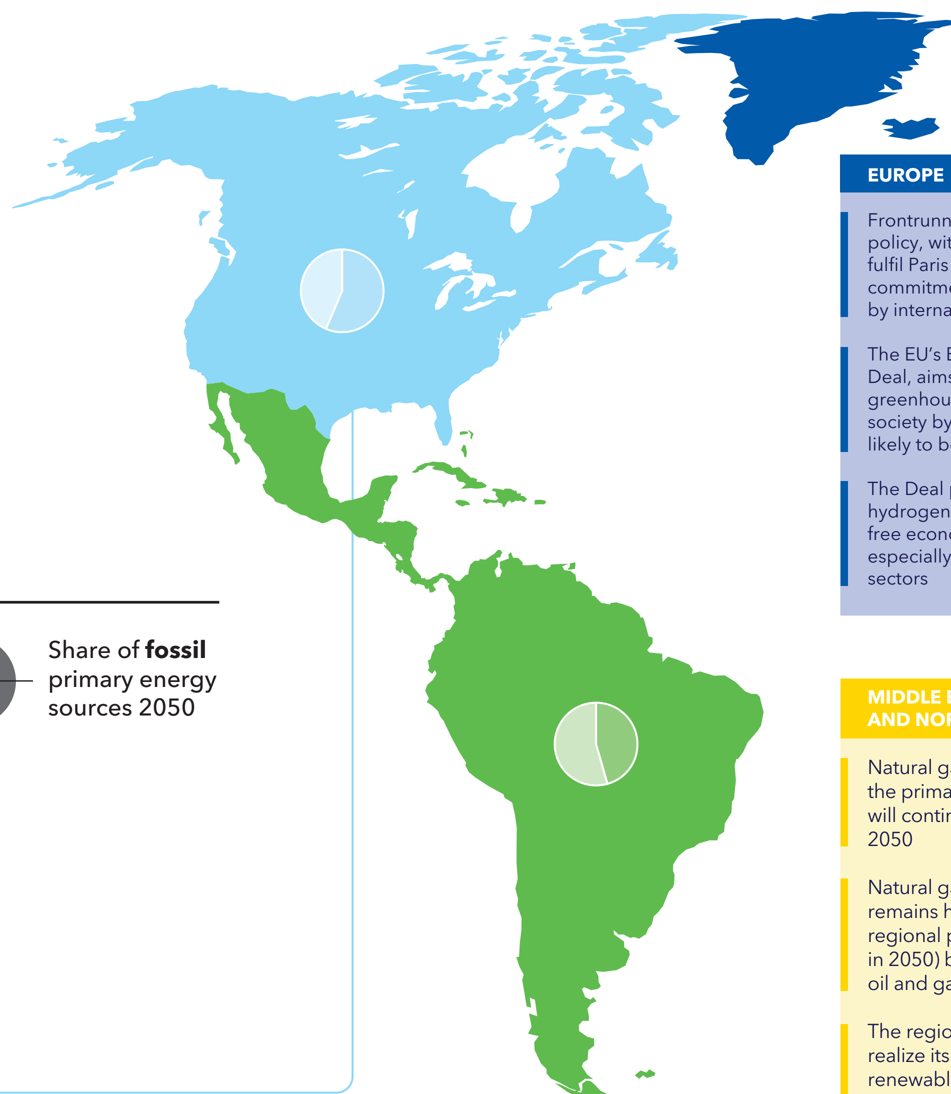
WE ANALYSE 10 GLOBAL REGIONS



KEY

Share of **non-fossil** primary energy sources 2050

Share of **fossil** primary energy sources 2050

EUROPE

- Frontrunner in transition policy, with the EU aiming to fulfil Paris Agreement commitments, but hampered by internal discrepancies
- The EU's European Green Deal, aims at a net-zero greenhouse gas emission society by 2050, which is not likely to be met
- The Deal prioritizes green hydrogen to support carbon-free economic growth, especially in hard-to-abate sectors

MIDDLE EAST AND NORTH AFRICA

- Natural gas and oil dominate the primary energy mix and will continue to do so until 2050
- Natural gas consumption remains high (50% of the regional primary energy mix in 2050) benefitting from low oil and gas extraction costs
- The region will start to realize its vast potential for renewable energy, reaching a 20% share in primary energy mix in 2050

NORTH AMERICA

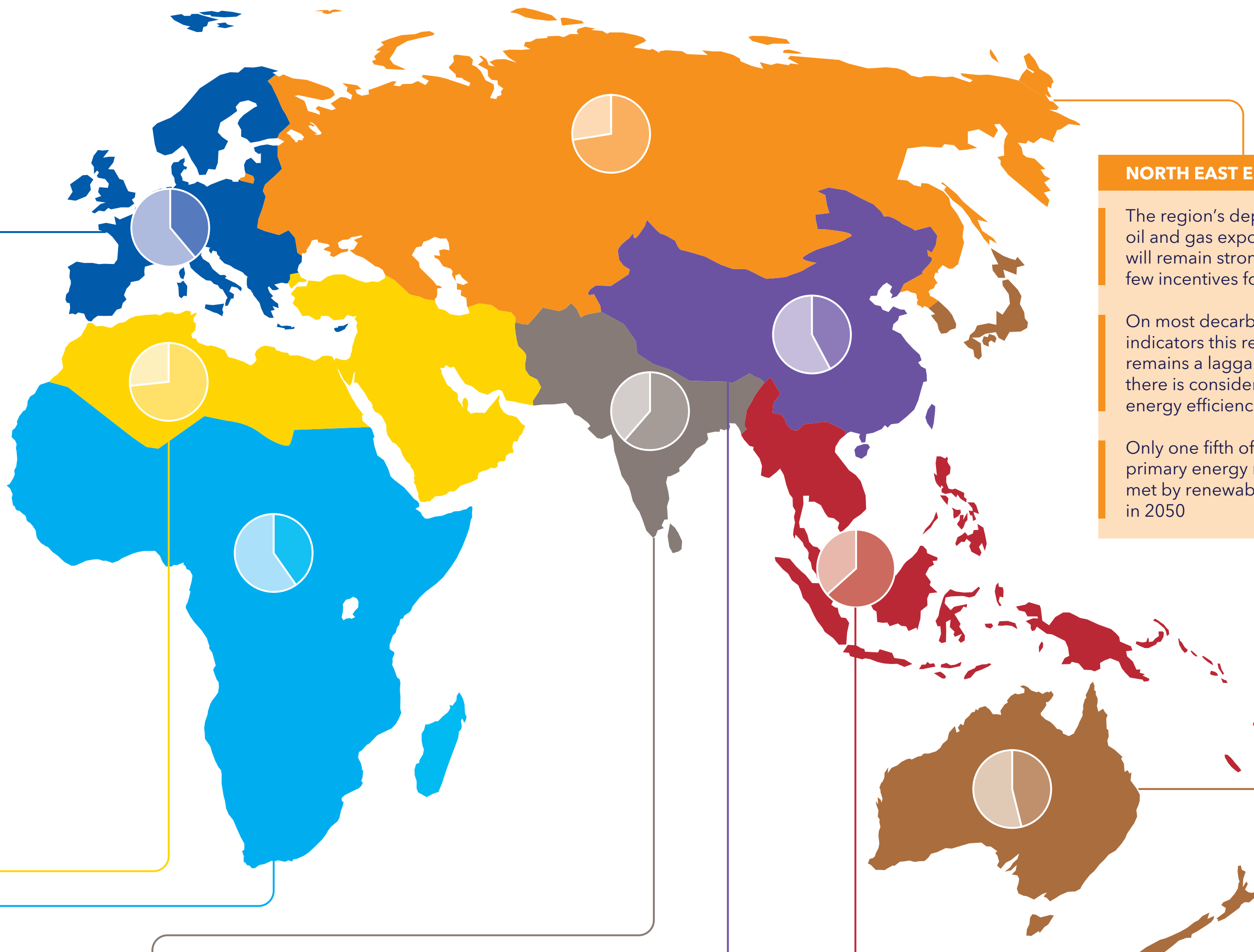
- Business cases and sub-regional policies will drive towards substantial regional decarbonization
- Oil use declines by more than two thirds and coal will have a marginal role from the mid-2020s on
- Strong natural gas growth supplies increasing domestic demand and unfolds LNG export boom in the coming decade

LATIN AMERICA

- Will switch from energy exporter to energy importer for reasons such as global energy system transformation, international competition behind supply, and shrinking demand for fossil fuels
- Electricity production from hydropower, natural gas and fuel oil will diversify into hydropower, solar, and wind
- Fossil fuels will represent less than 50% of the primary energy mix in 2050

SUB-SAHARAN AFRICA

- Least-developed and least-electrified world region; only 42% of its people currently have access to electricity
- Soaring energy demand from a growing population and economy will be counteracted by efficiencies, e.g. traditional biomass cooking replaced by gas and electricity
- Off-grid solar PV plays a significant role in energy access, and with grid-connected solar, accounts for almost 40% of power generation in 2050



NORTH EAST EURASIA

The region's dependence on oil and gas export revenues will remain strong, and give few incentives for change

On most decarbonization indicators this region lags and remains a laggard, although there is considerable focus on energy efficiencies

Only one fifth of the region's primary energy needs will be met by renewable sources in 2050

INDIAN SUBCONTINENT

500 million more people and GDP growing fourfold will see rising energy demand in this region

Despite the rapid growth of renewables, fossil-energy sources will also grow and represent 62% of the energy mix in 2050

The region's enormous two- and three-wheeler vehicle fleet will transition almost entirely to electricity before 2040

GREATER CHINA

Powerhouse for renewables growth and the energy transition, both for domestic use and abroad

The share of electricity in final energy demand will grow from 23% in 2018 to 52% in 2050 –highest of all regions, over 90% from renewable sources

Coal will reduce its dominant share in the power mix (currently 60%) to 12% over the forecast period

SOUTH EAST ASIA

Energy demand, especially from space-cooling and appliances, grows significantly but levels off towards the end of the forecast period

Increasing use of natural gas and renewables to supply domestic demand for electrification, will result in lower importance of coal and oil

Manufactured goods production more than doubles until 2050, driving demand for natural gas and transforming this region into a net-importer of LNG

OECD PACIFIC

Falling population and improved efficiencies will almost halve energy use over the forecast period. 2050 electricity mix is dominated by wind, and at 50% of final energy demand, is the second-most electrified region in 2050 after China

Hydrogen will gain a foothold (9% of energy use), sourced initially from Australia through SMR processes, but later mainly via renewably powered electrolysis

NORTH AMERICA (US)

This region consists of Canada and The United States

CHARACTERISTICS AND CURRENT POSITION

The Trump administration has rolled back Obama-era environmental regulations. Political partisanship has sidelined US climate policy. Federal tax incentives for wind and solar have remained stable, though a gradual ramp down of incentives starts in 2021 for wind, and for solar PV after 2024. Canadian federal policy remains supportive of climate action and emissions reduction.

Decentralized decisions by US states, Canadian provinces, and large cities is as important as federal policies in steering the energy transition. These players maintain strong climate policies, linking extreme-weather events to climate change. Wildfires, particularly devastating in California, are revealing the potential costs of climate change.

'Activist' investors, and corporations signing PPAs, are driving decarbonization. Global equity and infrastructure investors see North America as comparatively stable and attractive for renewables investing. Coal, now uneconomic, is on its way out, boosting demand for renewables. EVs and related infrastructure are becoming more common, though not yet pervasive. While cheap natural gas is the 'go-to' for new fossil-fuel generation, it also facilitates renewables integration through its ability to rapidly offset variability in renewable power output.

The energy sector is decarbonizing at a healthy pace. GHG emissions are down, partly due to switch from coal to renewables and gas, though controlling fugitive methane remains a concern. Overall declining demand also accounts for significant emissions reductions.

Globally and in North America, COVID-19 and oil supply/demand imbalances have created great uncertainty and volatility. There is also uncertainty over the size and longevity of the federally driven economic stimulus to restore jobs and economic activity.

(US)	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2018	364	288 105	60.600 22.1
2050	437	146 64	70.600 30.9

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- The US federal economic recovery stimulus could be positive for infrastructure modernization and the energy transition, though current trade policies create uncertainty for renewables. US federal elections in November 2020 will impact heavily on the energy transition.
- Switching from coal to gas and renewables for generation will continue, mainly due to US market forces and Canadian federal policies. 20+ GW of offshore wind projects are in the pipeline on the US east coast, with movement towards floating wind offshore California. Global strategic renewables players (Avangrid, EDF, EDPR, Ørsted) and oil majors (Equinor, Shell, etc.) are investing massively in US offshore wind.
- The Climate Mayors coalition of 438 US mayors backs climate action and local air pollution control. Cities will control energy-efficiency measures, municipal transport systems, investment in renewables, and joint orders for EVs. Within the 25-member US Climate Alliance (USCA), state governments are advancing renewables and decarbonization goals, and upholding Paris Agreement commitments. In 2019, USCA's collective commitments included, among others, ramping up zero-carbon energy generation – with eight states targeting zero-carbon generation by 2040.
- Corporate and industrial offtakers have signed more than 20 GW of PPAs in four years. This strategy will expand with falling technology costs and availability of PPAs, pushing policy makers, regulators and utilities towards cleaner energy supplies. Declining storage costs, and greater participation by strategic developers diversified across renewables and gas, will enable greater 'firming and shaping' of renewables generation to better match demand patterns.
- Standardization is fostering storage integration in wholesale markets. Battery storage will grow strongly through the next decade, with services like frequency regulation, ramping/spinning reserve, load following and load management, and excess solar and wind generation.

6.1 NORTH AMERICA

ENERGY TRANSITION

North America's final energy demand (Figure 6.1.1) has levelled off and will reduce in the coming years. The transport sector's energy demand will decrease significantly due to electrification of the road-vehicle fleet. With a further decline of the secondary sector, and increased efficiencies, energy demand from manufacturing will continue to fall. Energy demand in buildings will remain nearly constant over the forecast period, with counteracting forces of population increase and improved energy efficiency.

The share of electricity in final energy demand will continue to rise, more than doubling from 21% in 2018 to 44% in 2050. The buildings sector has the highest electricity share, and this will continue to grow, while the fastest growth in electrification is within transport. In 2050, electricity generation will be dominated by onshore wind and solar PV, with 24% and 21% of the power mix respectively.

Electrification of transport will be the strongest driver of the reduction in oil consumption over the forecast period. Natural gas will overtake oil as the region's largest primary energy source (Figure 6.1.2) and will consolidate that position over the coming decades with a share of more than 40%. Coal will decline rapidly, outcompeted by cheap natural gas and increasingly cheaper renewables. As electricity use expands and renewables become cheaper, wind and solar PV will see their electricity generation grow 7-fold and 15-fold respectively. By 2050, onshore and offshore wind produce more power than natural gas.

ENERGY TRANSITION INDICATORS

Figure 6.1.3 presents North America's developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

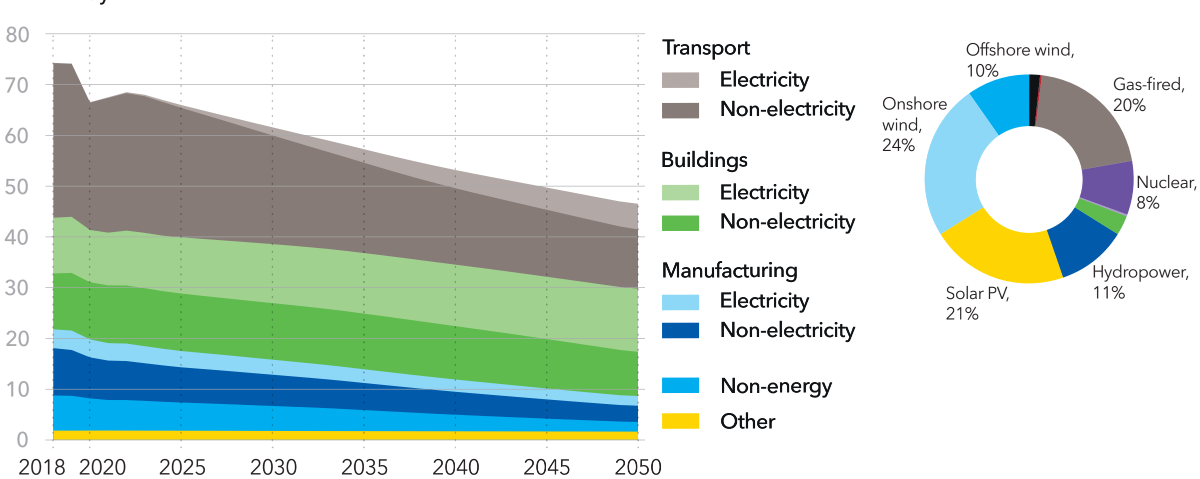
– The share of electricity in final energy demand mix will more than double between 2018 and

FIGURE 6.1.1

North America final energy demand by sector

2050 electricity mix

Units: EJ/yr



2050, reaching almost 45%, similar to developments in Europe or OECD Pacific.

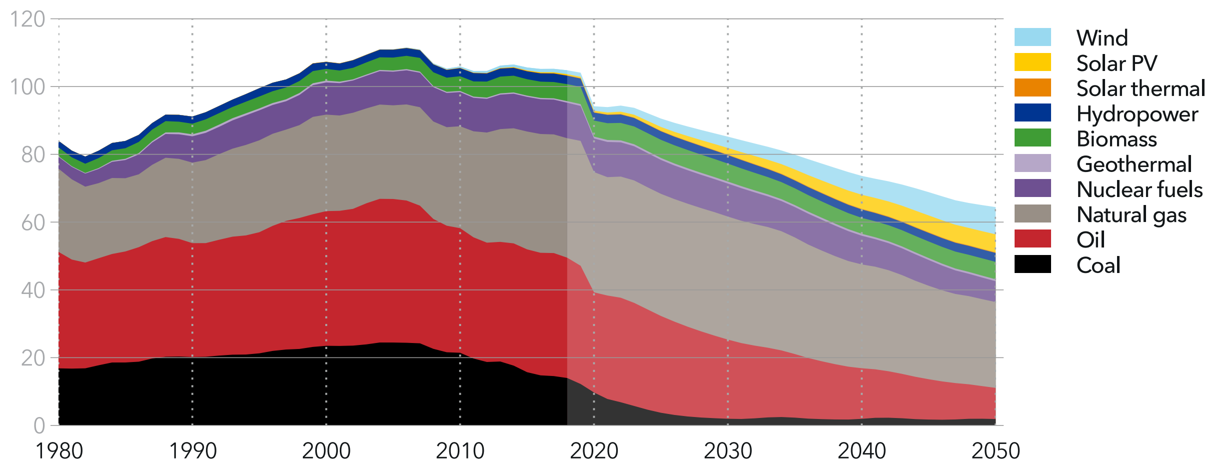
– There is a significant decline in energy intensity in North America, more than halving the primary energy consumption per unit of GDP over the forecast period compared to 2018 values. The 2050 value of 2 MJ/USD is among the leaders regarding this indicator.

– Carbon intensity, measured as tonnes of carbon dioxide per terajoule of primary energy consumption, declines by 42% but remains higher than carbon intensity from Europe or OECD Pacific.

FIGURE 6.1.2

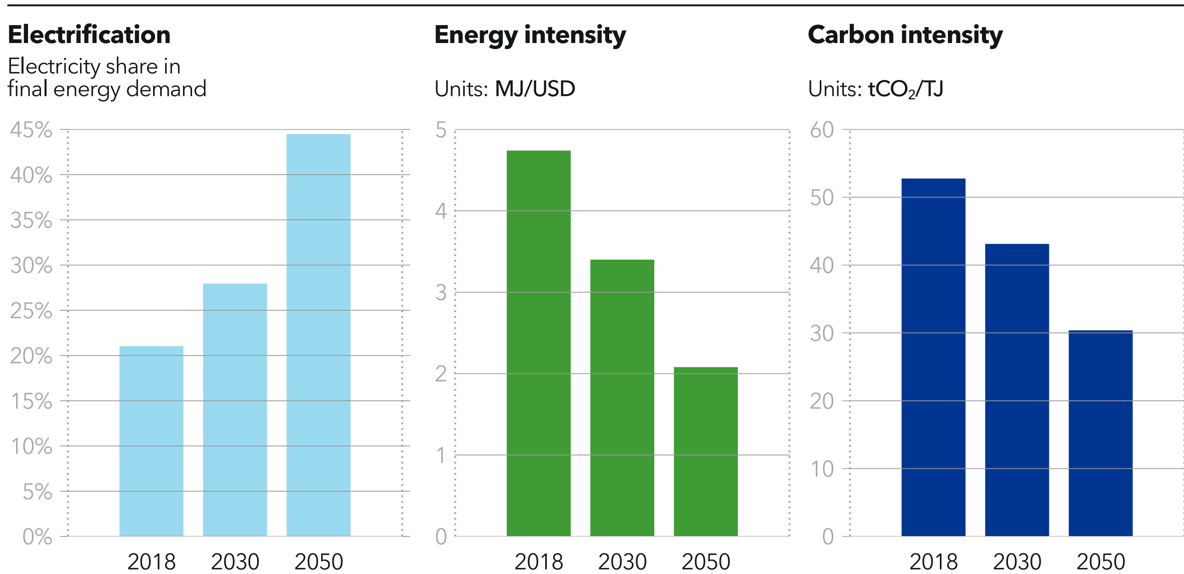
North America primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.1.3



EMISSIONS

We project an average carbon-price level of USD 50/t across the region by 2050. Pricing will be dominated by developments in US cap-and-trade schemes such as California Cap-and-Trade Program, Regional Greenhouse Gas Initiative, and Western Climate Initiative. Other factors include possible system linkages to Latin America, and the Pan-Canadian approach setting an economy-wide carbon price.

Energy-related CO_2 emissions from North America peaked around 15 years ago. They will continue declining to a level in 2050 about a third less than today (Figure 6.1.4). All-sector declines in emissions are being driven by changing energy mixes – more gas, and more power from renewables. Transport emissions decline two-thirds with the rapid uptake of EVs in the coming decades.

Emissions from coal are falling rapidly and will be less than 10% of overall emissions in about 5 years' time. With its growing share of the energy mix, emissions from natural gas overtake those from oil in about 2025. CCS uptake rise gradually to a level of 270 $MtCO_2$ per year in 2050, reducing overall net emissions by 14%.

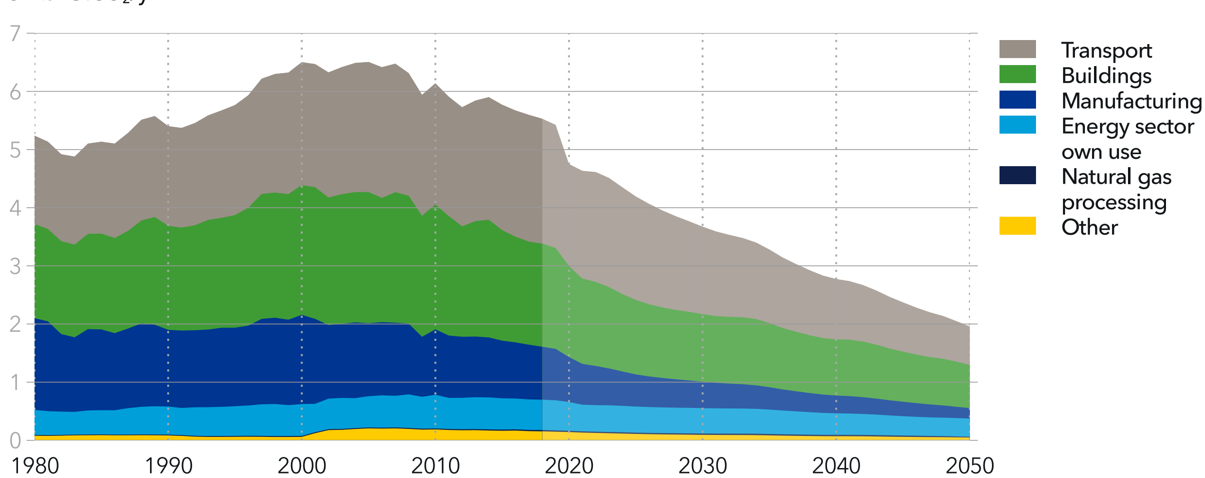
Interpretation and calibration of country NDC pledges under the Paris Agreement indicate that North America viewed as a region is targeting energy-related emissions reductions of 13% by 2030 relative to 1990. Our Outlook points to such emissions falling about 31% by 2030, suggesting that the current pledge will be easily achieved. The US withdrawing from the Paris Agreement is not likely to change this outcome.

Regarding relative CO_2 emissions, North America's 4.4 tCO_2/person in 2050 is less than half of the present level but will share company with North East Eurasia's figure in still being the highest of all our Outlook's regions.

FIGURE 6.1.4

North America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



BIG CARS AND A FAST TRANSITION

Though North America' vehicle fleet will shift from ICEVs to BEVs, the region will continue its love affair with large cars with long ranges. That means big batteries. Figure 6.1.5 shows the average battery capacity of passenger BEVs in North America is the largest among all regions – 79 kWh in 2020, rising to 143 kWh in 2050. However, these long-range high storage-capacity vehicles will be expensive to own, with the total cost of EV ownership at nearly USD 43,000 in 2030, and nearly USD 55,000 in 2050. They will still be cheaper to own than their fossil-fueled counterparts. Over their lifetimes, BEVs will be around USD 10,500 cheaper in 2030, and even cheaper towards 2050.

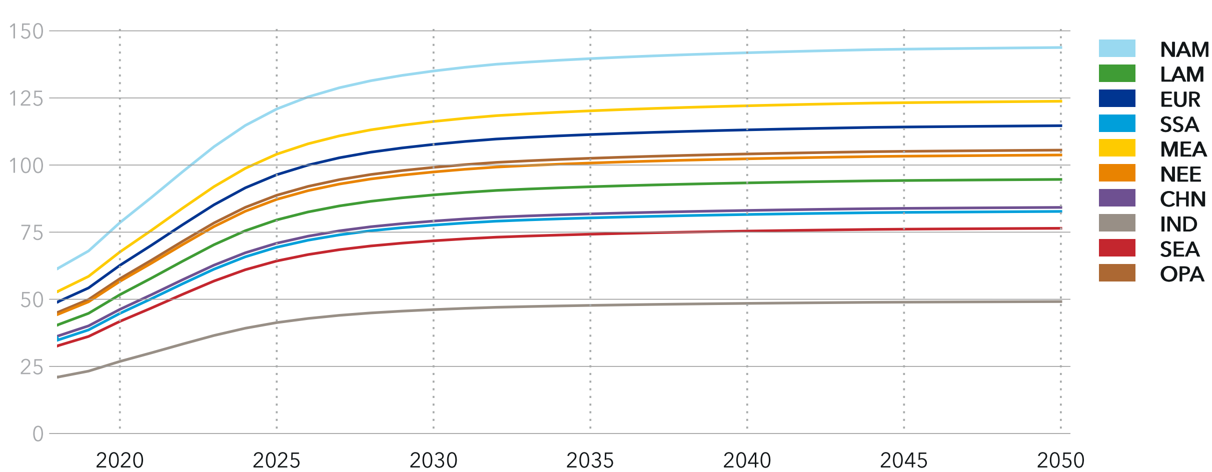
Although the desire for big cars in North America put EVs at a disadvantage because of large battery needs, we expect a rapid transition to EVs, with the EV share of the passenger car fleet reaching 50% in 2040 and 77% by 2050 – rates of growth comparable to those we predict for Greater China, Europe and OECD Pacific.

This growth is enabled both by the strongest power grid of all regions, which makes it easier to build the required charging infrastructure, and the quickly decarbonizing power mix, which increases the value of EVs in the eyes of climate-conscious consumers and policymakers seeking ways of reducing emissions. Bigger batteries and an expanding charging network will rapidly increase the number of fast chargers within range of vehicles by more than 200-fold by 2050, significantly increasing the utility of EVs for consumers relative to ICEs.

FIGURE 6.1.5

Battery size of new passenger vehicles by region

Units: **kWh**



LATIN AMERICA (LAM)

This region stretches from Mexico to the southern tip of South America, including the Caribbean Island nations

CHARACTERISTICS AND CURRENT POSITION

Latin America's energy sector is the least carbon-intensive among major emerging economies thanks to its natural wealth – wind, biomass, geothermal, hydro, and solar resources. Hydropower generation is longstanding with high penetration, especially in Brazil (>60% of power generation). Production is still increasing in the region but challenged by climate variability increasing hydrological risk and hampering security of supply.

Latin America is at the heart of the energy transition. This is exemplified by mineral wealth in Chile's northern Atacama Desert, which has the world's largest reserves of copper and lithium, and by Uruguay proving the feasibility of renewables integration (>95%) in electricity systems.

Brazil, Mexico, and Venezuela lead regional oil production. Natural-gas pipelines have increased Mexico's import capacity from North America. The region holds world-class unconventional oil and gas resources. Brazil, Mexico, Venezuela and Argentina contribute to 80% of regional GHG emissions.

Latin America is rapidly diversifying its electricity mix. Renewables undercut the prices of fossil-fuel energy, and uptake is economically driven with governments relying on capacity quotas, auctions and predictable PPAs. The market-led approach makes the region a leader in renewable energy expansion globally (IADB, 2019), and an attractive destination for investments.

Bogotá in Colombia and Buenos Aires in Argentina joined the C40 Steering Committee in 2020, calling cities to climate action. Transport is the fastest-growing source of energy-related emissions, and worsening air pollution push focus on local emissions, efficiency measures, low-carbon options and public transport. Blending mandates, combined with Brazil's long-established production of ethanol and flex-fuel models by car manufacturers, make ethanol widely used in transport.

(LAM)	**Population** (M)	**Energy use/person** (GJ) **Energy use** (EJ)	**GDP/person** (USD) **GDP*** (USD TRN)
2018	651	57 37	15 800 10.3
2050	763	50 38	25 300 19.3

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- Argentina requires 20% of power in 2025 from non-hydro renewables (6% in 2019), and is de-risking projects, creating a boom. Tapping unconventional hydrocarbons, and providing natural gas pipelines for LNG export, will require huge investment.
- Brazil aims to maintain hydropower output and boost solar and offshore wind. It wants oil production doubled by 2030 and is auctioning offshore acreage. Land-intensive liquid biofuels production challenges the forest-fuel-food balance amid increased pressure to conserve the Amazon.
- Chile aims for 70% of power to be from renewables by 2030, and carbon neutrality by 2050. Coal-fired plants will close by 2040, with renewables targeted to fill the gap. EVs will be promoted, initially in public transport. Mining, Chile's largest industry, is pursuing wind and solar energy to reduce energy costs.
- Colombia held renewables auctions in 2019. 2050 targets include 20% less fossil-fuel use by then, greater use of gas and electricity, and EVs making up a third of the fleet. Infrastructure is needed to tap vast wind and solar potential. Current market dynamics may weaken the investment case for unconventional oil and gas resources.
- Mexico's government wants more control over energy, creating uncertainty for energy investors across the spectrum. With low gas prices and pipelines in place, imported gas is expected to boost power generators and industry. Despite regulatory risks, uptake of renewables is expected to continue because they align with energy sovereignty priorities.
- Venezuela will have to confront its energy shortages and unpredictable electricity supply. Turbulent political mismanagement will continue to impede domestic energy developments and discourage private investors.

6.2 LATIN AMERICA

ENERGY TRANSITION

Latin America's final energy demand (Figure 6.2.1) has levelled off proportionally with economic stagnation and will remain low for a while as GDP growth is expected to be low the next decade. The largest increase in energy demand will come from buildings, due to population growth and an increase in income per capita leading to greater demand for appliances. Energy demand from manufacturing will grow, though efficiency gains will dampen the rise. Transport will see a slight decrease in its energy demand.

The share of electricity in final energy demand will continue to increase, more than doubling from 18% in 2018 to 42% in 2050, observable in the transport, manufacturing and buildings sectors. By 2050, hydropower will have lost its present status as the largest source of electricity with a 28% share in mid-century, surpassed by wind and solar PV with 34% and 29% respectively. At the end of our forecast period, fossil fuel-based electricity production in the region is down to about 5%.

Figure 6.2.2 illustrates that oil, the region's largest energy source, will slowly decline towards the end of the forecast period, when uptake of EVs starts accelerating. Natural gas initially declines then levels off, based on demand patterns from the manufacturing and power sectors; but it will not overtake oil as the largest primary energy source within the forecast period. Coal will remain an insignificant energy source in the region. Renewables, led by biomass and hydropower, and supported by strong solar PV and wind growth, will supply 52% of primary energy by 2050.

ENERGY TRANSITION INDICATORS

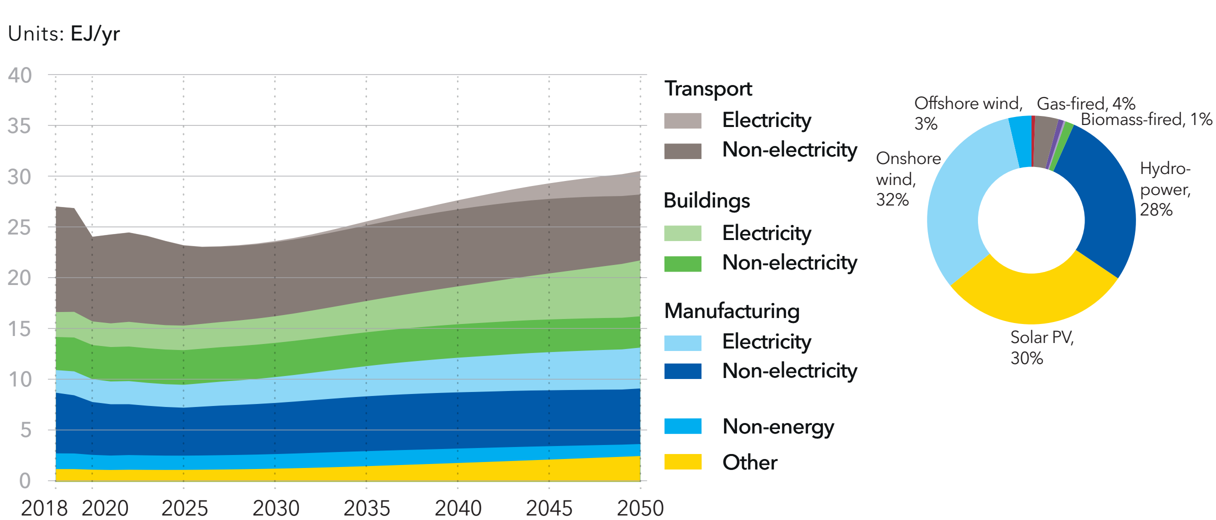
Figure 6.2.3 presents Latin America's developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

– The region's share of electricity in final energy demand increases to more than 40% by 2050, which is almost as high as the electrification seen in North America and Europe.

FIGURE 6.2.1

Latin America final energy demand by sector

2050 electricity mix



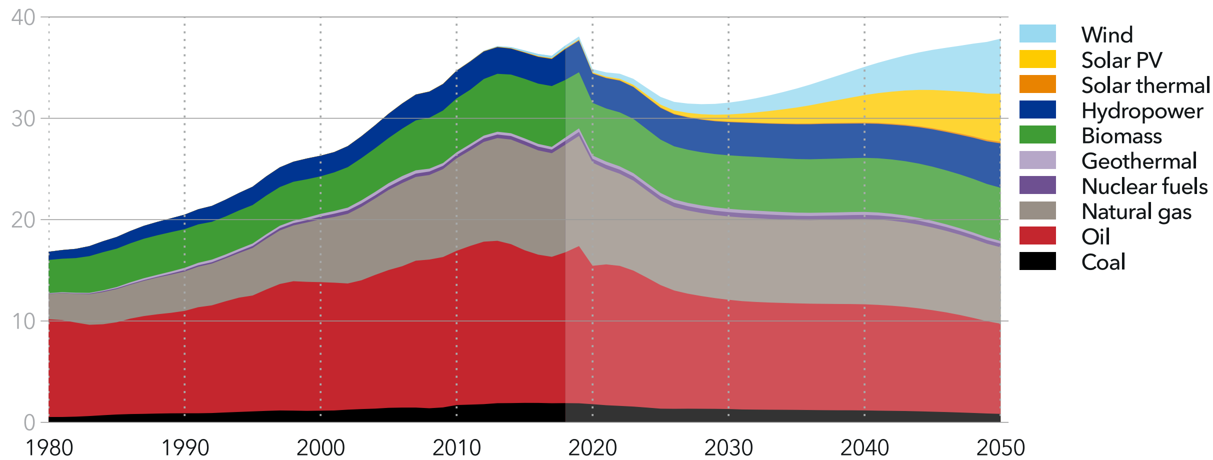
– Supported by both electrification and energy efficiency gains, Latin America is reducing its energy intensity to about 2 MJ/USD, indicative of a decoupling of energy use from GDP.

– The region will almost halve its carbon intensity between 2018 and 2050, reaching a final 2050 value of 26 tCO_2/TJ, placing it among the leaders regarding this regional indicator.

FIGURE 6.2.2

Latin America primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.2.3

Electrification

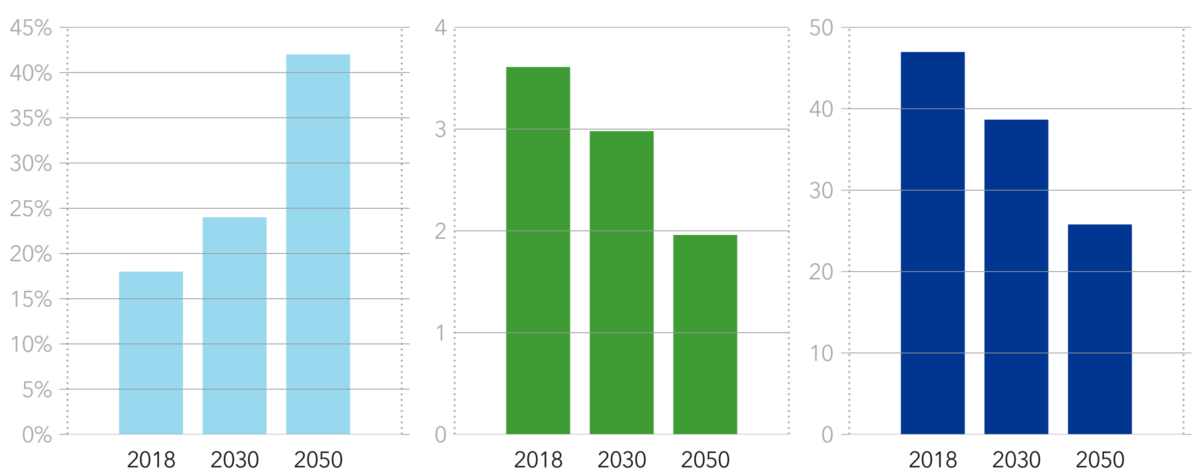
Electricity share in final energy demand

Energy intensity

Units: MJ/USD

Carbon intensity

Units: tCO_2/TJ



EMISSIONS

The region's average carbon-price level is projected to be USD 40/t by 2050. Current carbon taxes in Argentina, Chile, Colombia and Mexico will be augmented in 2022 by Mexico's Emissions Trading System (ETS). Brazil is also assessing carbon pricing instruments. Higher pricing could also come to avoid carbon-border tax adjustments from large trading partners, e.g., Europe and China, both with carbon pricing in place.

Latin America's energy-related CO_2 emissions peaked around 2015. They will reduce through the 2020s, stabilize in the 2030s, then decline to 40% less than today in 2050 (Figure 6.2.4). The decline is in all main demand sectors and is driven by efficiency gains and a changing energy mix.

Today and in the future, oil contributes most to emissions. Coal use and coal emissions stay low during the entire forecast period. In 2050, CCS will reduce CO_2 emissions by 62 Mt, equivalent to 6% of the region's emissions at that time.

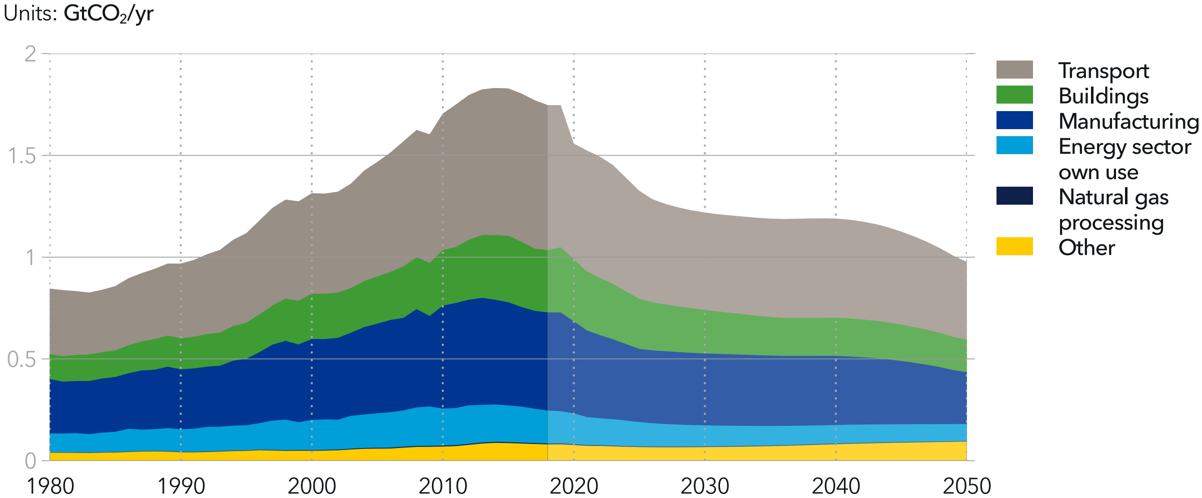
Country NDC pledges indicate a regional target of limiting emissions increases to about 63% by 2030 relative to 1990. Our Outlook indicates energy-related emissions rising 25% over the same period. This suggests the regional target will be achieved by a good margin, indicating that it is a low level of ambition. Note that there are uncertainties in comparing targets and forecasts; some countries are unclear about whether targets in NDCs also include non-energy related CO_2 emissions.

Latin America's 1.3 tCO_2/person emissions level in 2050 is the third lowest of all regions after Sub-Saharan Africa and Europe, and is nearly 50% less than the region's current carbon emissions per person.

FIGURE 6.2.4

Latin America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



ENERGY IMPORTS COULD HELP THE TRANSITION

Historically, Latin America has produced enough fossil fuel to cover its demand, though logistical challenges meant imports from other regions were cheaper in some countries. But with more than a decade of declining oil and gas production in Mexico, and more recent developments in Venezuela resulting in sharply reduced output, the region's net oil and gas production surplus has diminished, and even turned into a net deficit for gas. The story for coal is similar, but for different reasons. The world's fifth largest coal exporter, Colombia, has faced steady decline in demand from the US and Europe. Continued decarbonization of power systems globally means a 50% reduction in coal production in the next 30 years, which is just enough to cover the coal demand in the region. Latin America's oil industry faces a similar future as steadily declining global demand for oil, and cheap oil from competing regions, will squeeze the region's oil exporters.

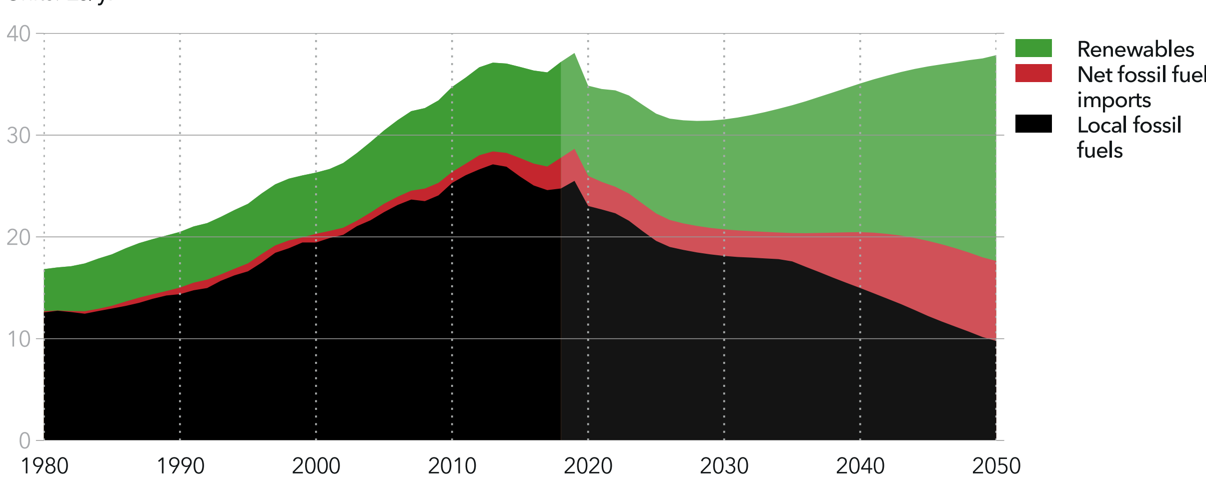
For the economies reliant on energy exports, these trends have devastating financial and social consequences. Exacerbated by the impact of COVID-19, Latin America faces economic stagnation over the next decade. Under the shadow of widespread corruption and significant inefficiencies, state-run fossil-fuel companies and the respective governments have been promoting the status-quo of the energy system.

In the long term, the external pressures on fossil-fuel demand, and cheap renewable technologies, will force Latin American economies and the energy industry to diversify and consider importing energy. If the region's countries use this opportunity wisely, changing the energy mix can help to democratize the energy system, reduce energy costs, create new jobs, and make power generation market-driven and more flexible.

FIGURE 6.2.5

Increasing share of fossil fuel imports in Latin America

Units: EJ/yr



EUROPE (EUR)

This Region Comprises all European countries, including the Baltics, but excluding Russia, all the former Soviet Union Republics, and Turkey

CHARACTERISTICS AND CURRENT POSITION

Europe is a frontrunner in the energy transition. The EU steers energy policy to align with the Paris Agreement and integrate economic, industrial, and environmental policies. The new Green Deal targets a sustainable EU economy and faster decarbonization.

End-use energy demand is moderate given Europe's developed state. EU dependency on energy imports is a main driver of policy concerns around energy security and energy-efficiency targets. However, the fossil-fuel share in the energy mix is declining, driven by ambitious policies.

EU climate and energy targets for 2030 include: 40% less GHG emissions than in 1990; 32% of final energy consumption from renewables including 14% in transport; and curbing consumption growth by 32.5% compared with a 2007 primary-energy baseline. The Green Deal plans to raise the 2030 GHG emissions reduction target to at least 50% by enabling green technology adoption and a regional circular economy.

Renewables supply more than half the power consumed in each of Austria, Denmark, Latvia, Portugal and Sweden (eurostat, 2020). Finland and Sweden lead in renewable transport fuels. Norway pioneers EV uptake. North Sea offshore wind is a global leader. The EU aims to be a hydrogen and CCS first-mover. While coal dominates power generation in Poland and the Baltics, eight EU members plan to phase out coal in national plans for 2021–2030, and Germany by 2038.

The Green Deal's 'just transition mechanism' highlights the EU's aim to 'leave no-one behind' to ensure greater regional alignment on long-term carbon neutrality policy. 17 European climate and environment ministers have called for the Green Deal investment plan to drive a just transition and green recovery after COVID-19.

	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2018	540	139 75	41 900 22.7
(EUR)			
2050	542	83 45	52 900 28.7

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- The adopted 'Clean energy for all Europeans' package will advance EU implementation of its 2030 climate and energy framework and springboard more progressive policy such as the Green Deal.
- The EU push to meet NDCs and cement a leading position in shaping global climate action policy will be strengthened by the combination of: the 2050 strategic vision 'A Clean Planet for all'; the proposed EU Climate Law seeking to make carbon neutrality a legal requirement; and the Green Deal set to formulate accompanying policy roadmaps.
- The long-term, low-carbon investment signals and the 2030 reform and cap trajectory for the EU Emissions Trading System (ETS) will help sustain predictable carbon prices.
- The increase in variable renewable energy will heighten focus on power-system integration, stability, reinforcement and flexibility management. More low-cost renewables will drive up the value of energy-storage and increase the push for storage solutions like batteries and power-to-x (gas, heat, liquid).
- Currently adopted pathways will see modest growth of zero-carbon gases (hydrogen, biomethane, etc.). An accelerated decarbonization pathway, outlined in the Green Deal, is needed for significant technology deployment and to achieve break-even prices for CCS before 2030.
- Blue hydrogen (SMR with CCS) will be used to decarbonize hard-to-abate economic sectors. Dedicated hydrogen infrastructure will be developed. Green hydrogen (electrolysis) will become economical in the medium to long term as investment ramps up.
- Hydrocarbon production will continue declining while natural gas overtakes oil as the largest primary energy source before 2030. More LNG import terminals and continued construction of large pipelines will support long-distance gas transmission.

6.3 EUROPE

ENERGY TRANSITION

Europe's final energy demand (Figure 6.3.1) will continue to decline towards mid-century. With a transition to more efficient EVs, transport will see the strongest reduction in energy demand. Manufacturing's energy demand will also reduce, due to shrinkage of the secondary sector in Europe's economy and to greater manufacturing efficiency. With a stable population and switching to more efficient technologies, especially for heating, buildings energy demand falls slightly in absolute terms but increases its share.

Figure 6.3.1 shows electricity's share in final energy demand rising from 20% in 2018 to 44% in 2050. Buildings have the highest share, which will keep increasing, but the fastest growing share is for transport. Wind dominates the 2050 electricity mix – onshore 24%, and offshore 23%. Solar PV will account for 23%. Gas-based electricity supply, much of it from green gas with CCS, falls to about 4%. Green hydrogen from surplus electricity shows strong growth from the mid-2030s to account for 60% of European hydrogen production in mid-century. Hydrogen's share of final energy demand is 15% in 2050, the highest among all regions.

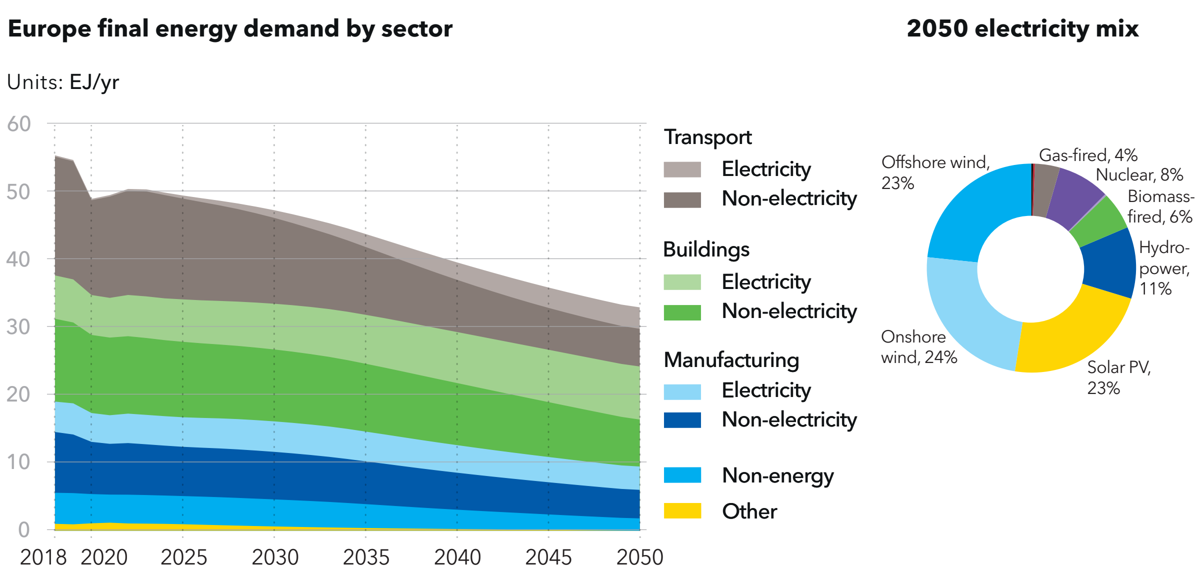
Electrification of transport will be the strongest driver for reducing oil consumption. More than half of Europe's vehicle fleet will be electric by 2038. Natural gas overtakes oil as the largest primary energy source by 2030 (Figure 6.3.2), consolidating that position over following decades. Coal will continue to decline in the next few years. Biomass will maintain a high share at around 13%; in Europe, this is modern biomass from waste-fills and similar sources. Fossil energy share in primary energy consumption falls to 39% by 2050.

ENERGY TRANSITION INDICATORS

Figure 6.3.3 presents Europe's developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

– The region's share of electricity in final energy demand will reach almost 45% by 2050, a level

FIGURE 6.3.1



similar to North America, and explained by strong growth from renewables.

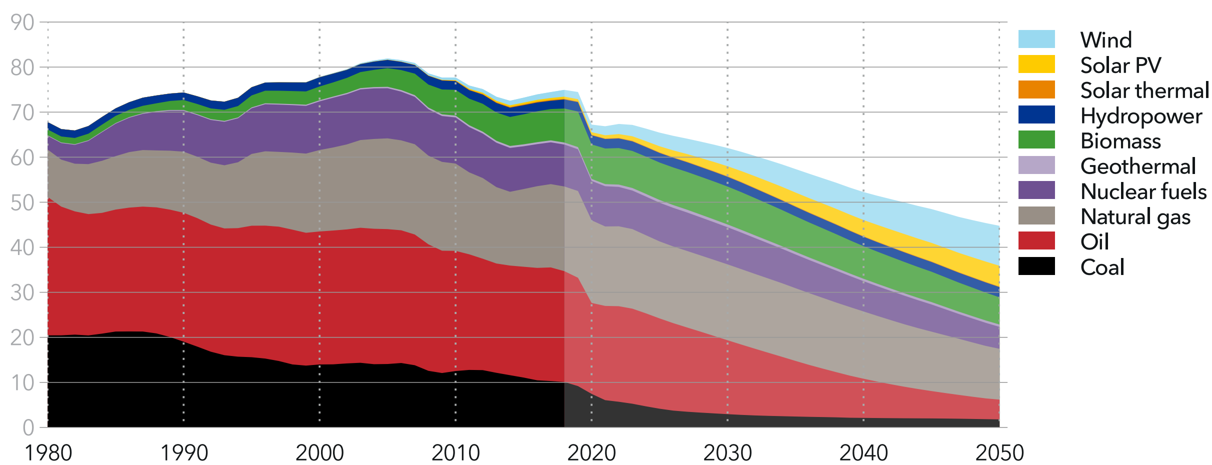
- Energy intensity in 2050 will be at low 1.5 MJ/USD, representing efficiency gains amounting to a reduction of more than 50% from 2018 values, and reaching the lowest value of all regions.

- Both of these developments support the c. 75% decline in Europe's carbon intensity by 2050 – the most rapid decarbonization globally. Carbon intensity in 2050 is the lowest of all regions, more than 30% lower than Greater China and OECD Pacific, in second and third place respectively.

FIGURE 6.3.2

Europe primary energy consumption by source

Units: EJ/yr

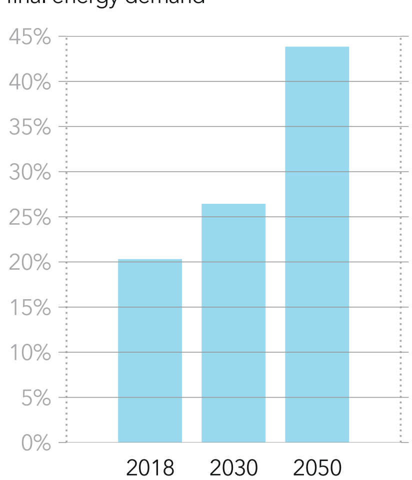


Historical data source: IEA WEB (2019)

FIGURE 6.3.3

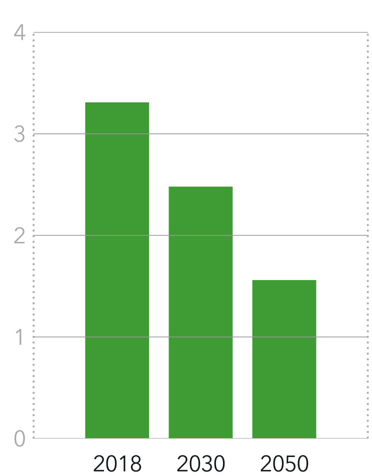
Electrification

Electricity share in final energy demand



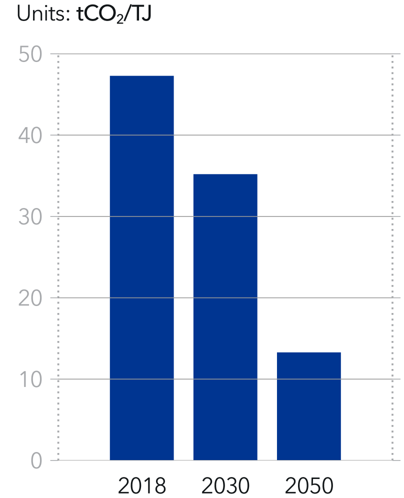
Energy intensity

Units: MJ/USD



Carbon intensity

Units: tCO_2/TJ



EMISSIONS

We project the region's carbon price-level to be USD 80/t on average by 2050. It rises steadily due to: Green Deal initiatives; EU ETS-system reform tightening the cap and addressing the market imbalance of allowances through the Market Stability Reserve (MSR); and to many countries also having national carbon taxes and price-floor mechanisms on non-EU ETS sectors.

We project CO_2 emissions to keep falling to be 83% less in 2050 than in 2018. While Europe will continue to lead other regions on both energy-intensity and carbon-intensity, the emissions reduction forecast still does not meet the EU's net-zero ambition.

The EU's new NDC pledge, promised by September 2020, looks likely to target a 55% reduction in CO_2 emissions by 2030 relative to 1990. Our forecast does not include country-specific, non-energy-related CO_2 emissions, and Europe is larger than the EU. With that caveat, we see Europe's energy-related emissions down 45% by 2030, more than the EU's initial Paris Agreement pledge of 40%, but certainly less than 55%.

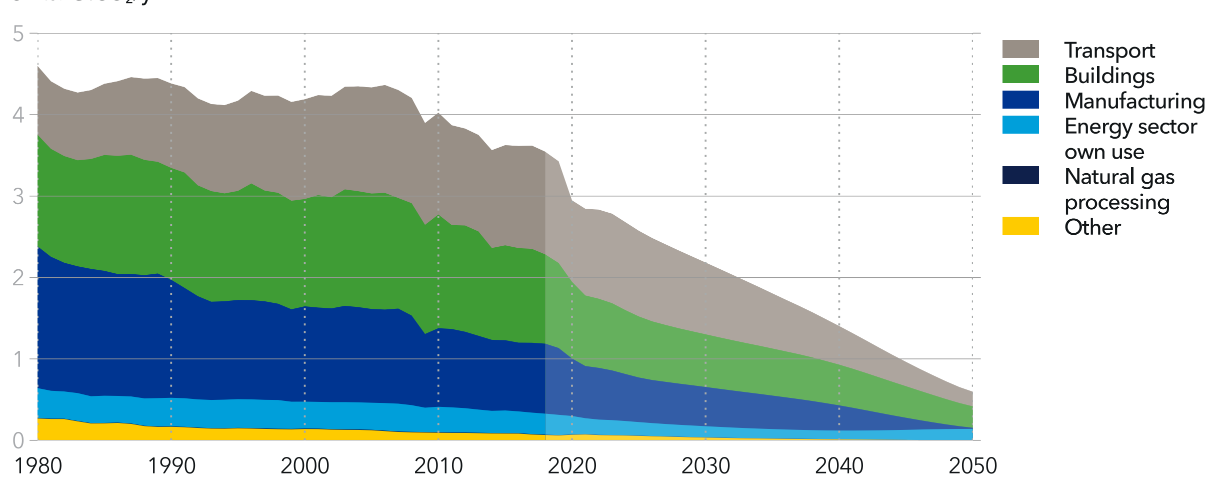
Figure 6.3.4 shows transport and manufacturing reducing emissions quickest. In manufacturing, this is mainly due to sharply declining direct use of coal and gas, and greater use of green electricity.

Emissions from using gas will become the largest source of CO_2 emissions by energy carrier in 2033. Emissions from coal use will reduce rapidly, almost disappearing, while those from oil will gradually decline by 2050 to less than a fifth of today's level. Overall emissions in 2050 are 620 $MtCO_2$ after subtracting 600 $MtCO_2$ because of CCS, which captures half of Europe's remaining emissions in 2050, the largest such share among all regions. In relative CO_2 emissions, Europe's 1.1 tCO_2/person is second lowest of all regions after Sub-Saharan Africa.

FIGURE 6.3.4

Europe energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



TOWARDS THE HYDROGEN ECONOMY

In 2030, hydrogen will still represent less than 1% of final energy demand in Europe. However, it will scale up from the late 2030s, with Europe dominating its use globally until 2044, by then accounting for 27% of global hydrogen demand. In 2050, this will be 21%, second to China's 42%.

By mid-century, nearly half (48%) of the hydrogen produced in Europe will be used in transport, 35% for manufacturing, and 17% in buildings. Hydrogen accounts for 12% of transport energy use worldwide in 2050, but meets 27% of the sector's energy use in Europe (Figure 6.3.5).

Hydrogen use will grow rapidly in Europe's manufacturing in the 2040s to reach a 23% share of the sector's energy mix by 2050. In buildings, it will become a new energy source for heat-related end-uses as existing gas distribution infrastructure makes hydrogen a direct alternative to natural gas.

Still, hydrogen will represent only 6% of total energy use in Europe's buildings by 2050, less than a fifth of the share of natural gas.

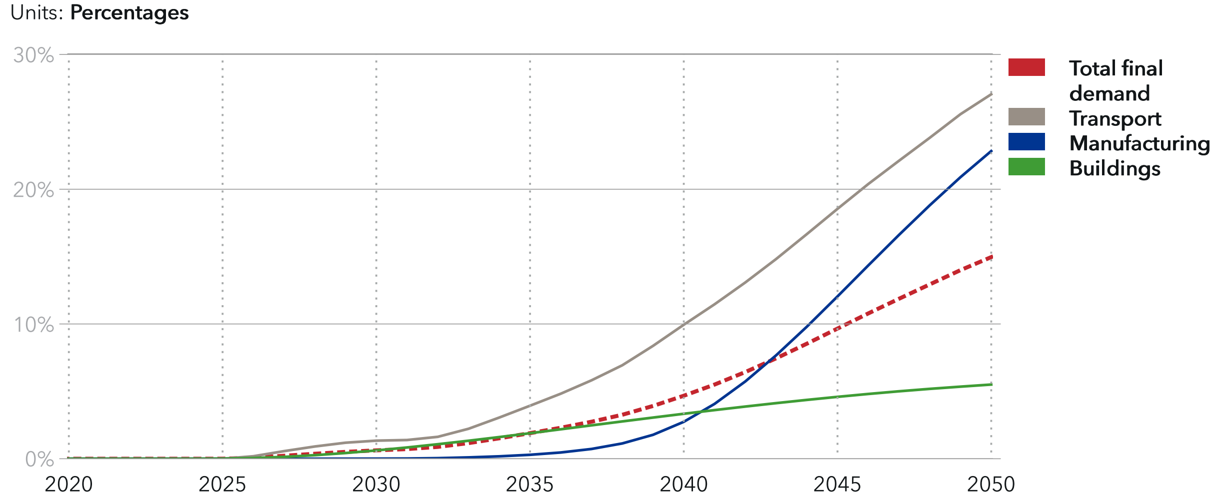
SMR technology with CCS will increase rapidly in the early 2030s to dominate hydrogen supply. Expansion of variable renewables in Europe will support the share of electrolysis-based hydrogen production, increasing to 58% in 2050.

Current costs associated with hydrogen supply and use make it unlikely that its uptake as an energy carrier will be rapid enough to include it in a balanced energy mix in the medium term. However, as costs continue to decrease, we expect a combination of high demand, availability of distribution infrastructure, renewables expansion and decarbonization policies will enable Europe to move towards a balanced energy mix including hydrogen in the long term.

FIGURE 6.3.5

Europe hydrogen share in final energy demand by sector

Units: **Percentages**



SUB-SAHARAN AFRICA (SSA)

This region consists of All African countries except Morocco, Algeria, Tunisia, Libya and Egypt

CHARACTERISTICS AND CURRENT POSITION

This region has a diversity of natural resources. Nigeria and Angola are the largest petroleum producers, while 93% of the region's coal production is from South Africa, where it is the main primary fuel for power generation. Congo has high hydropower potential, and the continent has abundant solar radiation and wind resources.

Sub-Saharan countries have one thing in common: the growing demand for energy. This is the least-developed and least-electrified world region characterized by energy poverty, despite the region's rich resource potential. Only 42% of the region's people have access to electricity.

Energy deficiency is an impediment to economic development. The region requires power generation and infrastructure to supply unserved and growing populations. Supply has hitherto not kept pace with population growth and industrialization. Sub-Saharan Africa is the region least-equipped to face extreme climate events.

Large parts of the region struggle with corruption and weak governance and internal conflict. Incumbent actors in centralized energy subsectors exercise significant influence on decision-making. There is often a mismatch between ambitious energy projects and failing or inadequate grids.

Urbanization growth rates in Sub-Saharan Africa are among 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. The region holds abundant renewable energy resources providing large potential for leapfrogging development stages through technology, such as distributed, less carbon-intensive generation, and also by leveraging the capabilities of the large generation of youth, digital technologies, and connectivity as catalysts of entrepreneurial activity.

(SSA)	**Population** (BN)	**Energy use/person** (GJ)	**Energy use** (EJ)	**GDP/person** (USD)	**GDP*** (USD TRN)
2018	1.09	27	29	3.900	4.3
2050	2.0	25	49	8.100	16.2

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE ▶▶▶

- SDG #1 and SDG #2, on poverty and hunger respectively, remain paramount. Potential conflicts around natural-resource use related to the water, food, and energy sectors will require management.
- To support utility-scale renewables, partnerships and development banks will play key roles in energy projects, clean energy corridors for interconnections, and power pools. Leapfrogging costly, polluting production and transport will be an opportunity. Upskilling local staff for renewables technology is important; e.g. Kenya's skills development for geothermal energy.
- Encouraged by foreign funding (particularly from China and Japan), decision makers will continue to favour large, centralized energy plants, thus perpetuating coal use, hydropower expansion, and greater use of natural gas.
- Lower renewable-energy costs create affordable opportunities for the region. Solar PV, onshore wind, and storage technologies will boom. Future national-energy plans will consider distributed technologies and mini-grids for rural electrification as quick, low-cost options. We anticipate supportive national policies for the buildout, starting in non-oil-producing economies. Pioneers include Ethiopia, which aims to achieve national energy access by 2025.
- Ghana and Kenya both aim to boost renewables through feed-in tariffs. Kenya aims to raise electricity capacity ten-fold to 23 GW by 2033. Tanzania's goal is for renewable power to reach 70% by the mid-2020s, but its Power System Master Plan emphasizes the role of coal and gas-fired power generation until the 2040s. Political and economic turmoil regarding coal dominance in South Africa may steer the generation mix towards lower-cost renewables and gas from Mozambique.
- The region will have limited explicit carbon-pricing instruments. South Africa's first phase of carbon-tax implementation is scheduled for mid-2022. Carbon-pricing policies are expected to be announced in NDCs for 2025 or 2030 onwards.

6.4 SUB-SAHARAN AFRICA

ENERGY TRANSITION

Sub-Saharan Africa's final energy demand (Figure 6.4.1) will keep growing over coming decades as the population almost doubles and the economy quadruples. Greater energy efficiency counteracts this partially, particularly in buildings replace highly inefficient traditional biomass for cooking and kerosene for lighting. The largest rise in energy demand, a tripling, comes from manufacturing as the region starts to scale up manufacturing production. Energy demand for transport almost doubles as a much higher share of the population gains access to modern transport.

Figure 6.4.1 shows electricity's share in final energy demand rising from 7% in 2018 to 18% in 2050. Despite this growth, the 2050 share is the lowest of all regions. Solar PV's 33% share dominates the 2050 grid electricity mix. Adding in off-grid PV, solar's share is almost 40% by mid-century. Infrastructure challenges are a major obstacle to faster electrification; see story on next page.

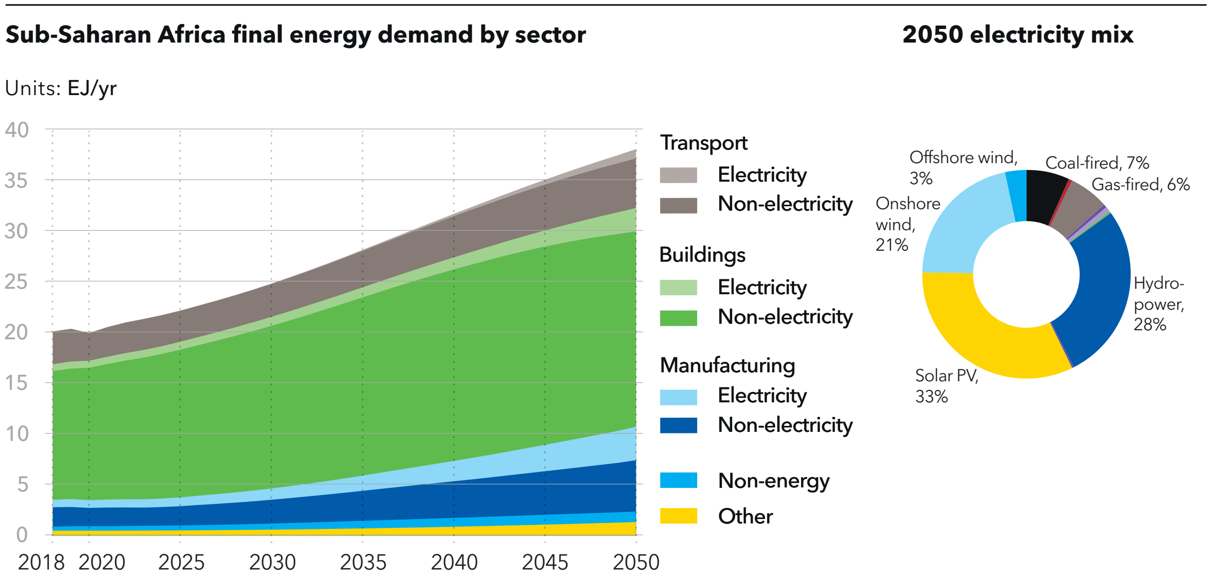
Biomass will remain the dominant source of energy, though its share will decrease (Figure 6.4.2). It brings many challenges including adverse health effects, inefficiencies, and availability of traditional biomass impoverishing arable land. Oil and coal will decrease slightly in absolute terms. Natural gas will see the largest growth, with increased demand for it in buildings, manufacturing and power generation. The largest relative growth will come in solar PV, off-grid PV, and wind, but as electricity's share in final demand is relatively low, uptake of these renewables is also less than in many other regions.

ENERGY TRANSITION INDICATORS

Figure 6.4.3 presents Sub-Saharan Africa developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

- The pace of electrification is fast in the region, with an almost tripling electricity share in final

FIGURE 6.4.1



energy demand between 2018 and 2050. Even so, its final share of 18% is lowest among all regions.

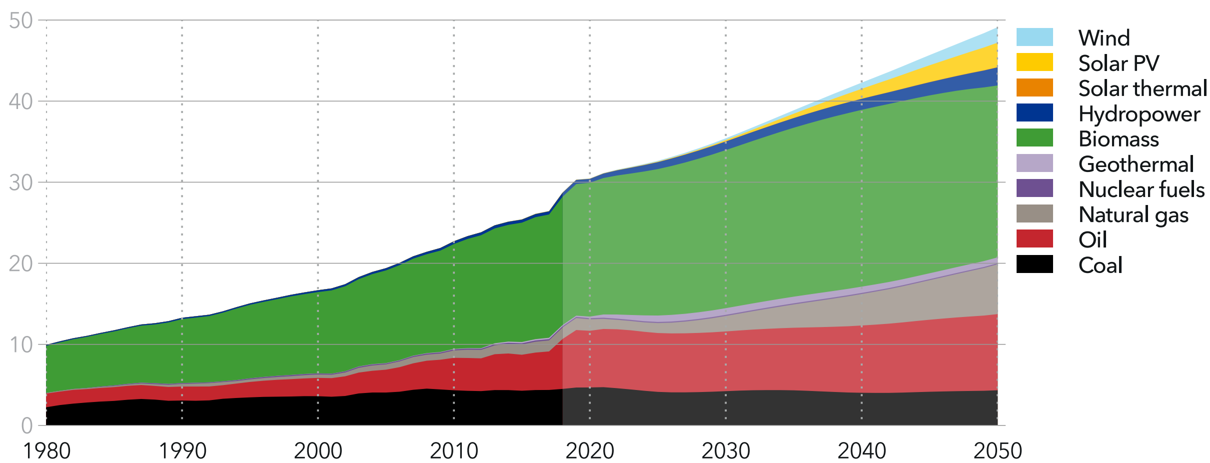
– A strong decrease of energy intensity will occur after 2030, more than halving by 2050. Still, the achieved level of about 3 MJ/USD is second highest in all regions, which can be explained, inter alia, by the extensive use of biomass and the low share of electricity compared with the other regions.

– Over the same period where energy intensity is more than halved, there is only a marginal reduction of carbon intensity.

FIGURE 6.4.2

Sub-Saharan Africa primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.4.3

Electrification

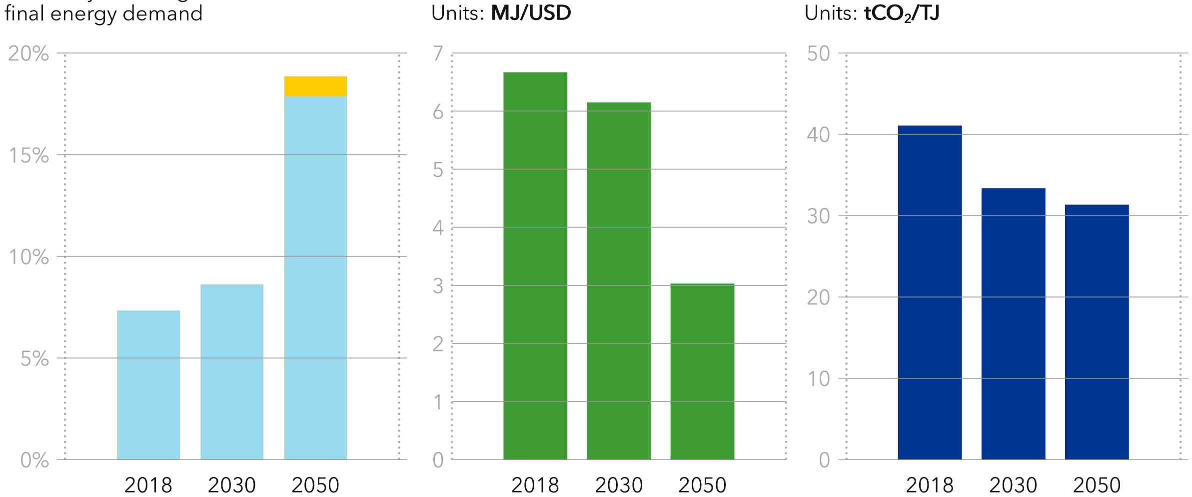
Electricity and off-grid PV share in final energy demand

Energy intensity

Units: **MJ/USD**

Carbon intensity

Units: **tCO_2/TJ**



EMISSIONS

We project an average carbon price of USD 25/t by 2050 in Sub-Saharan Africa, which will have limited explicit carbon-pricing instruments. South Africa's first phase of carbon-tax implementation is scheduled for mid-2022. Carbon pricing policies are expected in NDCs for 2025 or 2030 onwards, mostly motivated by access to climate finance and to avoid carbon border-tax adjustments.

The region's energy-related CO_2 emissions will dip a little in the coming years of lower growth after COVID-19. Thereafter, they rise to be 30% higher in 2050 than today amid a near doubling of the population and quadrupling of the economy. Figure 6.4.4 shows growth coming from all sectors, and even considerable efficiency can only partially counter mounting final energy demand linked to population and economic growth.

Emissions from oil are the largest today and will remain so over the forecast period. While coal emissions will stay relatively flat, gas emissions will grow as it is used in buildings, manufacturing and power. CCS uptake is negligible at 21 $MtCO_2$/yr in 2050, 1% of total CO_2 emissions.

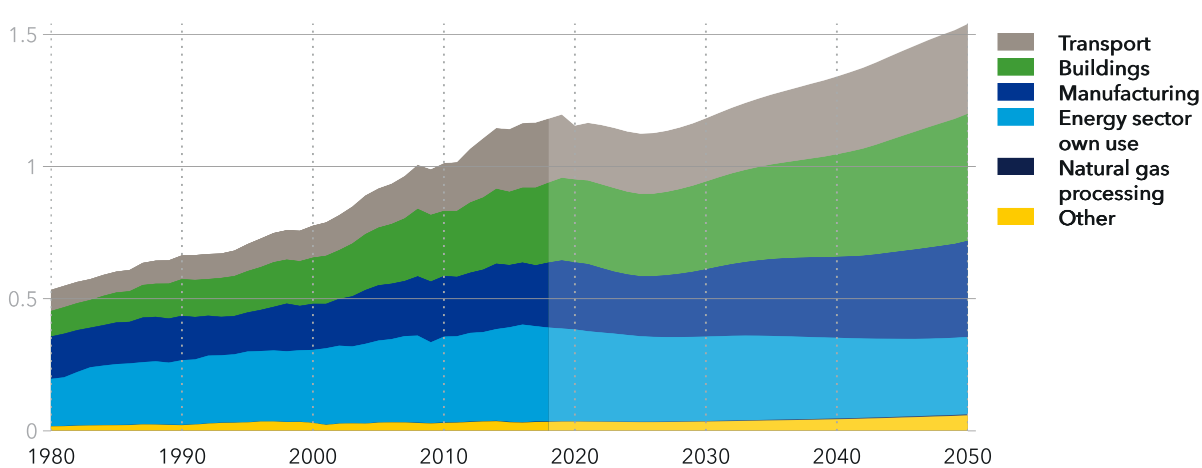
NDC pledges imply a regional target for emissions to grow no more than 185% by 2030 relative to 1990. Our Outlook indicates energy-related emissions rising 73% over the period, suggesting that the pledges' ambitions are very low in this regard. There are some uncertainties in the comparisons of targets and forecasts as some countries are unclear about whether targets in NDCs also include non-energy-related CO_2 emissions.

Despite economic growth and rising standards of living, Sub-Saharan Africa's 0.77 tCO_2/person emissions in 2050 are 30% less than today. It will remain the lowest emitting region, primarily due to the region not transitioning to the same standard of living as other regions.

FIGURE 6.4.4

Sub-Saharan Africa energy-related CO_2 emissions by sector

Units: **$GtCO_2$/yr**



INFRASTRUCTURE CHALLENGES SLOWING THE TRANSITION

Lack of infrastructure – roads, power grids, and power generation – is a major hurdle for further development. However, the region is well suited for power-system leapfrogging, as seen with other technologies like mobile telephony and banking. We have previously shown that off-grid PV solutions will provide electricity access to hundreds of millions over the next decade (DNV GL, 2019e). However, such installations will compete with small petrol or diesel power generators, and only provide sufficient power for smaller appliances, not for cooking and space-cooling needs.

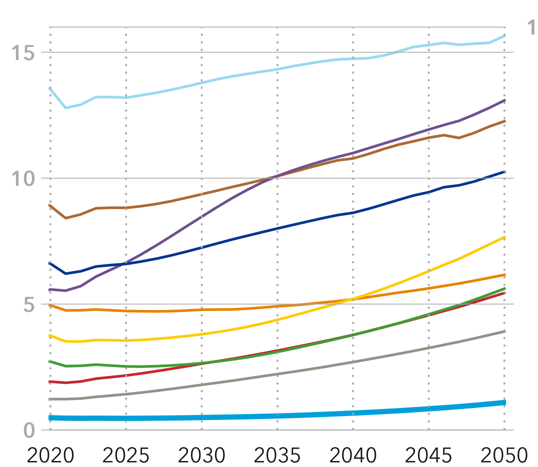
The lack of power grids, and poor maintenance and reliability where these exist, has contributed to a downward spiral where defecting customers raise costs for remaining customers such that connection costs are prohibitive for most households. This is especially troublesome, as top-heavy decision-making structures have given preferential treatment to major power projects in coal and hydropower – foreign-funded projects often regrettably tainted by corruption. These technologies scale less well than wind, solar PV, or gas power installations.

From the mid-2030s onwards, we forecast only a modest start of EV uptake in this region. The region's lowest ranking for power generation per person explains the share of electric passenger vehicles being the second lowest in the world. Lack of grid quality is clearly a barrier to fast uptake of EVs, but uptake will be helped by modest average vehicle sizes, with smaller batteries and lower costs. With the right policy backing, there is considerable potential for microgrids to serve recharging and other access needs, but it will take some doing to wean the region's governments off centralized power ambitions.

FIGURE 6.4.5

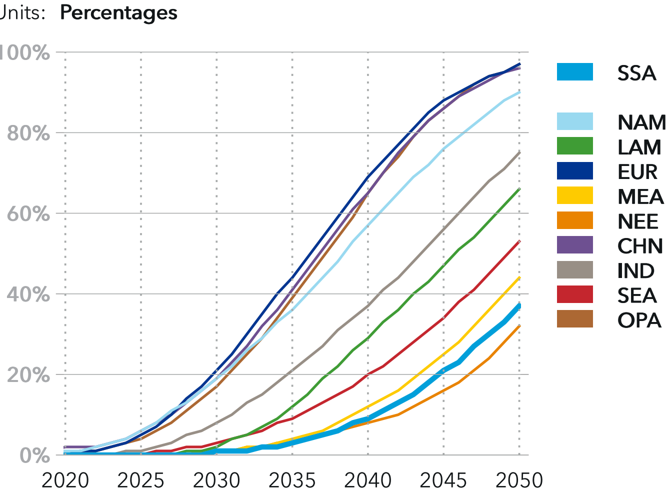
Electricity generation per person

Units: **MWh/(p-yr)**



Share of electric vehicles in passenger vehicle sales

Units: **Percentages**



MIDDLE EAST AND NORTH AFRICA (MEA)

This region stretches from Morocco to Iran, including Turkey and the Arabian Peninsula

CHARACTERISTICS AND CURRENT POSITION

Economically and politically, the region is diverse and has vast petroleum resources, the largest being in Saudi Arabia, Iran, Iraq, United Arab Emirates (UAE), and Kuwait.

Being at the core of the geopolitical system of extraction and trade in oil and gas, the OPEC members in the region are trying to maintain a delicate balance of keeping oil prices and revenues high. Volatilities in oil prices and conflicts have hampered economic growth in recent years.

The region faces challenges associated with socioeconomic development, youth unemployment, and the need to meet rapidly growing energy demands while considering water and food security, climate change, and local air pollution.

The 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 realize its vast renewable-energy potential and diversify its energy sources but continues to face external criticism for ignoring the sustainable-energy agenda. Saudi Arabia's Vision 2030 strategy plans large investments in renewables. 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 renewable generation, and to attract foreign investors.

The region is also taking steps to implement demand-side management measures, including subsidy and tariff reforms, building retrofits, energy-management systems, and private-sector involvement.

(MEA)	**Population** (M)	**Energy use/person** (GJ) **Energy use** (EJ)	**GDP/person** (USD) **GDP*** (USD TRN)
2018	531	92 49	20 600 11.0
2050	728	80 58	33 000 24.1

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- The geopolitical shift towards a more electrified world, the rise in unconventional sources, and the tapering off of oil demand will force this region's fossil-fuel producing countries to adopt more diversified economic models.
- With these nations now feeling the effects of climate change, rising water scarcity, and a need to liberate fossil fuels for export, key policies will aim 'to green' supply chains and reduce per capita energy consumption. Water constraints will give a further push towards renewable energy, e.g., solar PV and wind, for which water is neither a major input nor cost component, and which could be used to replace fossil-fuelled desalination.
- The region has vast renewables potential, particularly solar PV. The renewable build starts from a very low base, but investment and uptake will mature. Egypt aims to obtain 42% of its electricity from renewables by 2035; Turkey has raised its target to 50% renewable power by 2023; Saudi Arabia targets 30% by 2030; and UAE is calling for 70% decarbonization and 44% clean-energy power generation by 2050.
- Rising power demand and increased variable renewable generation will see grid interconnections established between the Gulf nations and the rest of the Middle East, despite political tensions. Cooperation will have to overcome a historical preference for self-sufficiency for security reasons, distortions in electricity prices due to subsidies, and state-owned monopolies not yet run on a commercial footing. Battery energy-storage will expand to support flexibility and renewables integration.
- Systemic subsidization of energy will likely reduce slowly owing to growing budgetary pressures linked to growing population and consumption. Reduced fossil-fuel subsidies will be the first step towards a price on carbon, but we foresee slow adoption of, and low, carbon prices for the region.

6.5 MIDDLE EAST AND NORTH AFRICA

ENERGY TRANSITION

Figure 6.5.1 shows Middle East and North Africa final energy demand growing throughout the forecast period. The growth is distributed across all sectors, though efficiency gains in transport will see energy use peak there first. Efficiency improvements will limit growth of final energy demand in all sectors, thereby counteracting the effect of population and economic growth.

The share of electricity in final energy demand continues to increase, from 17% in 2018 to 38% in 2050. Buildings see the strongest electrification, with transport and manufacturing following later in the forecast period. The 2050 electricity mix will be dominated by solar PV, natural gas and onshore wind. Even in this oil and gas rich region, variable renewables will produce more than half the power in 2050.

Figure 6.5.2 shows natural gas and oil dominating the primary energy mix through to 2050. Whereas oil use will see a slight decrease after 2040, natural gas's contribution will stay about constant at 2018 levels, and with around 40% of the gas going to the power sector. Solar PV and wind increase, but the uptake before 2030 is very limited. Coal, nuclear, hydropower and biomass are all minor players.

ENERGY TRANSITION INDICATORS

Figure 6.5.3 presents Middle East and North Africa developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

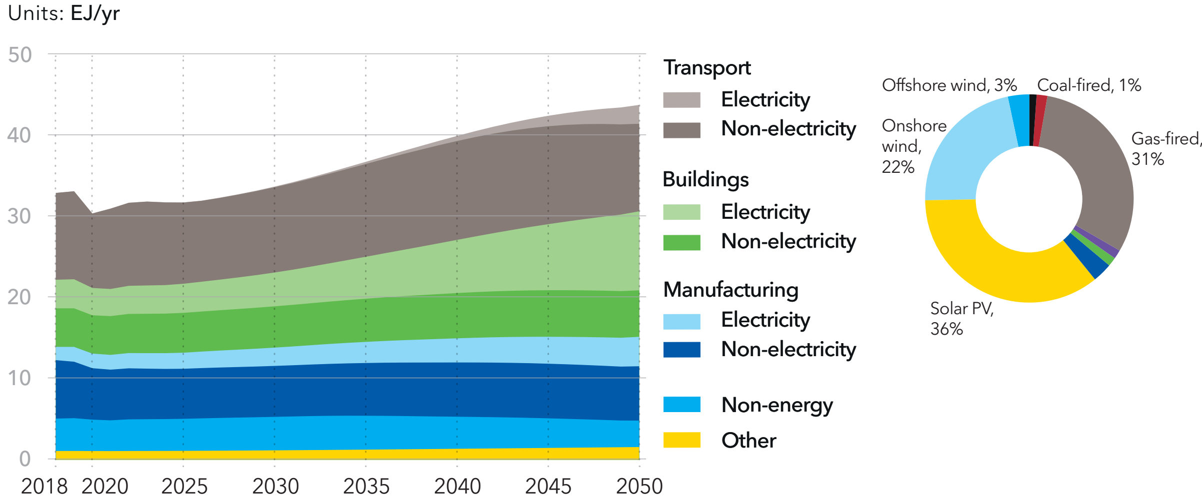
- The region will see a strong increase in the share of electricity in its final energy demand mix after 2030 in an order of magnitude of 17%.

FIGURE 6.5.1

Middle East and North Africa final energy demand by sector

2050 electricity mix

Units: EJ/yr

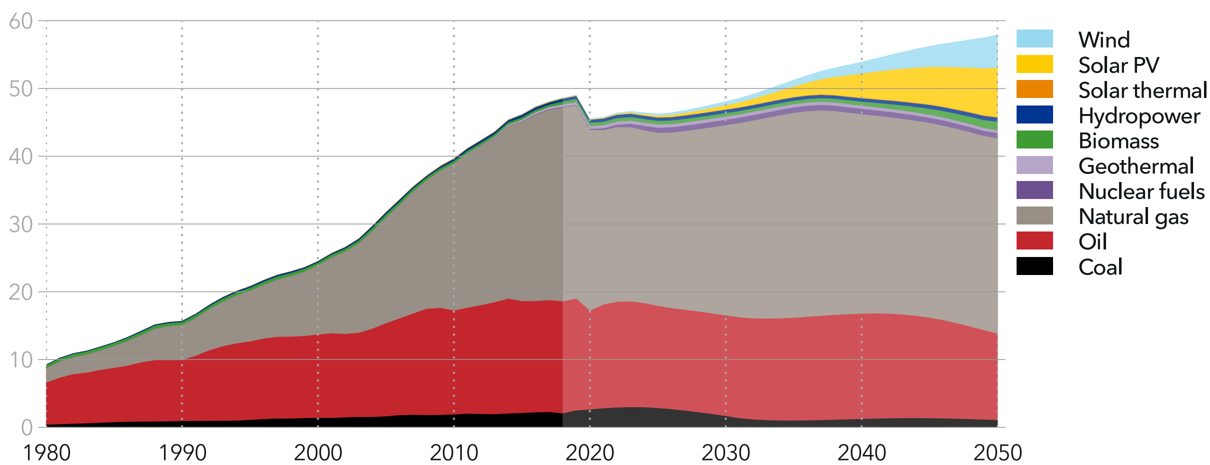


- Energy intensity in this oil and gas rich region will reduce by more than 40% between 2018 and 2050.
- The high share of fossil fuels in the energy mix will counteract further carbon-intensity reductions, reaching little more than 40 tCO_2/TJ in 2050 and representing highest value of all regions.

FIGURE 6.5.2

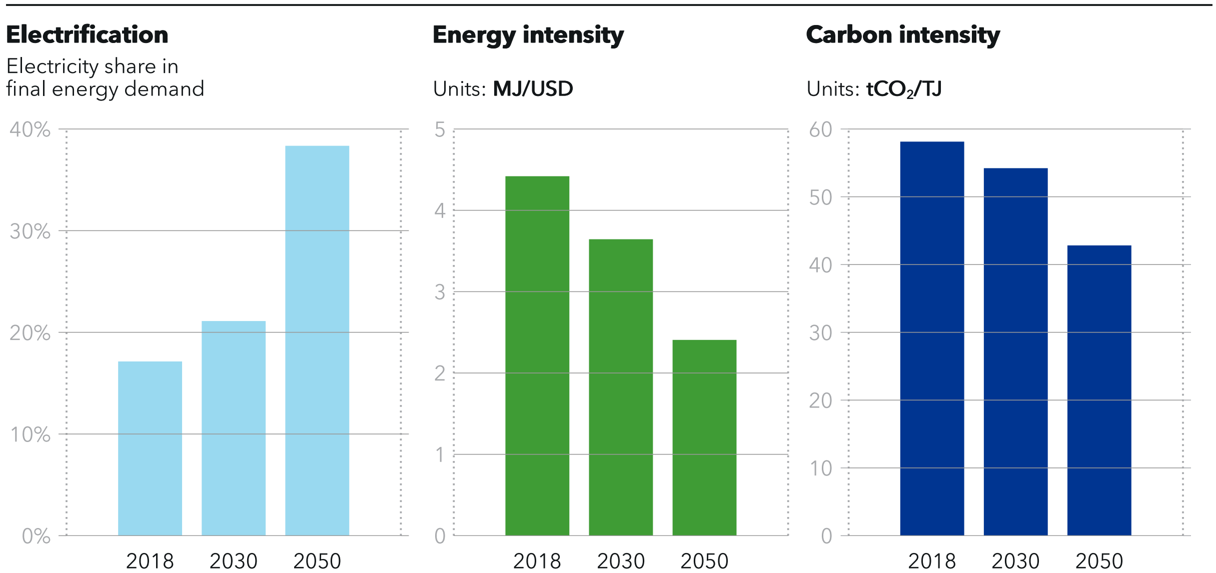
Middle East and North Africa primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.5.3



EMISSIONS

We project the region's average carbon price to be USD 20/t by 2050. There will be limited explicit carbon-pricing instruments; negative carbon prices currently exist, and the likely first step towards carbon pricing will be to eliminate fossil-fuel subsidies.

Energy-related emissions from the Middle East and North Africa follow an almost flat course over the next three decades. Figure 6.5.4 shows little change in the contribution from the three demand sectors, with a small decline in manufacturing emissions and a small increase in transport emissions.

Among the energy carriers there is also little movement, with only emissions from natural gas showing a small increase and coal and oil a small decline.

As the carbon price remains low, the expected uptake of CCS is negligible in the region; at 31 $MtCO_2$/yr in 2050, 1% of total emissions.

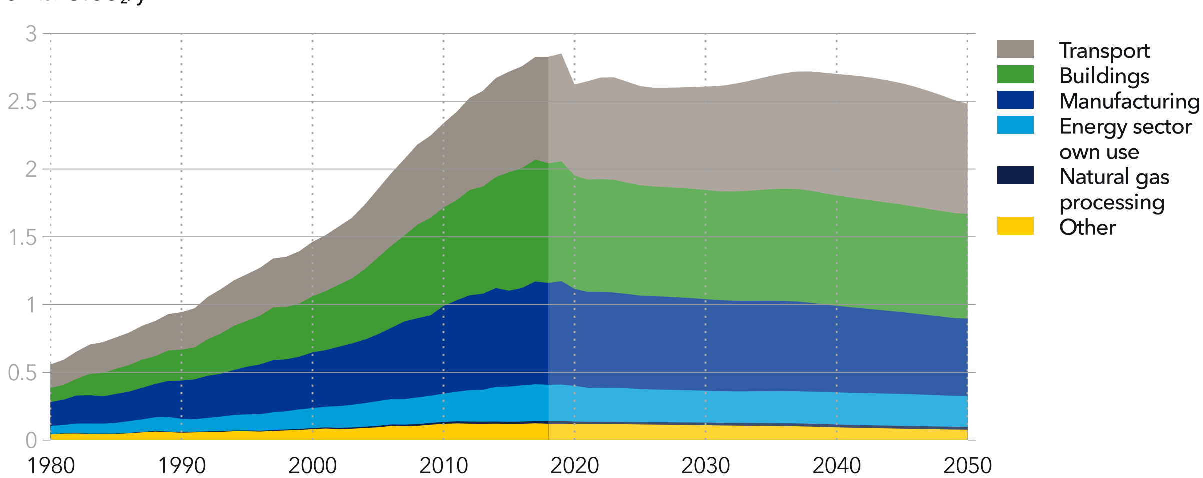
NDC pledges imply a regional target for emissions to increase by no more than 305% by 2030 relative to 1990. Our Outlook indicates that energy-related emissions will be limited to a 175% increase by then. There are some uncertainties in the comparisons of targets and forecasts as some countries are unclear about whether the targets reported in NDCs also include non-energy related CO_2 emissions.

The Middle East and North Africa's forecast emissions of 3.4 tCO_2/person in 2050 are two-thirds of the present level, and among the highest of all regions. This fossil rich region has a relatively slow transition, with emissions reducing less than in other regions with the same standards of living.

FIGURE 6.5.4

Middle East and North Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



FAST UPTAKE OF RENEWABLES IN A FOSSIL-RESOURCE RICH REGION

Electricity demand in the Middle East and North Africa will almost triple from 1,680 TWh in 2018 to 4,900 TWh in 2050. Due to the uptake of EVs, transport shows the greatest electricity demand growth, followed by cooling and non-substitutable electricity in buildings. Climate change will have significant implications for future electricity demand due to the expected rise in demand for cooling and water desalination.

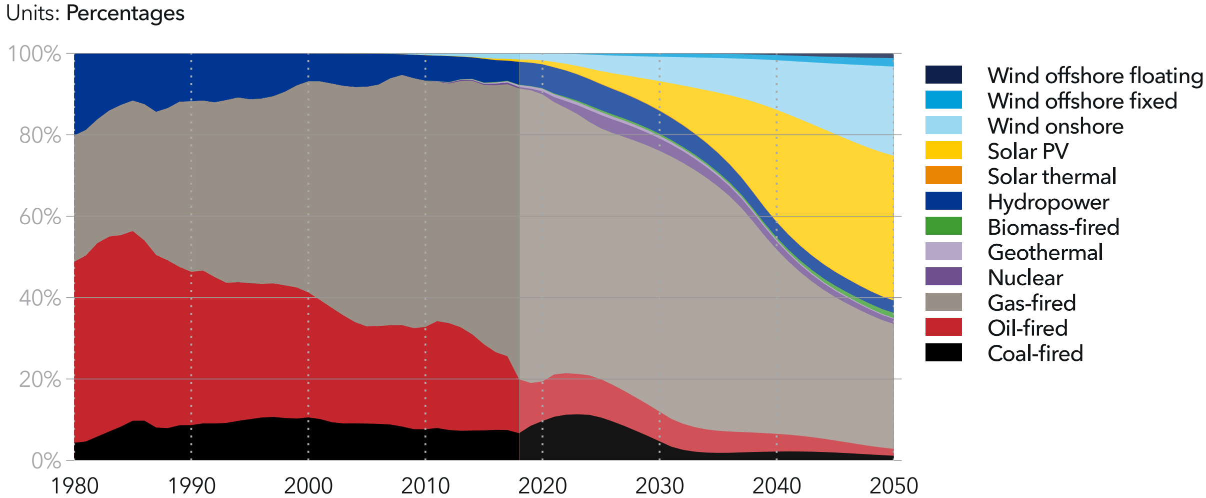
Though rich in fossil-fuel resources, the region will need a diversified mix of generation options to meet growing electricity demand. While natural gas will remain the dominant source of power generation in the medium term, there will be fast uptake of renewable technologies (Figure 6.5.5). Wind and solar resources currently have a combined contribution of just 2% to generation, the lowest among all regions. We see wind's contribution reaching 26% in 2050. For solar PV, the region will see the largest relative increase, 178-fold, between 2018 and 2050. Since the levelized cost of solar PV continues to decrease, due to the reliable year-round sunshine and a high capacity factor, its share in the generation mix will reach 35% by 2050, the second highest of all regions after the Indian Subcontinent's 36%.

The large contribution of variable solar and wind resources will require expansion of electricity-storage technologies. We estimate that the region will require a utility storage capacity of 133 GW by 2050, utilizing 141 TWh of electricity. This utility-scale storage, together with additional storage from grid-connected EVs, will provide a total resupply of 388 TWh to the power system, representing about 7% of total electricity generation by 2050.

FIGURE 6.5.5

Evolution of power generation mix in Middle East and North Africa

Units: Percentages



NORTH EAST EURASIA (NEE)

This region consists of Russia, Mongolia, North Korea and all the former Soviet Union States, except The Baltics

CHARACTERISTICS AND CURRENT POSITION

North East Eurasia produces 21% of the world's natural gas, and 16% of global petroleum liquids. Coal is also abundant. The region's dependence on oil and gas export revenues is strong, with risk and sensitivity to the global energy transition.

In this region, Russia is dominant in size, population, and economy. The Russian Federation is the world's second largest producer of hydrocarbons. Energy resources are responsible for about 55% to 75% of Russian annual export revenues.

Europe and the countries of the Commonwealth of Independent States (CIS) are the main markets for the region's hydrocarbon resources. Uncertainty has recently increased significantly in world markets, including unpredictable dynamics of oil prices, low growth in demand for the region's energy resources, and the probability that oil demand has peaked.

The region is at risk of falling behind in technology development becoming standard worldwide, given global decarbonization trend.

Common to all North East Eurasian countries are the high energy intensity of GDP and the recognition that energy savings and national policies to improve energy efficiency are key to national economic development. For example, maximizing the effective use of natural energy resources and decreasing the energy intensity of the economy are the primary objectives in Russian energy policy.

	Population (M)	Energy use/person (GJ)	Energy use (EJ)	GDP/person (USD)	GDP* (USD TRN)
2018	318	138	44	17 400	5.5
(NEE)					
2050	316	108	34	29 900	9.4

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- Abundant fossil-fuel reserves, along with economic dependence and substantial political will to develop these, eclipses the energy transition as a priority. The largest contribution to lower energy use and decarbonization will come from modernization and improved energy efficiency in all sectors.
- For Russian gas exports, the Energy Strategy to 2030 foresees retention of volumes to CIS and European markets. Export infrastructure, such as the Nord Stream 2 pipeline, will aim for diversification of transit routes to supply EU markets. For the entire region, an increase of exports in an eastern direction (China, Japan, the Republic of Korea) is expected, but mainly as LNG.
- Russia modestly aims for about 5% renewables in final energy consumption by 2030. A multi-sectoral focus of the Energy Strategy 2035 aims to lower the energy intensity of GDP by 50% (compared with 2010 levels).
- Russia ratified the Paris Agreement in September 2019. It targets a 30% emissions reduction from 1990 levels by 2030, with domestic focus on energy efficiency, reforestation, and carbon-free nuclear and hydropower. Emphasis on climate change and pollution reduction, especially in Europe, and hydrogen focus in Japan, makes hydrogen from natural gas a key priority, to maintain Gazprom's competitiveness in global markets.
- Kazakhstan's National Concept for Transition to a Green Economy sets a timeline for 3% renewable energy power by 2020, 30% by 2030, and 50% by 2050. Ukraine's 2050 Low Emission Development Strategy awaits an implementation plan.
- The relaunched Kazakhstan's Emissions Trading Scheme (ETS) started trade by end of 2019, and Ukraine is taking steps to develop an ETS scheme in the 2020s. In Russia, there is push-back and industrial opposition to carbon pricing measures from leading businesses.

6.6 NORTH EAST EURASIA

ENERGY TRANSITION

North East Eurasia's final energy demand, as shown in Figure 6.6.1, has increased slightly over the last few years, but will now start a slow decline. All sectors from manufacturing to buildings and transport will see a slight reduction in demand. With flat population development and a relatively slow transition to electricity, efficiency improvements generally counter the effects of economic growth to give a relatively flat energy demand.

As Figure 6.6.1 shows, the share of electricity in the final energy demand will continue to rise, from 14% in 2018 to 22% in 2050; which is still second lowest of all regions, after Sub-Saharan Africa. The buildings and transport sectors are both increasing their electricity share, while for manufacturing, North East Eurasia is the only region that does not see an increase in the electricity share of that sector, mainly due to high electricity prices. The 2050 electricity mix will be dominated by hydropower, with 30% of generation with a doubling of production in the next decades. Solar and wind have limited shares compared to most other regions, but still have strong relative growth. The natural gas share of electricity supply decreases from 44% in 2018 to 15% in 2050, and nuclear production is relatively flat.

The region's primary energy mix remains dominated by fossil fuels over the forecast period as shown in Figure 6.6.2, with oil as the main energy source in the transport sector and natural gas in the manufacturing, buildings, and power sectors. In 2050, natural gas, oil, and coal will still cover more than 70% of the region's primary energy use; nuclear will be 10% and renewable energy, at 17%, will be the lowest of all regions.

ENERGY TRANSITION INDICATORS

Figure 6.6.3 presents North East Eurasia developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

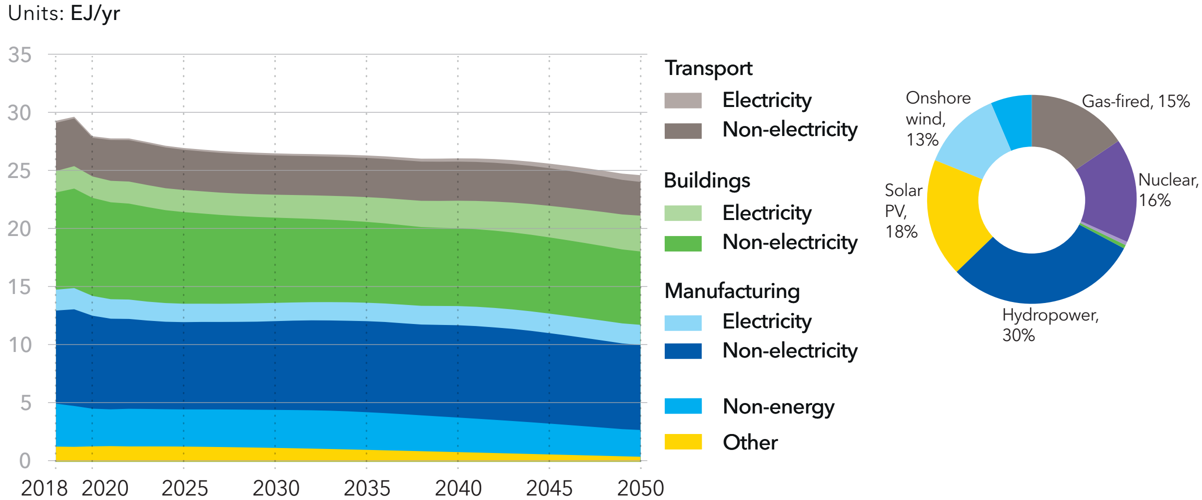
- Although, the region will increase its electricity share in the final energy demand mix to 22%

FIGURE 6.6.1

North East Asia final energy demand by sector

2050 electricity mix

Units: EJ/yr



(mainly after 2030) it still represents the second-lowest electrification value of all regions.

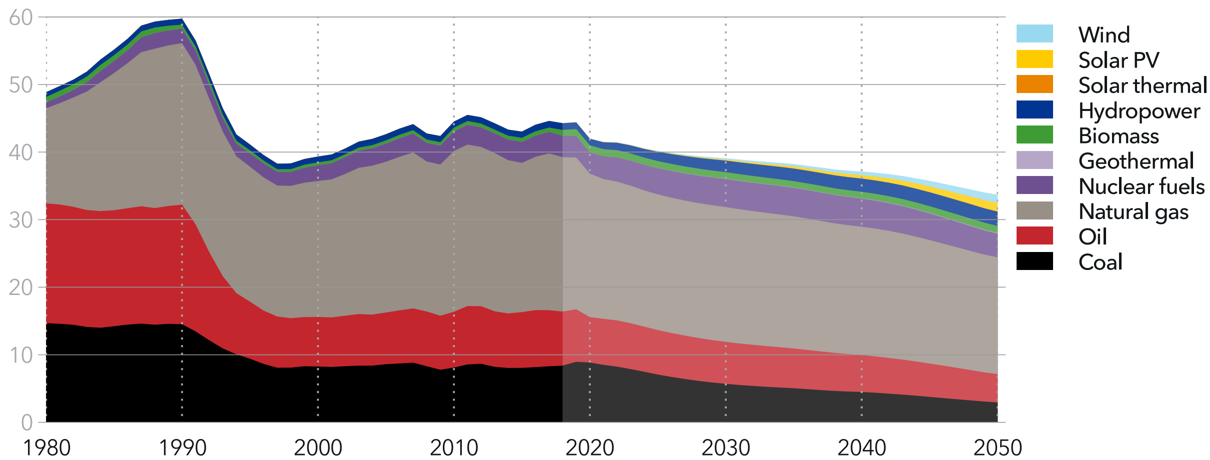
– The more than 50% reduction of region energy intensity is a significant decrease, resulting in one of the highest efficiency improvements of all regions by 2050. However, it remains the region with the highest energy intensity of all.

– Only a minor reduction is achieved regarding carbon intensity, reaching little more than 40 tCO_2/TJ in 2050, slightly lower than Middle East and North Africa and thus second highest of all regions.

FIGURE 6.6.2

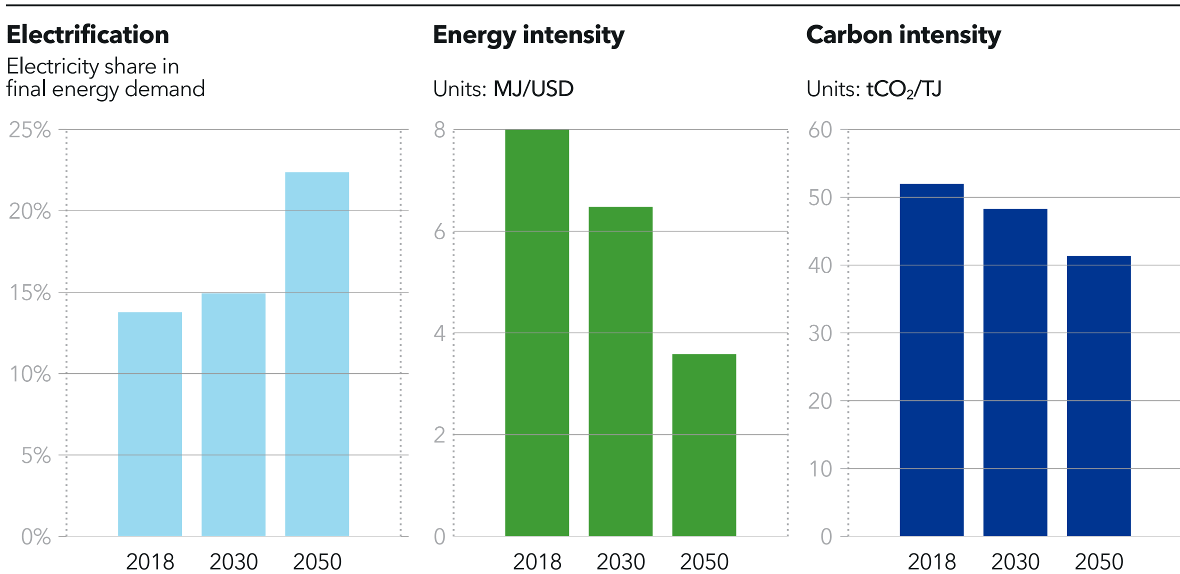
North East Eurasia primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.6.3



EMISSIONS

We project the region's average carbon price to be USD 20/t by 2050. Reduced fossil-fuel subsidies will likely be the early step towards a price on carbon. Slow adoption and low carbon prices are expected, although the region is likely to embrace some form of carbon pricing to avoid carbon border-tax adjustments from the EU.

After a slow increase over the last two decades, energy-related emissions from North East Eurasia are likely to decline slowly from now onwards, and in 2050 they will be about 40% lower than they are today. The decline is evenly distributed among all the main sectors, and manufacturing and buildings will dominate emissions in 2050.

Already today, emissions from natural gas are the largest in the region, and towards mid-century this trend will increase, with gas emissions double of oil and coal emissions combined.

The expected uptake of carbon capture and storage is negligible in the region; at 11 $MtCO_2$ it is lowest of all regions and less than 1% of total emissions in 2050 are captured.

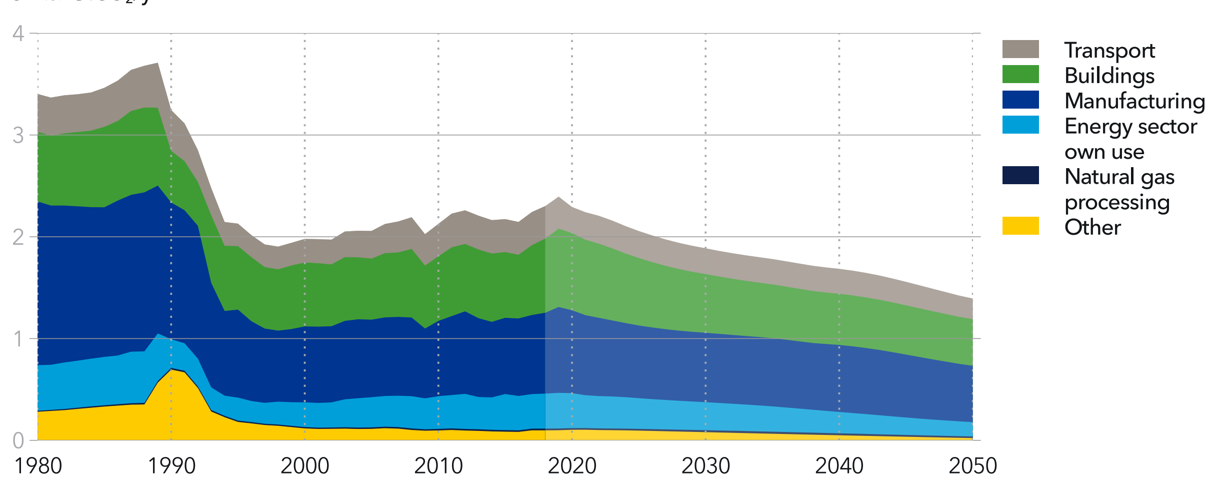
Interpretation and calibration of country NDC pledges indicate that the region has a regional target of reducing energy-related emissions by 18% by 2030 relative to 1990. Our Outlook indicates that the energy-related emissions will be down 42% by 2030.

In relative CO_2 emissions, North East Eurasia's 4.4 tonnes CO_2/person is highest of all regions, together with North America. As described in the regional story opposite, the fossil rich region has a slow transition and few incentives for change.

FIGURE 6.6.4

North East Eurasia energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



LITTLE PUSH TOWARDS A TRANSITION

Compared with most other regions, the incentives for change are relatively small in North East Eurasia. The region has a large resource base of oil, gas, and coal, and the economy depends on continued exports of these fuels. The public pressure to decarbonize is low, and the low economic and public incentives for change are considered the most important causes of this slow transition. The nature and resource base of the region also plays a role, and these different factors are also of course linked.

The result is something of a status quo. The region does electrify and decarbonize – along with our other regions – but for many indicators, like energy intensity of GDP, electrification rate, or share of renewables in primary energy consumption, the region lags behind the other regions, and maintains this position towards mid-century.

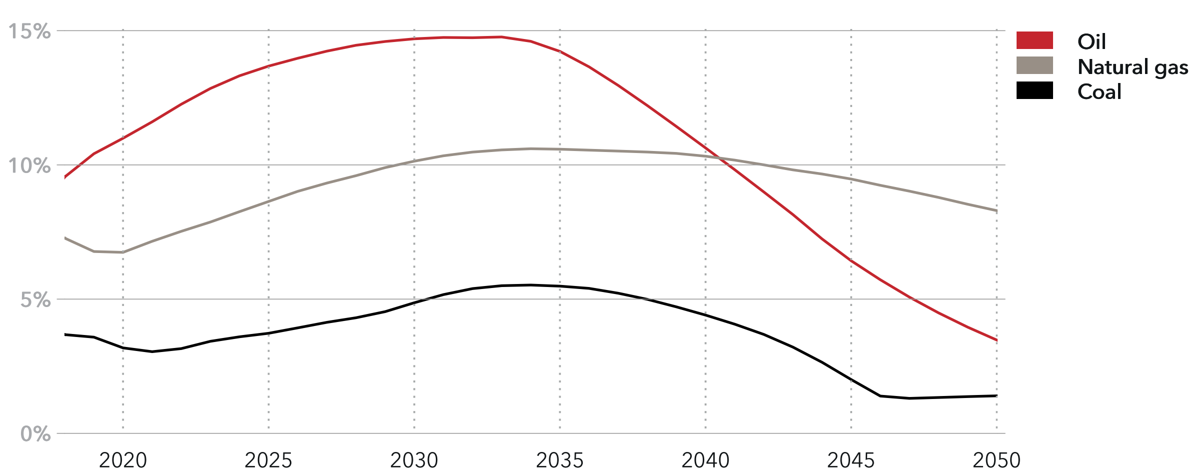
Reduced energy intensity of the economy and improved energy efficiency of the various sectors is mentioned as a priority, and the forecast does show improved efficiency in transport, buildings and manufacturing. The energy intensity in the region is very high today but will improve by an average of 2.5%/yr towards mid-century, and though this rate is a little higher than world average the energy intensity still remains high.

North East Eurasia's gas share is today the second highest of all regions and natural gas will maintain its share of around 50% of primary energy consumption towards the end of the forecast period, at which time this gas share is the highest of all regions. Gas export remains high throughout the forecast period (Figure 6.6.5). As fossil fuel consumption is falling only modestly, the region will use an increasingly higher share of oil and coal production domestically, but still maintain significant exports.

FIGURE 6.6.5

Ratio of North East Eurasia fossil fuel exports to global production

Units: **Percentages**



GREATER CHINA (CHN)

This region consists of Mainland China, Taiwan, Hong Kong and Macau

CHARACTERISTICS AND CURRENT POSITION

Greater China is the undisputed leader in the energy transition, topping investments in renewable power and fuels. At least 35% of power generation is to come from renewables by 2030, and China has begun its shift to a subsidy-free era relying on renewables obligations and tendering systems.

Local air pollution is a key driver of climate policy. China has played a pivotal role in climate negotiations, and the central government is actively steering domestic decarbonization efforts and the energy transition by stipulating targets and delegating responsibilities for energy efficiency, peak emissions, and non-fossil shares, i.e. higher than 20% of the energy mix and above 50% non-fossil power by 2030.

The government emphasizes a shift from high-quantitative growth to high-quality economic growth, with a corresponding shift towards a clean, low-carbon, safe, efficient and intelligent energy system towards 2050. Issued in 2017, the Energy Supply and Consumption Revolution Strategy (2016–2030) outlines strategies for the energy sector, beyond the 13th Five Year Plan. Examples of these strategies include controlling primary energy consumption within 6 billion tonnes of coal equivalent (176 EJ), expanding natural gas to 15% of the energy mix, transitioning to ultra-low polluting coal-power plants, and meeting new energy demand mostly by clean energy.

The central government aims to speed up development of 'new infrastructure', e.g., intercity high-speed railways and charging systems for EVs.

The overarching ambition is to secure supply while curbing environmental degradation and restoring the already-fragile environment. China's green strategy is a platform to become a world leader in green technologies and strategic emerging industries, combining energy, climate, and industrial-policy objectives. It promotes manufacturing technologies with export potential (solar, wind, nuclear, EVs, batteries) and also the benefit of large domestic markets.

(CHN)	**Population** (BN)	**Energy use/person** (GJ) / **Energy use** (EJ)	**GDP/person** (USD) / **GDP*** (USD TRN)
2018	1.44	101 146	20 100 29
2050	1.33	96 128	47 200 63

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE ▶▶▶

- Domestic renewable energy sources limit energy imports, which will remain high regardless. Growth in renewables will continue, though ongoing reform to financial support – a shift to market-oriented systems to alleviate subsidies – may slow developments in the short term.
- China's Action Plan for Winning the Blue Sky will tighten emissions standards, mandate industry-conservation targets and coal-to-gas switching, improve fuel-economy standards, restrict ICEV sales, and massively expand public transit.
- LNG import is soaring in line with China's policy on coal-to-gas switching in industry, and in households to curb air pollution. Natural gas infrastructure buildout continues, also aiming for 46 LNG terminals by 2030. China is expected to lead CCS activity in Asia Pacific with one large-scale facility already operating, two in construction and five in early development.
- The Made in China innovation plan targeting higher value-added manufacturing will trigger electrification of industry. The Circular Economy Promotion Law (2008) will gradually increase the share of electric arc furnaces in iron and steel making as more steel is recycled. Increased pilot projects will pave the way for hydrogen use, with hydrogen envisioned to account for 10% by 2050, e.g., in transport and industrial applications. In combination, initiatives will reduce the energy intensity of industry.
- The nationwide carbon trading market starts with the power sector and 1,700 power plants accounting for one third of China's GHG emissions. The eight ETS pilot schemes began in 2011, and the national ETS started to operate in 2018, and is planned to cover all energy-intensive and high-emission sectors by 2025.
- China has a unique opportunity, and arguably an obligation, to replicate domestic decarbonization progress abroad, by directing state bank investments ploughed into infrastructure projects across Asia and Africa to low emission, clean-energy systems.

6.7 GREATER CHINA

ENERGY TRANSITION

Figure 6.7.1 shows Greater China's final energy demand growing strongly in the coming decade to peak around 2030. The peak and subsequent decline will be due to population stabilization, a reduction of the secondary sector's share in the economy, and energy-efficiency gains in all sectors. These forces are stronger than the effect of economic growth, which is also set to continue.

The share of electricity in final energy demand will continue to increase, from 23% in 2018 to 52% in 2050 – the highest of all regions. Manufacturing will see particularly strong electrification, and transport – China is the frontrunner in EVs – and buildings will see a rapid shift to electricity. The 2050 electricity mix will be dominated by wind and solar PV, with 37% and 35% shares respectively. Hydropower will also be among the main contributors, taking the renewable electricity share above 90%.

Figure 6.7.2 illustrates our expectation of a complete turnaround in Greater China's energy mix within the forecast period. Coal is currently by far the largest primary energy source, but its use in the coming decade is almost flat, followed by a strong decline after 2030. Oil is the second largest energy source and will grow for another decade, when electrification of the vehicle fleet starts to reduce demand for oil. The use of natural gas will almost double in the next 15 years, mainly due to increased demand from manufacturing. Significant growth is expected for renewable energy sources, and China will have the second highest wind share (after OECD Pacific) and among the highest PV shares of all regions.

ENERGY TRANSITION INDICATORS

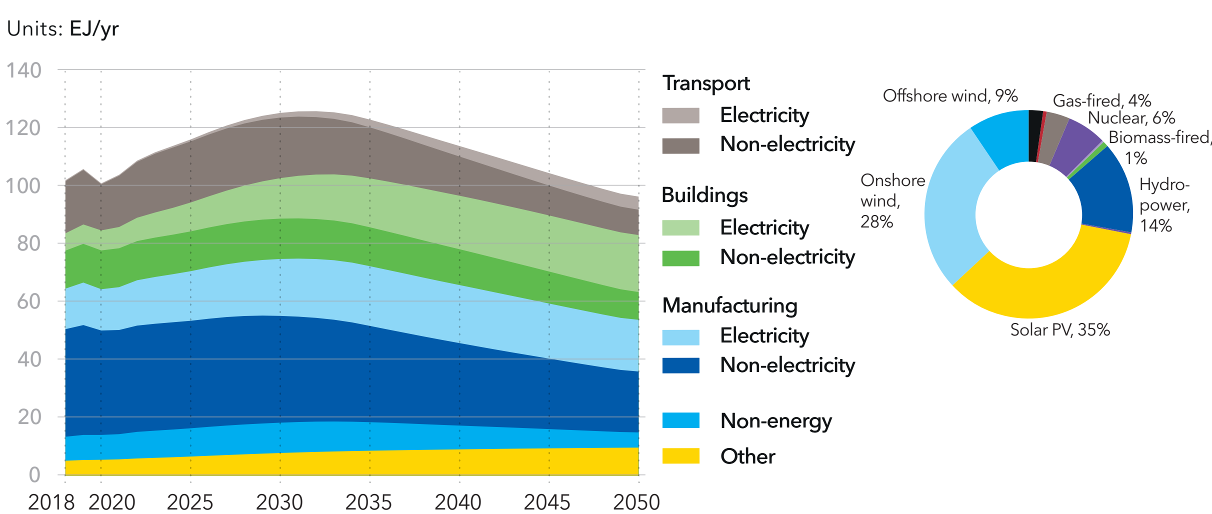
Figure 6.7.3 presents Greater China developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

– More than half of final energy demand is supplied by electricity in 2050. This is the

FIGURE 6.7.1

Greater China final energy demand by sector

2050 electricity mix



highest of all regions and driven by electrification of all demand sectors – transport, manufacturing and buildings.

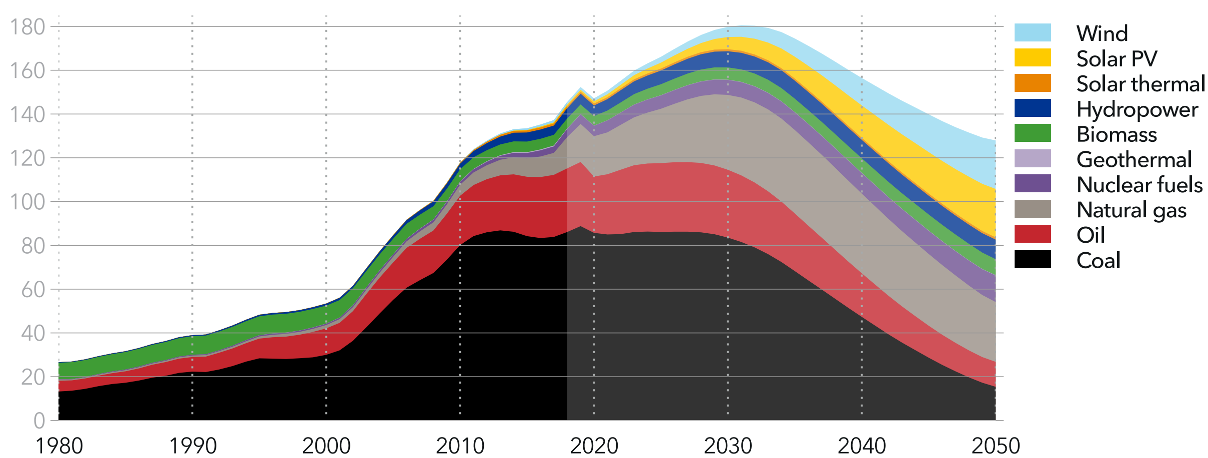
– The region's energy intensity is going to reach 2 MJ/USD, showing a similar pattern between 2018 and 2050 as many other world regions that strive for continuous efficiency improvements and electrification of energy end-use.

– Carbon intensity will significantly decrease after 2030 by more than two thirds, reaching a level which is amongst the lowest of the ten regions and comparable to the OECD Pacific region.

FIGURE 6.7.2

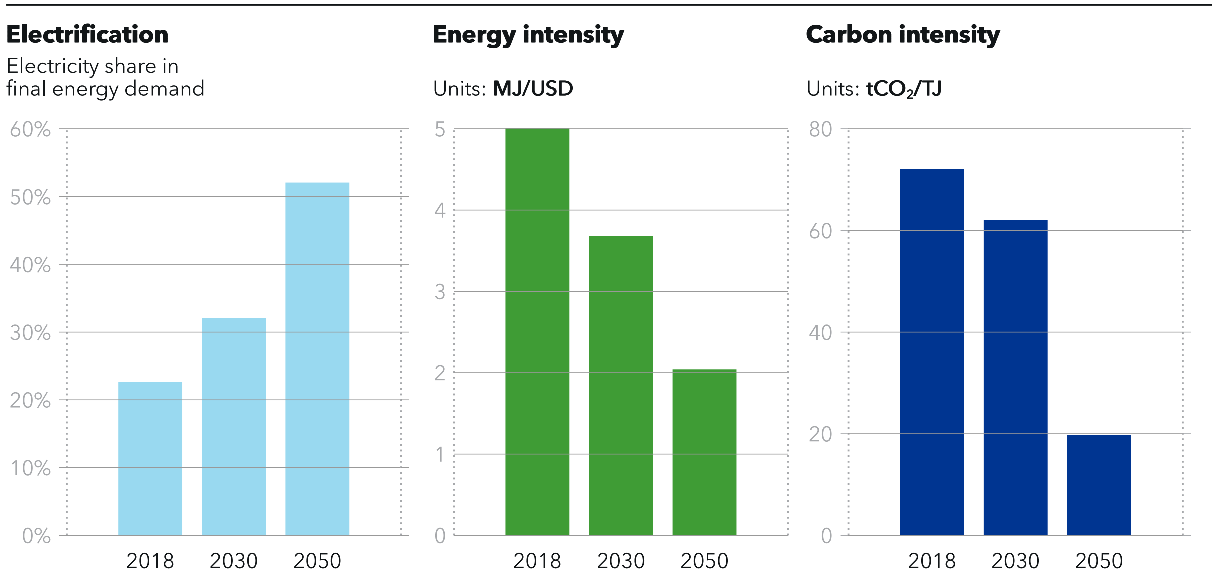
Greater China primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.7.3



EMISSIONS

We project an average carbon price of USD 60/t by 2050 in the region after a steady rise from a lower starting level than in Europe. The latter region will be the only one with higher carbon prices than Greater China by mid-century. China's nascent ETS could eventually link with carbon-pricing systems in neighbouring countries like South Korea.

Greater China energy-related emissions are almost 30% of global emissions today, so their future trajectory is vital. We foresee these regional emissions tracking sideways in the 2020s before declining to 75% less than today in 2050. Emissions from manufacturing have peaked and will do so in transport and buildings around 2030, then decline steeply in all these sectors. Coal is behind more than 75% of China's CO_2 emissions today. Coal emissions fall and gas emissions rise to be the largest source towards 2050.

The forecast 840 $MtCO_2$/yr CCS in Greater China in mid-century will better any other region, after rising rapidly from only a tenth of this capacity in 2040. Uptake in China benefits from CCS technology costs falling globally; high carbon prices in Europe being one driver for this. CCS in Greater China in 2050 will equate to a quarter (25%) of the region's total emissions.

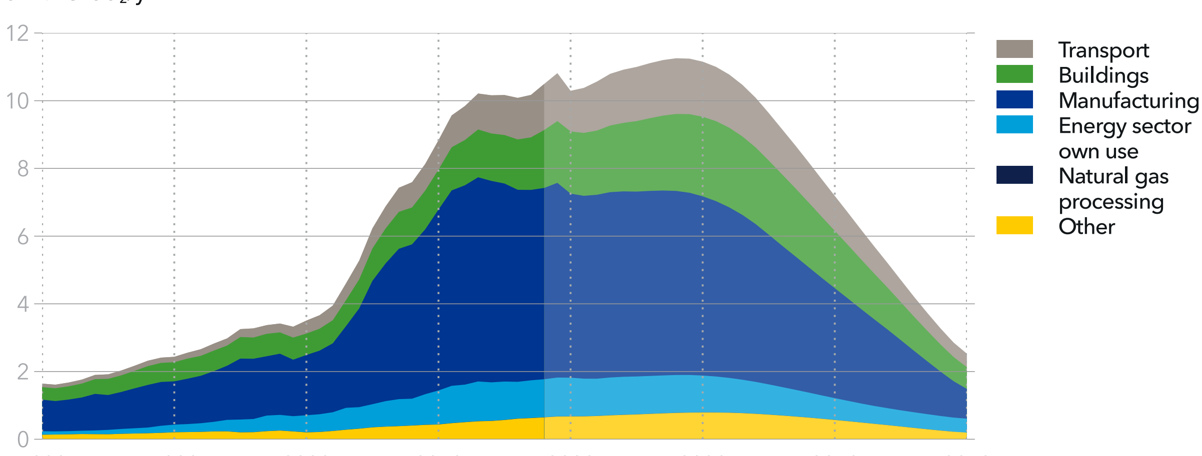
China targets a 60% to 65% reduction in carbon intensity (below 2005 levels) by 2030. Exact comparison is difficult as our model does not regionalize non-energy related CO_2 emissions. However, our Outlook indicates a 66% reduction in carbon intensity by 2030, i.e. the target would be barely achieved.

The region emits 1.7 tonnes CO_2/person in 2050, slightly below the global average, because of a rapid transition from coal in two decades beyond 2030.

FIGURE 6.7.4

Greater China energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



SPEARHEADING THE TRANSITION: IRON AND STEELMAKING

Manufacturing will continue to play an outsized role in Greater China. With related emissions relatively hard to abate, what happens in this sector will greatly affect the pace of the energy transition.

In our Outlook, base materials production including iron and steel rises 50% to peak in 2034, then declines 25% by 2050. Manufactured goods plateau in the mid-2030s at about 65% more than in 2018. However, energy-efficiency gains mean total energy use in manufacturing is only 10% higher in 2030 than in 2018, and then declines 31% by 2050.

Energy use in iron and steelmaking falls 50+% from current levels, while electricity use for machinery grows 31% by 2050. These trends reflect a much-reduced share of base materials in the region's future manufacturing. While decarbonization of electricity will ensure manufacturing becomes virtually green by 2050, industrial heat will largely retain a 60+% share in the sector's energy use up to mid-century.

Iron-ore reduction will remain coal-based until the mid-2040s; but over 2045–2050, coal's share will drop 20% because of increasingly cost-competitive hydrogen and hydrogen technologies.

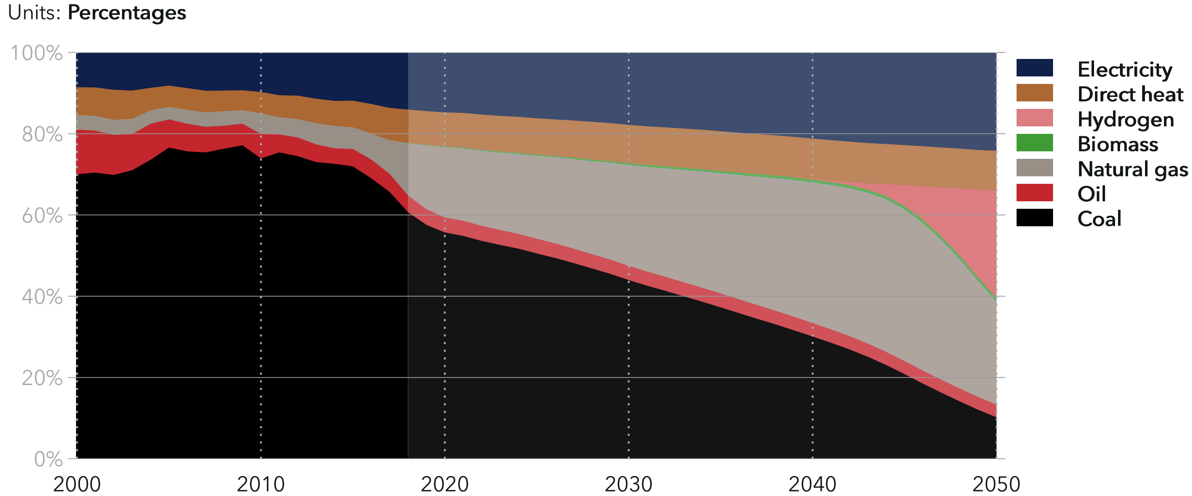
Electricity powers some industrial heat (Figure 6.7.5), notably for processing recycled steel. Today, coal's share of this is 75%, electricity's is 20%, rising to 50+% by mid-century. This rise is assisted by the declining cost of electricity and the increased share of recycled steel, and by consequent growth of electric arc furnaces.
Gas use grows from 2% today to more than 15% in the early 2040s. It is then increasingly replaced by hydrogen, which will supply up to a quarter of industrial heat requirement by 2050.

Extrapolating trends from our Outlook beyond mid-century, we foresee a zero-carbon Chinese manufacturing sector by 2060, with only electricity and hydrogen use in industrial heat processes.

FIGURE 6.7.5

Greater China industrial heat energy mix by carrier

Units: **Percentages**



INDIAN SUBCONTINENT (IND)

This region consists of India, Pakistan, Afghanistan, Bangladesh, Sri Lanka, Nepal, Bhutan and The Maldives

CHARACTERISTICS AND CURRENT POSITION

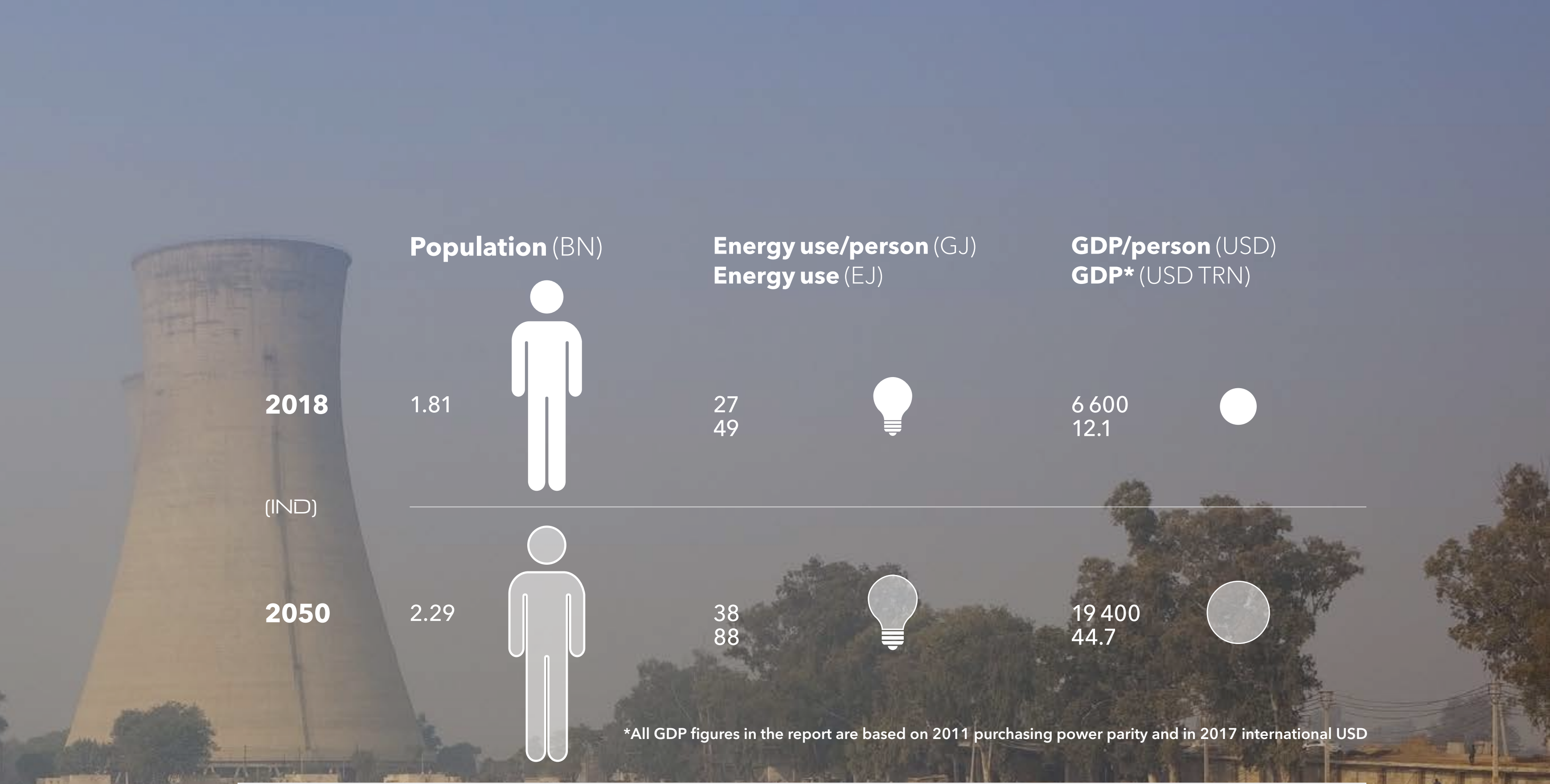
The region's energy demand is growing, fuelled by economic and population growth. Energy supply is the main issue, and in terms of electricity access, of the 141 ranked economies in the 2019 Global Competitiveness Report, India is ranked 105th, Bangladesh 108th, and Pakistan 111th (Schwab, 2019).

India's choices for powering further economic growth, plugging energy gaps, and addressing local air pollution will largely determine the rate of the transition in this region. Its hazardous air consumes 7% of GDP in health and welfare losses (NITI Aayog et al., 2018). Although India's coal-intensive energy sector is vast, the past decade has seen a steady growth in renewables.

Pakistan faces severe energy deficiencies. Its energy mix is dominated by fossil fuels with reliance on imports, although it has domestic coal reserves. Unlike India with its slowdown in new coal, Pakistan targets coal as a way out of a shortage of gas and growing reliance on oil-based generation.

Bangladesh also faces high dependency on imported energy (LNG, coal, oil, power). Electricity access has expanded to more than 90% of the population (Government of Bangladesh, 2019), helped by off-grid rooftop solar power.

With its high population density and cities in low-lying floodplains, the Indian Subcontinent is vulnerable to climate change. More frequent flooding and longer periods of drought are expected – Afghanistan, India and Pakistan are already among the most water-stressed countries.



(IND)	Population (BN)	Energy use/person (GJ) / Energy use (EJ)	GDP/person (USD) / GDP* (USD TRN)
2018	1.81	27 49	6 600 12.1
2050	2.29	38 88	19 400 44.7

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE ▶▶▶

- India's 2019 National Clean Air programme aims for 20% to 30% less particulate matter in the air by 2024. It will trigger initiatives including, among others, emission standards on coal-fired plants, and fuel mix and vehicle-emission standards in transport.
- India has pledged a greater non-fossil fuel share in its energy mix, and that renewables capacity will rise by 2022 to well beyond a 175 GW target, and later to 450 GW (Prime Minister's Office, 2019). With 87 GW installed as of March 2020 (Government of India, 2020), 175 GW looks challenging. The government is working towards major reforms like a real-time electricity market and amending the Electricity Act-2003 to assist the transition.
- India's energy storage and flexibility resources will progress. The National Mission on Transformative Mobility and Battery Storage will spur renewables integration with grids, and storage developments as part of electric mobility plans.

A common minimum grid code for cross-border electricity trade among South Asian countries will boost renewables in the region.

- Pakistan has abundant but largely unexploited potential in solar, wind and hydropower. However, government estimates suggest investment in coal-fired generation, in which the China-Pakistan Economic Corridor will be instrumental.
- Bangladesh is expected to strengthen renewable energy and energy-efficiency programmes to bridge its shortfall in energy supply. However, plans to reduce dependence on natural gas, with a move towards coal for 50% of total electricity by 2030, will pose significant climate risks as well as economic opportunity costs as renewables become cheaper. Addressing subsidies for industrial use of oil products and natural gas will be a key issue.

6.8 INDIAN SUBCONTINENT

ENERGY TRANSITION

With the population increasing by some 500 million people and GDP increasing 3.5 times, the region's final energy demand continues to grow rapidly over the coming decades in our Outlook (Figure 6.8.1). The largest increase comes from manufacturing, while transport also sees strong growth. However, electrification and efficiency gains in all sectors will curb this demand growth.

The share of electricity in final energy demand more than doubles, from 16% in 2018 to 42% in 2050. The 2050 electricity mix is dominated by solar PV with about 37%, the highest such share among all regions. Coal, gas and hydropower each have around 15% of the electricity generation mix.

Coal is currently the region's largest source of energy and will continue its growth before peaking around 2030 (Figure 6.8.2). The subsequent decline of coal will be due primarily to its replacement by natural gas in manufacturing and by renewables in power. Oil use in the region will see strong growth until around 2040, after which electrification of transport will send oil use into decline. Natural gas use will triple over the forecast period and eventually overtake coal as the biggest energy source. Despite the rapid growth of renewables, fossil-fuel energy sources will still represent 62% of the energy mix in 2050.

ENERGY TRANSITION INDICATORS

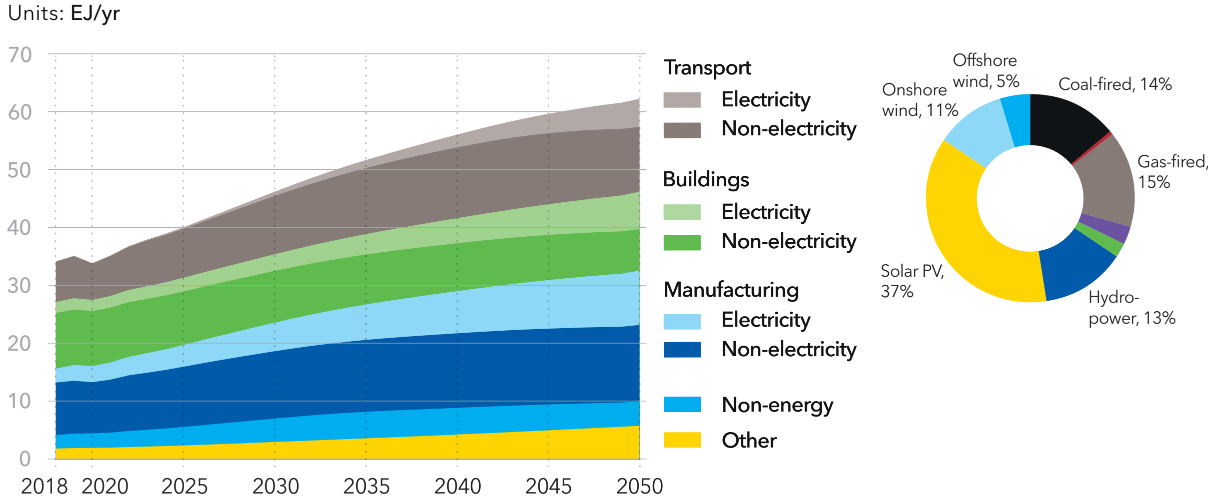
Figure 6.8.3 presents Indian Subcontinent developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

- The region's electricity share in final energy demand is almost tripling from 2018 onwards, reaching a 42% share in 2050, which is

FIGURE 6.8.1

Indian Subcontinent final energy demand by sector **2050 electricity mix**

Units: EJ/yr



comparable to developments in South East Asia and Latin America.

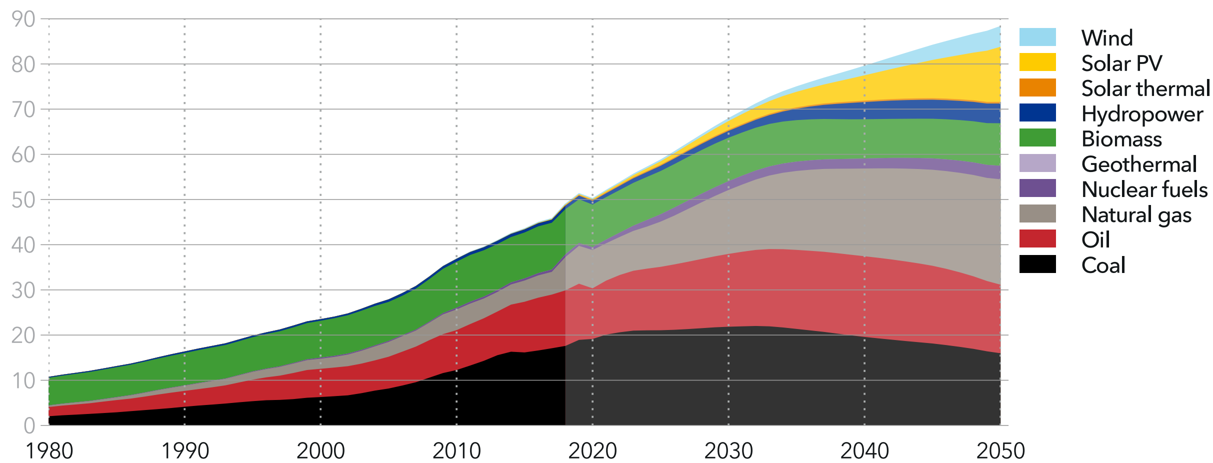
– Energy intensity will be down to 2 MJ/USD, which is in an order of magnitude similar to more than half of the regions.

– Carbon intensity in the region is heading towards 40 tCO_2/TJ, which is amongst the highest and comparable to the North East Eurasia and Middle East and North Africa regions.

FIGURE 6.8.2

Indian Subcontinent primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.8.3

Electrification

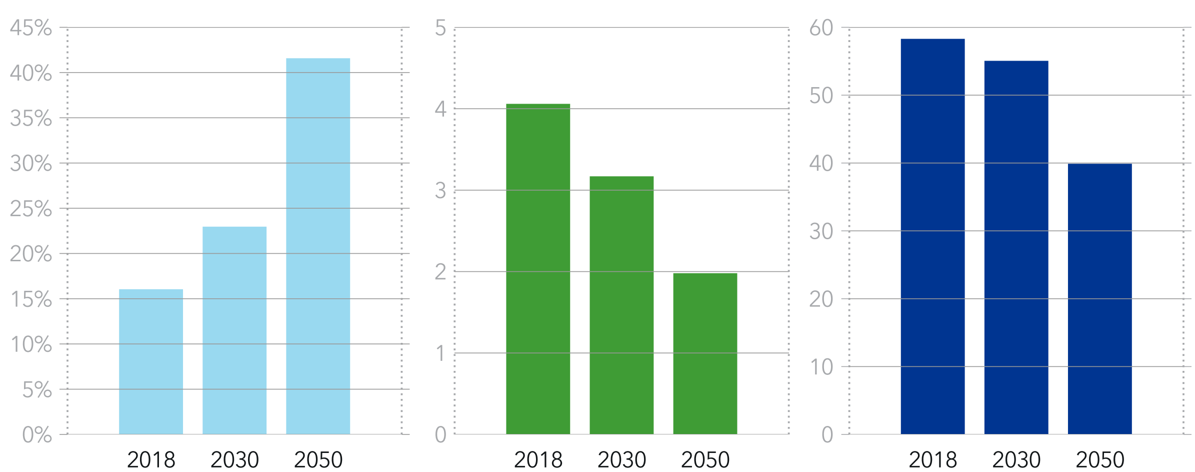
Electricity share in final energy demand

Energy intensity

Units: MJ/USD

Carbon intensity

Units: tCO_2/TJ



EMISSIONS

We project the region's average carbon price to be USD 35/t by 2050. Explicit carbon pricing instruments are expected no earlier than the mid-2020s. The prime drivers of carbon price developments will be access to climate finance, potential future carbon border-tax adjustments, and international trade in climate mitigation (Article 6 of the Paris Agreement).

The subcontinent's energy-related emissions have increased considerably in recent decades but are still relatively low among our Outlook's regions. Emissions will keep increasing to peak in the mid-2030s, driven by strong increases in manufacturing and transport emissions (Figure 6.7.4).

Emissions today are dominated by coal, which will remain the largest energy carrier despite its dominance in the mix reducing from 2030 onwards.

We see CCS capacity reaching 100 $MtCO_2$/yr in 2050 after steep growth in the final few years of the forecast period. This equates to less than 4% of the region's energy-related emissions by mid-century. There is relatively little support for CCS from the carbon price, which is among the lower levels projected for the Outlook's regions.

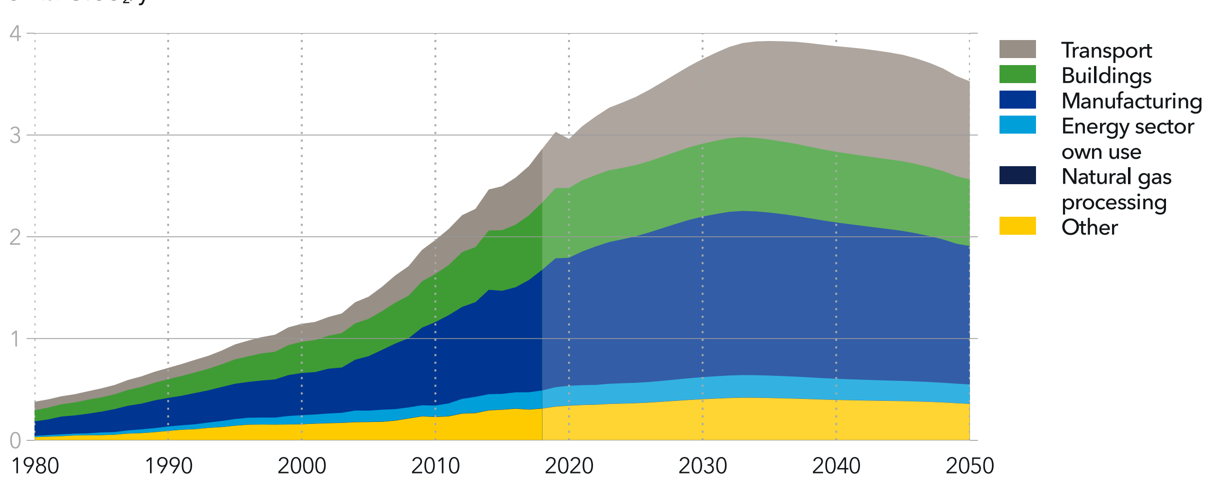
NDC pledges indicate that the region aims to limit emissions growth to no more than 503% by 2030 relative to 1990. Our Outlook indicates energy-related emissions increasing by 418%, suggesting that the target is not ambitious. There are some uncertainties in comparing the two numbers as some major countries in the region also include non-energy related CO_2 emissions in their targets.

The region's emissions are 1.5 tCO_2/person, and remain flat throughout the forecast period. Indian Subcontinent emissions are today very low compared with other regions, but only a little below average in our Outlook for 2050.

FIGURE 6.8.4

Indian Subcontinent energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



COAL VERSUS RENEWABLES

Only Greater China produces and uses more coal that the Indian Subcontinent, where production peaks in 2032 at 1,100 Mt/yr, falling to 800 Mt/yr by 2050. Despite the latter region's high domestic production (Figure 6.8.5), it will still need to import coal right through to 2050 to meet demand. Switching to renewables from coal comes later than in other regions, with coal still firing 45% of power generation in 2030.

That said, the Indian Subcontinent has large potential to diversify its energy mix. In our Outlook, solar PV, and floating and fixed offshore wind, show growth, high profitability, and are good candidates for replacing coal. This shift is evident in our forecast which has coal-fired generation rising 300 TWh/yr by 2040 while solar PV increases by 1,500 TWh/yr.

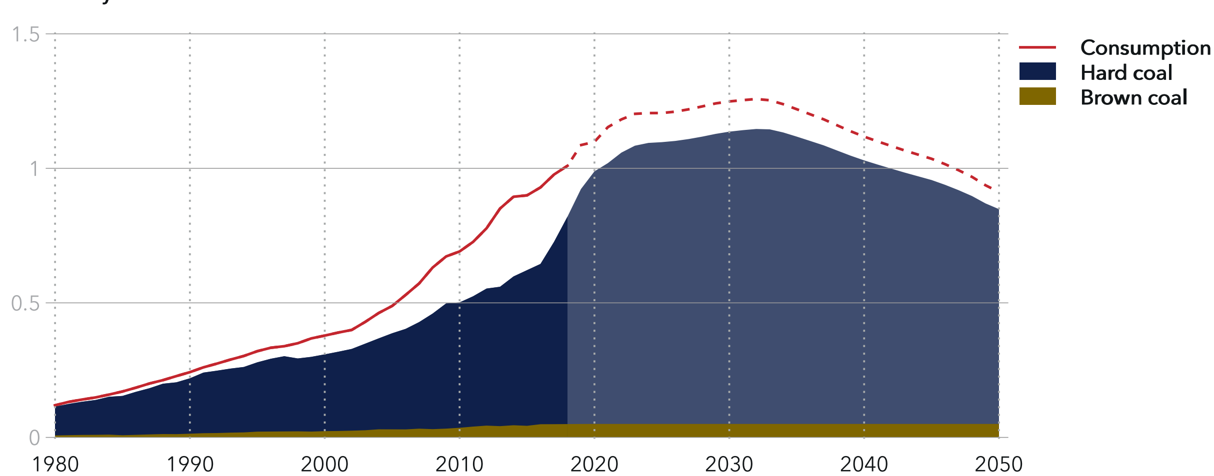
While the three largest sources of renewable energy – hydropower, solar PV and onshore wind – will generate around 30% of the region's electricity in 2030, this share will more or less double by 2050. As coal's role declines, these alternative energy resources will be needed to keep up with India's growing energy demand, notably in manufacturing and transport.

Electrification materializes much later than in OECD countries and China. The upside is that the Indian Subcontinent benefits from the evolution of technologies and cost-competitiveness – most notably in solar PV and wind – making renewables cheaper sources of energy than coal.

FIGURE 6.8.5

Indian Subcontinent coal consumption and production by type

Units: **Gt/yr**



SOUTH EAST ASIA (SEA)

This region stretches from Myanmar to Papua New Guinea, and includes the Pacific Ocean States

CHARACTERISTICS AND CURRENT POSITION

Indonesia, Thailand, and the Philippines are the largest economies. Singapore has the highest GDP per person. The region's economic weight is growing. So is its carbon footprint, despite it being among regions most vulnerable to climate change; e.g. typhoons and floods becoming more intense.

Pursuit of economic growth is the most prominent commonality of national energy policies. Meeting increasing energy demands from expanding economies and growing populations is a key priority for South East Asian countries. A growing urban middle class is the main driver of electricity demand in residential and service sectors. Flourishing manufacturing pushes up industrial energy demand.

Reliance on hydrocarbons in the energy mix is high, mostly oil for transport, and coal and gas for electricity. Facing declining domestic gas production, many countries will move from being exporters to net-importers, despite push to maintain or increase gas production. 'Clean' diversification is part of policy considerations to reconcile growth with domestic concerns over air quality and health, and to enhance national self-reliance.

Thailand leads the region in renewables. Singapore is pioneering smart-grid technology, EV uptake and considering hydrogen as a fuel to meet climate targets. Vietnam is the fastest growth market for new wind and solar developments. Regulatory uncertainty is dampening private-sector investment in renewables in most of the region.

Across the region there is increasing interest in PPAs with corporate clean-energy sourcing from global multinationals that set green goals to power operations and reduce carbon footprints.

Public funding gives impetus to fossil-based technologies; e.g. government subsidies for production and consumption, export credit guarantees like in Japan and South Korea, and coal power plant sales from China. These slow the transition towards renewable technologies in generation and energy efficiency.

(SEA)	**Population** (M)	**Energy use/person** (GJ) **Energy use** (EJ)	**GDP/person** (USD) **GDP*** (USD TRN)
2018	666	48 32	12 900 8.3
2050	783	59 46	30 200 23.6

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE

- There is a shift towards electricity for meeting final energy demand; traditional biomass is losing importance. With growing gas demand, increasing LNG imports will be critical, driving regasification capacity from about 37 Mt/yr now to 240 Mt/yr in mid-century. Electrification of transport will play a role as the region's traditional two-wheeler fleet electrifies.
- The region has significant renewables potential. Association of Southeast Asian Nations (ASEAN) member states are targeting 30% lower energy intensity than in 2005; and a higher (23%) share of renewables in primary energy supply by 2025, at 14% in 2019 (ASEAN, 2019). With coal power being the fastest-growing source of CO_2 emissions, the region has yet to seize the full opportunity of cost-competitive renewables. However, jobs and domestic module-manufacturing capacities in renewables will support deployment.
- Barriers to investment in renewables include regulatory uncertainty, fiscal support for and vested interests in hydrocarbons, and bank-dominated funding categorizing large-scale renewable projects as risky (ADBI, 2018). Climate-motivated shifts in foreign direct investment could be a game-changer to overcome these obstacles.
- There is cross-border bilateral power integration. In the future, multilateral trade and interconnection will spur deployment of variable renewables. The Laos-Thailand-Malaysia-Singapore Power Integration Project is a step towards this. Electricity market restructuring is unfolding in Malaysia, Philippines and Vietnam in a transition from vertically integrated market structures towards competition and customer choice. This will encourage new and more-efficient generation.
- Cheap coal from Australia and Indonesia, and lower demand from other countries, will flood the regional energy market, pressurizing transition mechanisms. Australia predicts that greater coal exports to Cambodia, Myanmar, and the Philippines will potentially replace its lost exports to China.

6.9 SOUTH EAST ASIA

ENERGY TRANSITION

South East Asia's final energy demand will continue to grow over the coming decades, starting to level off towards the end of the forecast period (Figure 6.9.1). The largest increase will come from buildings, associated with population growth and an increase in income per capita, leading to greater demand for space cooling and appliances. There will also be growth in the energy demand from transport and manufacturing.

Figure 6.9.1 also shows the share of electricity in final energy demand continuing to rise, from 16% in 2018 to 42% in 2050. All three main sectors see strong electrification within the forecast period. The 2050 electricity mix is dominated by solar PV supplying about a third of electricity, followed by natural gas and hydropower.

Oil is currently the largest energy carrier and will grow for another 15 years before starting to decline (Figure 6.9.2). In the next decade, natural gas will see the largest growth, driven mainly by growth in power sectors focusing on higher-efficiency CCGT, and in manufacturing. Coal will grow initially, but peak in about five years' time. Beyond 2030, natural gas will outcompete coal in manufacturing, with both coal and natural gas challenged by growing renewables in the power sector. Solar PV and wind will both see strong growth towards the end of the forecast period, but the fossil-fuel share remains high, at 64% in 2050.

ENERGY TRANSITION INDICATORS

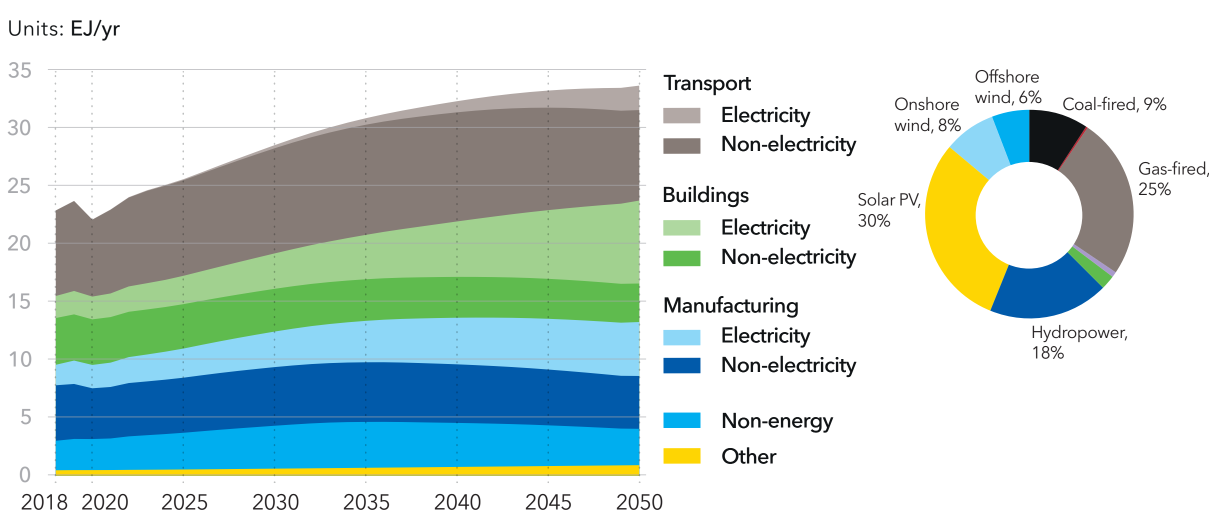
Figure 6.9.3 presents South East Asia developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

– The region's energy system transformation shows electricity to meet more than 40% of final energy demand by 2050.

FIGURE 6.9.1

South East Asia final energy demand by sector

2050 electricity mix



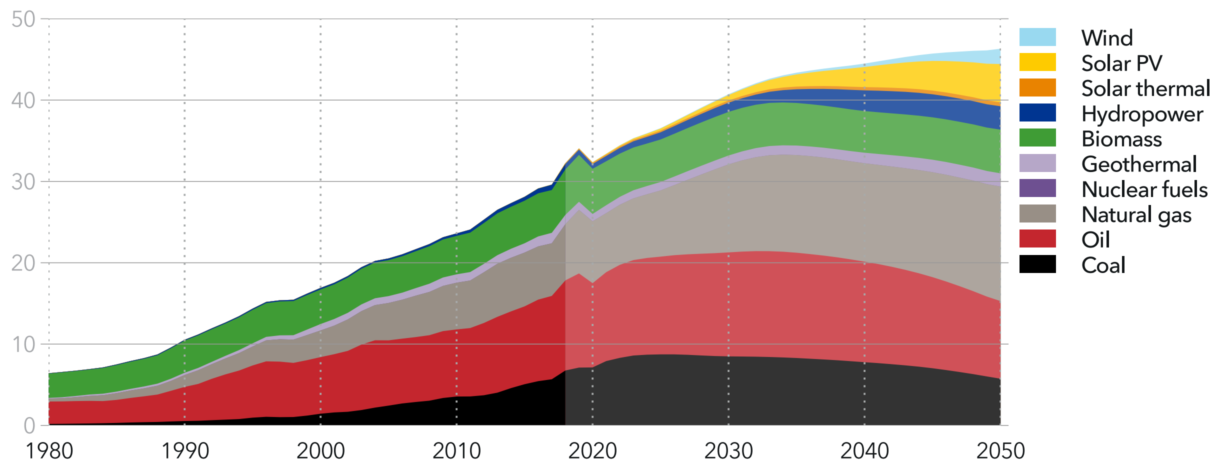
– Between 2018 and 2050, energy intensity is reducing by almost 50%, being slightly less than the energy intensity improvement of regions such as OECD Pacific.

– Between 2018 and 2030 there is almost no observable reduction in carbon intensity, but after 2030, there will be significant reductions of more than 20% until 2050. South East Asia`s 2050 carbon intensity is comparable to Latin America and Sub-Saharan Africa.

FIGURE 6.9.2

South East Asia primary energy consumption by source

Units: EJ/yr



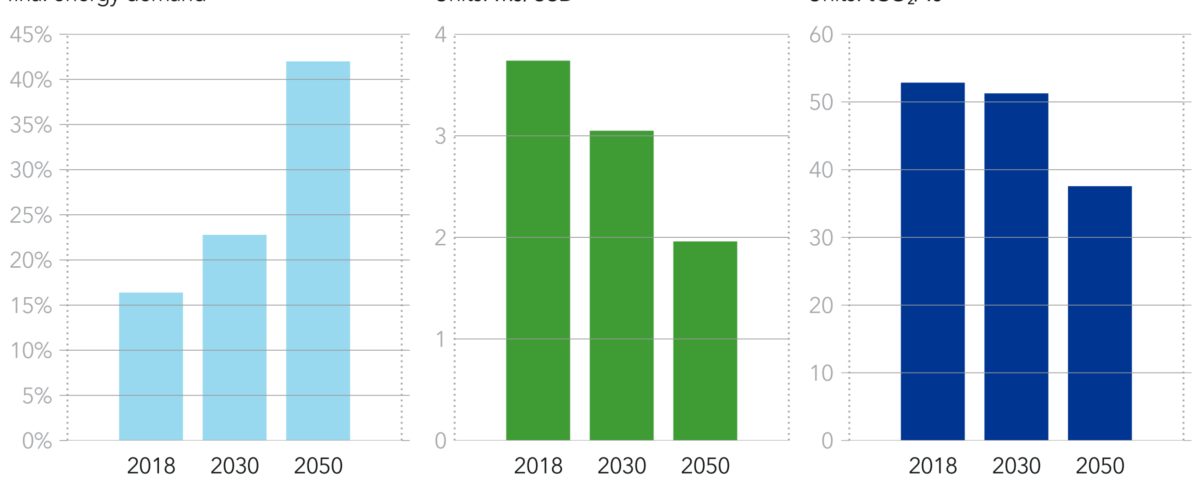
Historical data source: IEA WEB (2019)

FIGURE 6.9.3

Electrification Electricity share in final energy demand

Energy intensity Units: MJ/USD

Carbon intensity Units: tCO_2/TJ



EMISSIONS

We project the region's average carbon price to be USD 40/t by 2050. The application of explicit carbon pricing instruments is currently limited, and the likely first step is removal of fossil-fuel subsidies. Singapore introduced a carbon tax in 2019. Vietnam, Indonesia and Thailand are considering introducing a pricing scheme, but this is unlikely before the mid-2020s. The main drivers for carbon pricing will be international trade in mitigation (Article 6 of the Paris Agreement), possible carbon border taxes with trade partners, and access to climate finance.

South East Asia's energy-related emissions are increasing and will peak in the early 2030s before moving back to today's levels in 2050. Emissions from transport, manufacturing and buildings follow the same pattern in our Outlook (Figure 6.9.4).

Emissions from coal and oil dominate today, but will both peak and decline over the forecast period. Emissions from natural gas will overtake them both, increasing through the entire period and becoming the largest source of emissions in 2050.

We forecast CCS capacity of 88 $MtCO_2$/yr in 2050, equating to only 5% of energy-related emissions due to relatively low projected carbon prices.

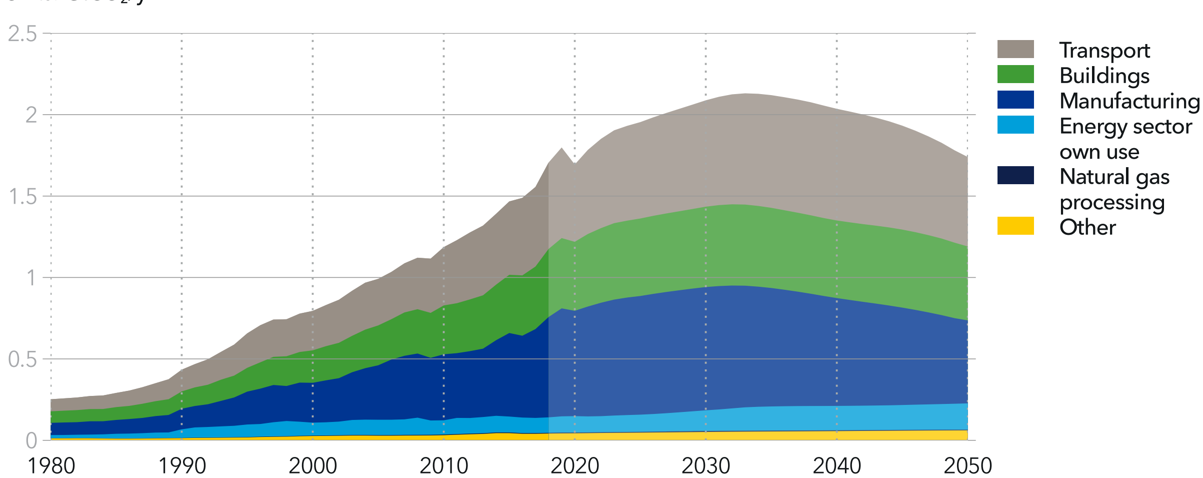
NDC pledges indicate a regional target of limiting emissions increases to no more than 505% by 2030 relative to 1990. Our Outlook shows energy-related emissions increasing by 378% by 2030, suggesting that these unambitious pledges will be met. There are some uncertainties in the comparisons of targets and forecasts as some countries are unclear about whether the targets in their NDCs also include non-energy related CO_2 emissions.

The region has emissions of 2.2 tCO_2/person in 2050, slightly above the global average in mid-century.

FIGURE 6.9.4

South East Asia energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



MANUFACTURING GROWTH AS A DRIVER FOR ENERGY SYSTEM TRANSFORMATION

Our Outlook sees South East Asia's final energy demand growing 50% by 2050, supplied by electricity's share in supply rising from 16% in 2018 to 42% in mid-century. This is significantly driven by a 'China Plus One' strategy in manufacturing (Figure 6.9.5). This entails expansion of China-related businesses to another region close by, preferably South East Asia (OECD, 2019).

This market diversification brings many opportunities for sustainable growth, but is also a challenge requiring supportive policies and financing mechanisms, at least early in the energy system transformation. To supply growing power demand from manufacturing, renewables' share will rise from one fifth now to two thirds in 2050. In this transition, solar PV is favoured most, accounting for 30% of South East Asia's power production by 2050. Installed hydropower will grow more than fourfold during the forecast period, whereas installed coal-fired generation capacity will be almost equal over the same time.

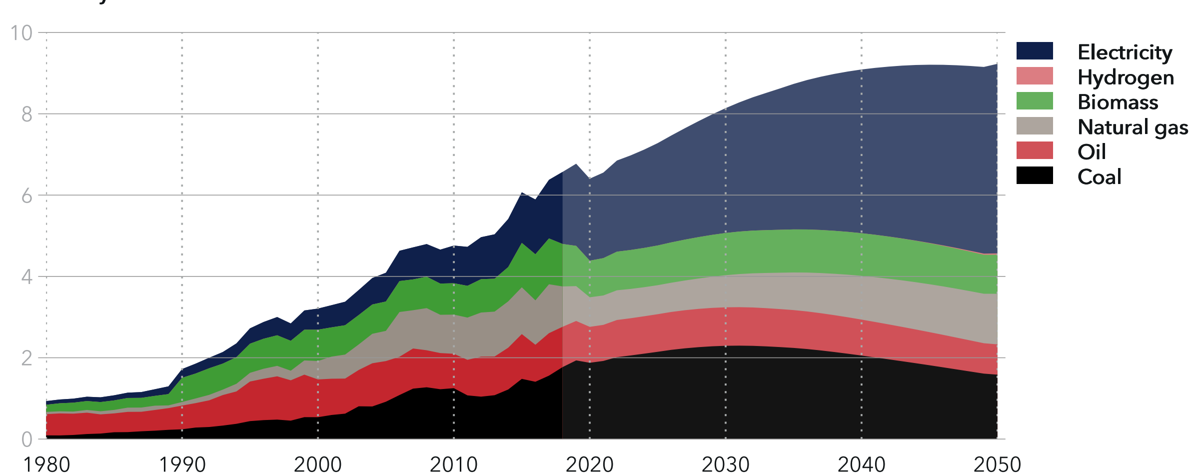
The additional demand for natural gas, based on increased demand from manufacturing and natural gas-based power production, will transform South East Asia from being an LNG-exporter to a significant LNG importer, with LNG regasification capacity rising 650%. Most of the gas imports will originate from OECD Pacific, North America, and the Middle East and North Africa. From the late 2030s, South East Asia will see a gradual uptake of hydrogen reaching about 300 PJ/yr in 2050 and being mainly used in transport and manufacturing.

According to our forecast, South East Asia will tackle the challenge of increasing energy demand through natural gas – including LNG imports – and domestic renewable power production.

FIGURE 6.9.5

South East Asia manufacturing sector energy demand by carrier

Units: **EJ/yr**



OECD PACIFIC (OPA)

This region consists of Australia,
New Zealand, Japan and South Korea

CHARACTERISTICS AND CURRENT POSITION

These mature economies have diverse energy use and resources. Australia is a net exporter of energy. New Zealand, Japan and South Korea are dependent on imported energy. Energy policies integrate energy security and sustainability to varying degrees. Japan, South Korea, and New Zealand price carbon; Australia repealed carbon tax laws.

Australia exploits its coal and gas resources for domestic energy use and, increasingly, for export revenue. Despite policy uncertainty, Australian renewables are booming with recent growth in wind, and utility-scale and rooftop solar. There is significant interest in hydrogen for export. Carbon emissions are rising, driven partly by rising LNG exports.

New Zealand relies heavily on renewables, particularly hydropower and geothermal, wind and solar to a lesser extent, for electricity; but fossil fuels still dominate energy supply. Transition policy emphasizes renewables in which hydrogen plays a part. A longstanding ETS is in place.

Japan imports a lot of coal, LNG, and almost all its oil. Most of its geothermal and hydropower potential is already deployed. Geographic factors constrain solar, onshore wind, and grid connectivity. Nuclear power remains contentious, and the shortfall in power supply has been balanced with imported fossil fuels and greater coal-fired generation. Future energy policy rests on '3E+S': energy security, economic efficiency and environment plus safety.

South Korea is a major importer of coal, oil and LNG, relying on coal and nuclear for some 70% of its electricity. Nuclear phase-out and focus on air pollution are driving a shift from nuclear and coal to renewables. Efforts to become a global hydrogen powerhouse have grown since 2017, and gas is seen as the bridge energy carrier in the energy transition.

	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2018	207	183 38	41 400 8.5
(OPA)			
2050	194	103 20	50 900 9.8

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

POINTERS TO THE FUTURE ▸▸▸

- Australia lacks clear policies on the Paris Agreement, and its GHG emissions continue to grow despite renewables reducing power-sector emissions. Electricity market design will need revising to facilitate renewables deployment. Reliability concerns are driving interest in pumped storage hydropower and batteries. There is capacity to expand coal exports, but the social license is unclear, particularly after devastating bushfires in 2019/20. Australia is the world's largest exporter of LNG, although impacted by COVID-19-related slumping demand in Asian markets, and is starting to explore domestic use and export of hydrogen.

- New Zealand law targets net zero by 2050 for non-agricultural emissions. It will pursue a range of initiatives, i.e., electrifying transport, afforestation and stopping exploration for new oil and gas reserves. Renewables development is resuming with electricity demand growth expected.

- In Japan, nuclear plants demonstrating improved safety will continue to re-open. It aims for nuclear to generate 20% of electricity by 2030. While new coal plants are planned, the government wants renewables to supply 24% of electricity by 2030. Its decarbonization plans include importing liquid hydrogen from Australia and ammonia from other OECD Pacific countries. Ambitious hydrogen price targets will encourage industry. A goal of reducing automotive emissions by 80% will drive growth in EVs and FCEVs and associated industry and infrastructure.

- South Korea targets 20% renewable power in 2030, and 30% to about 35% by 2040. Coal to gas switching is expected near term here and in Japan. The government's Hydrogen Economy Roadmap for production facilities, hydrogen in transport, and fuel-cell businesses by 2040, builds on existing strengths in FCVs. South Korea will seek to become a leading hydrogen economy by 2040. Domestic energy policies will be favouring LNG, renewable energy, and green transport, especially due to growing concerns over air pollution and public health.

6.10 OECD PACIFIC

ENERGY TRANSITION

OECD Pacific's final energy demand is now declining and will continue to outpace the fall in the population (Figure 6.10.1). Manufacturing will see the largest reduction, due to efficiency gains and production moving to lower-wage regions. Transport energy efficiency is improving strongly, driven by fast uptake of EVs.

Figure 6.10.1 shows electricity's share in final energy demand increasing from 24% in 2018 to 47% in 2050, second only to Greater China among our outlook's regions. Both manufacturing and transport will see high electrification. Wind will dominate the 2050 electricity mix. With almost half the region's electricity coming from wind, it will have highest such share of any region. With the solar PV also significant, the fossil-fuel share in power generation will be minor in mid-century (5%).

Electrification of transport will be the strongest driver for oil consumption reducing more than 70% over the forecast period. Coal, currently the region's second largest primary energy source, starts to decline rapidly in both the power and manufacturing sectors (Figure 6.10.2). Unlike in most other regions, natural gas use will also decline. In 2050, the fossil fuel share in primary energy supply is down to around 46%.

ENERGY TRANSITION INDICATORS

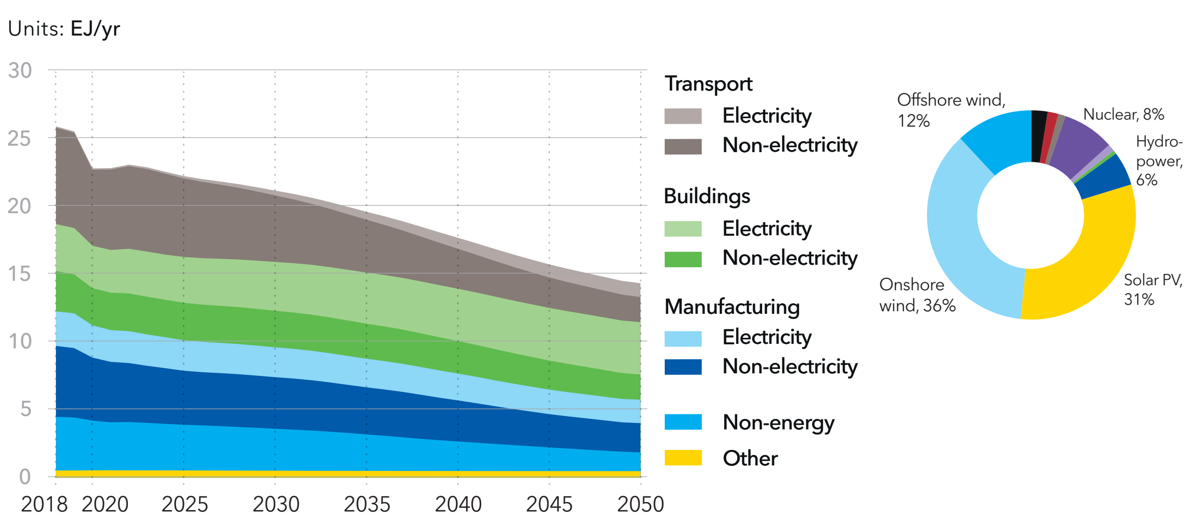
Figure 6.10.3 presents OECD Pacific developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 6.11).

– The region's electricity share of final energy demand is going to almost double between

FIGURE 6.10.1

OECD Pacific final energy demand by sector

2050 electricity mix



2018 and 2050, reaching 47%, which is the second highest electrification of all regions.

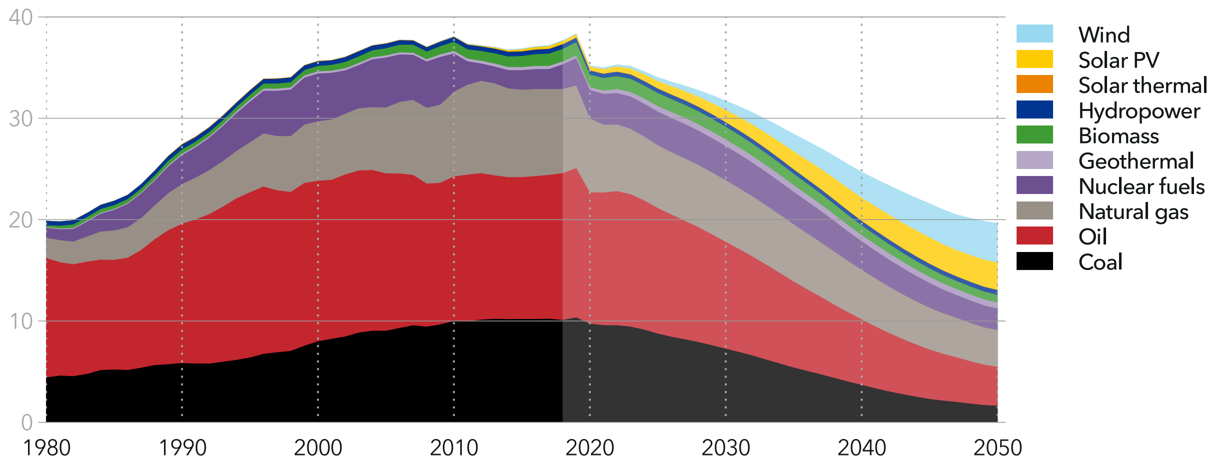
– Energy intensity is more than halved to a level of 2 MJ/USD, similar to developments in Greater China.

– The carbon intensity of region energy mix will be slightly below 20 tCO_2/TJ, representing a reduction of almost two thirds from 2018.

FIGURE 6.10.2

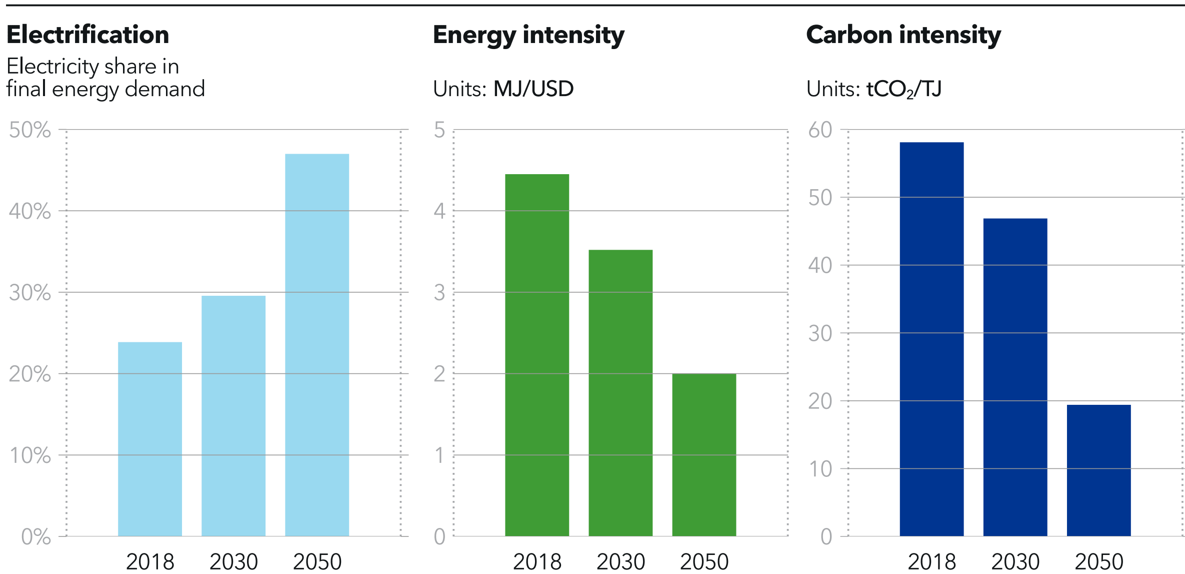
OECD Pacific primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2019)

FIGURE 6.10.3



EMISSIONS

We project the region's average carbon price to be USD 60/t by 2050. Post-2020 reform ensures a stricter cap in South Korea's national ETS, New Zealand is expected to strengthen its ETS to align with the zero-emission target, and Japan's carbon pricing measures will likely strengthen with decarbonization plans. The region trajectory develops similarly to that of the Greater China region, also with possible linkages through systems in Asia.

OECD Pacific energy-related emissions have been flat for a decade and are set for an 80% decline by 2050. The reduction will be strong in each of the three demand sectors (Figure 6.10.4).

Half today's emissions are from coal, and will decline by 90% by 2050. Oil and gas emissions will also decrease, but will remain greater than those from coal from 2040 onwards.

We project CCS capacity of 150 MtCO_2 in 2050, driven by a carbon price reaching USD 60/t CO_2 by then. This implies 30% of energy-related emissions being captured in mid-century, a share surpassed only in Europe. CCS uptake ramps up late in OECD Pacific, doubling over the period 2045–2050.

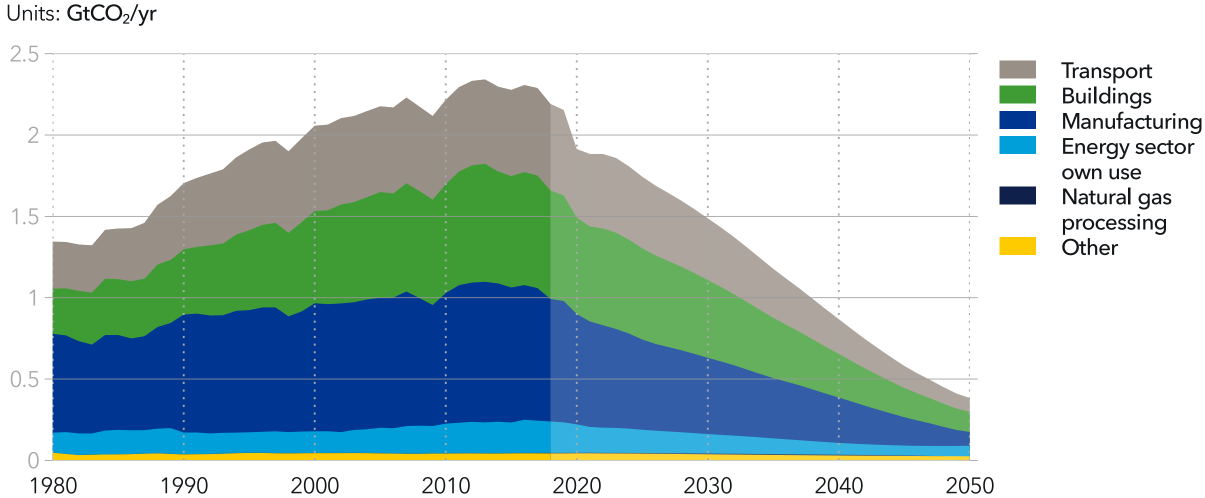
NDC pledges imply an OECD Pacific regional target of limiting energy-related emissions increases to no more than 7% by 2030 relative to 1990. Our Outlook indicates energy-related emissions decreasing 14% by 2030, suggesting that the target will be met and that the ambition level of current pledges is low.

The region emits 1.9 tCO_2/person in 2050, the same as the world average. The emissions decline of 82% between 2018 and mid-century is surpassed only in Europe.

FIGURE 6.10.4

OECD Pacific energy-related CO_2 emissions by sector

Units: GtCO_2/yr



EXPECTED GROWTH IN WIND ENERGY

OECD Pacific differs from other regions in that all its countries are industrialized but have no common borders or grid connections. Their energy infrastructures therefore vary and are based on existing resources. However, OECD Pacific countries have access to great wind resources and plenty of coastline to capitalize on the emerging offshore wind market.

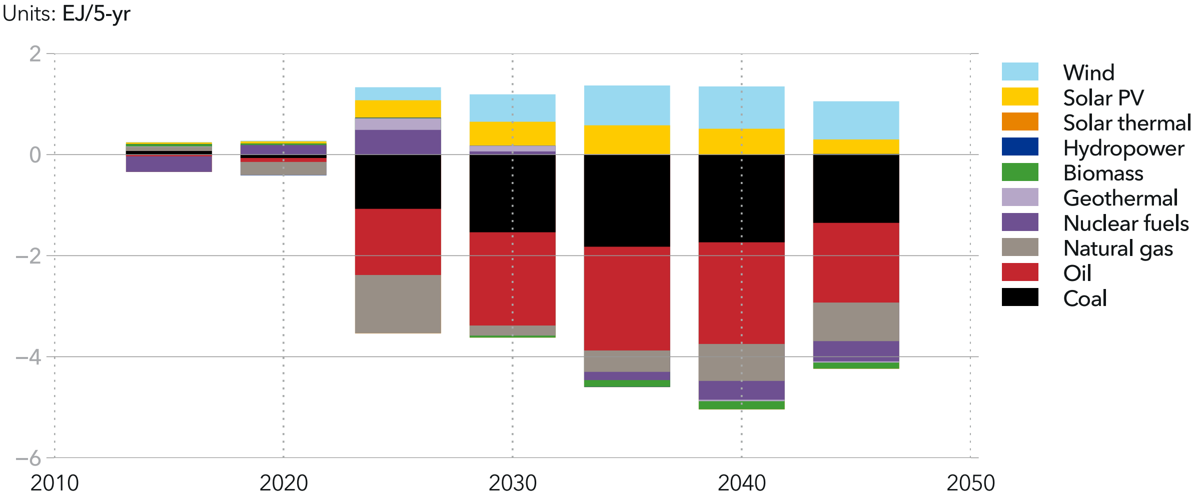
We forecast that wind will supply 20% of OECD Pacific energy in 2050, the highest share in any region. 77% of the installed capacity is onshore wind, 18% fixed-offshore wind, and 5% floating-offshore wind. We expect 320 GW of wind to be installed in the region by 2050, with 70 GW of it offshore. Wind energy will contribute 50% of electricity production in 2050 (Figure 6.10.1). This shift is already visible in 2025, when 50% of net energy additions consist of solar PV and wind. From 2030, 100% of net energy additions will be based on renewables (Figure 6.10.5).

The unit investment cost for offshore wind declines by at least 35% by 2030 and up to 70% by 2050, driven by standardization and scale effects. In the early 1980s and 1990s, Japan and South Korea developed a strong industrial ecosystem within shipbuilding. Both countries could do the same in offshore wind. Shore access, local steel manufacturing and industrial production capacity combined with experienced labour forces position the countries to construct and install offshore wind at home and in other regions.

FIGURE 6.10.5

Net change in OECD Pacific primary energy consumption at 5-yr intervals

Units: EJ/5-yr

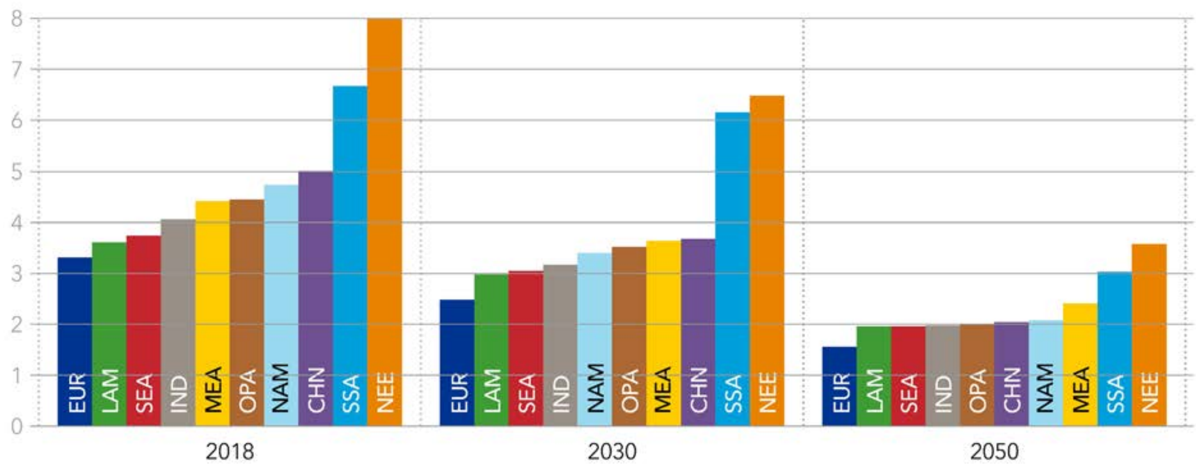


6.11 COMPARISON OF THE REGIONS

FIGURE 6.11.1

Energy intensity of GDP

Units: MJ/USD

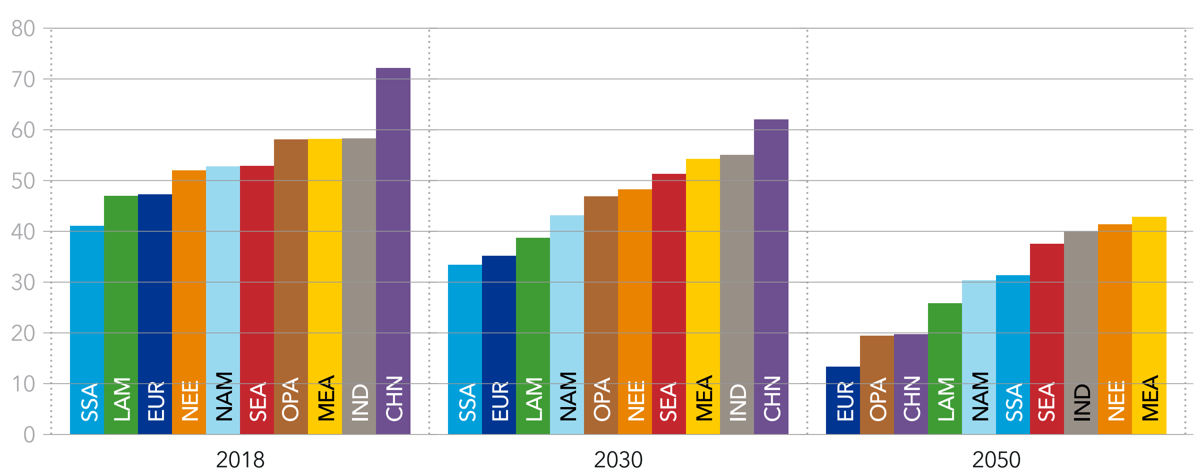


Energy intensity is measured as primary energy consumption per unit of GDP. All regions experience a decline in this measure. This is explained by efficiency gains, partly due to steady electrification of energy end-use. It is also because of the increasing share of renewables in electricity generation, through which electricity becomes more efficient as heat losses are smaller. Consequently, the decline in overall energy intensity accelerates. Despite a 55% decline between 2018 and 2050, North East Eurasia remains the region with highest energy intensity. Europe continues to require the least amount of energy per dollar of economic activity.

FIGURE 6.11.2

Carbon intensity of primary energy consumption

Units: tCO_2/TJ

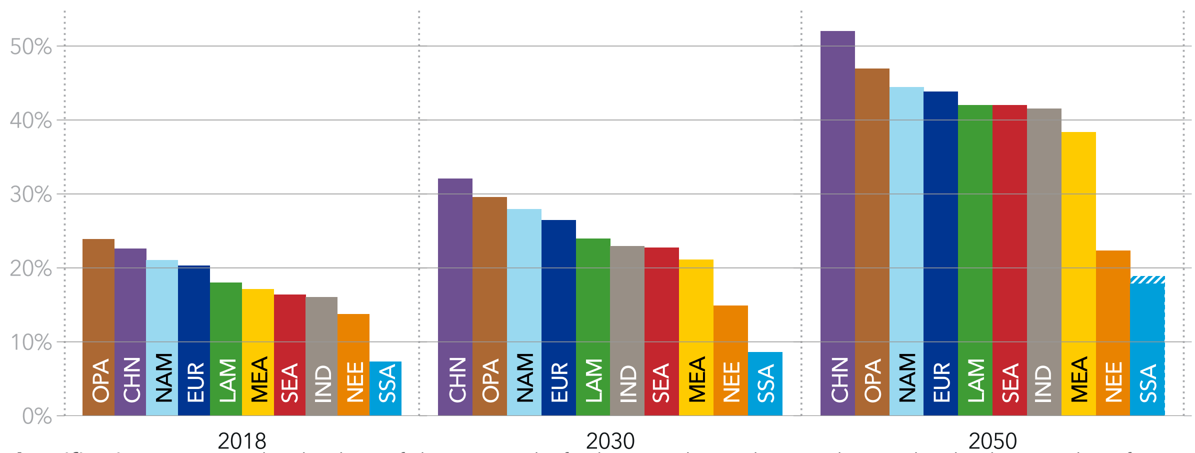


Carbon intensity is measured as tonnes of carbon dioxide per terajoule of primary energy consumption. Greater China has the most rapid decarbonization, with its carbon intensity declining by 73%, followed by Europe (72%), and OECD Pacific (67%). North East Eurasia will be the region with least improvement in carbon intensity (20%) and moves to become the second most carbon-intensive energy system in 2050 behind Middle East and North Africa.

FIGURE 6.11.3

Share of electricity in final energy demand

Units: Percentages

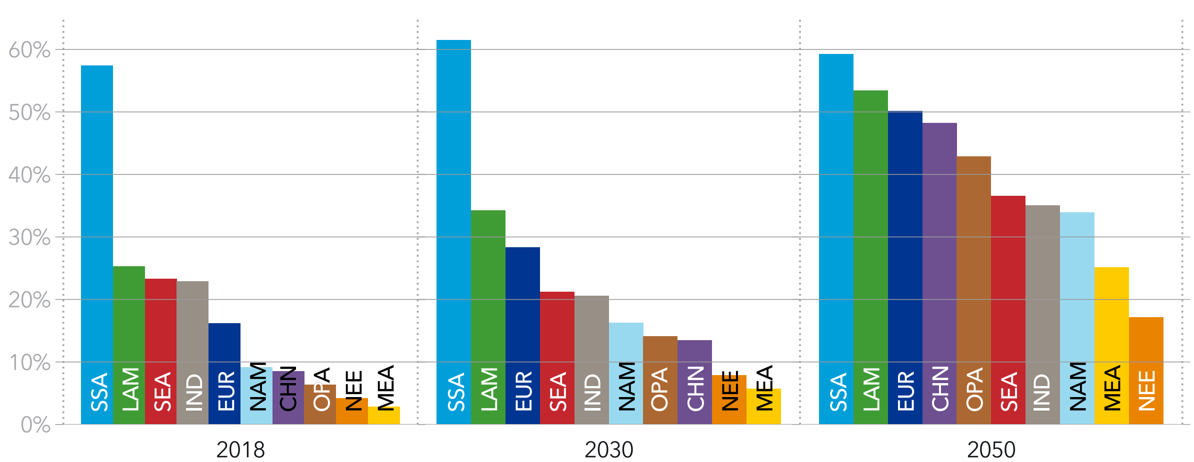


Electrification is measured as the share of electricity in the final energy demand mix, and, as can be clearly seen, electrification is taking place everywhere. The pace will be fastest in Sub-Saharan Africa, where the share of electricity will almost triple, from 7% in 2018 to 18% in 2050. However, this growth will not be enough to catch up with the other regions. By 2030, Greater China will overtake OECD Pacific as the leading region in terms of electrification with electricity meeting 52% of final energy demand.

FIGURE 6.11.4

Share of renewables in primary energy consumption

Units: Percentages



Renewables include biomass, solar, wind, geothermal, and hydropower. Because of its high share of traditional biomass, Sub-Saharan Africa remains the region with the highest share of renewables. The Middle East and North Africa will see the fastest relative growth rate on this measure, from 3% in 2018 to 25% in 2050, but still the overall share of renewables is the second lowest of all regions because of the dominant role of fossil fuels. OECD Pacific will see the second-largest relative increase, with its share of renewables growing from 6% to 43%.

HIGHLIGHTS

We quantify the energy-related CO_2 emissions associated with our forecast through to 2050. We find that energy related emissions in 2030 will be only 10% lower than they are today, and that emissions in 2050 will be at 17 Gt per year, exactly half of the present level.

To those figures **we add emissions from non-energy sources** (e.g. agriculture and industrial processes) to give a full picture of CO_2 emissions from human activity.

We find that the carbon budget associated with global warming of 1.5C is exhausted in 2028 and the carbon budget for 2°C is exhausted in 2051.

The question then arises, what level of global warming is associated with our forecast?

To answer that question, we also have to take account of remaining emissions beyond 2050 through to 2100 (when we think it is likely to arrive at net-zero emissions).

From these calculations we derive a global warming of 2.3°C by 2100 – a level considered dangerous by scientists. We caution that this figure is uncertain. For example, global warming could be slowed by net negative emissions technology, or accelerated by the triggering of critical climate tipping points.

CHAPTER

7

EMISSIONS AND CLIMATE IMPLICATIONS

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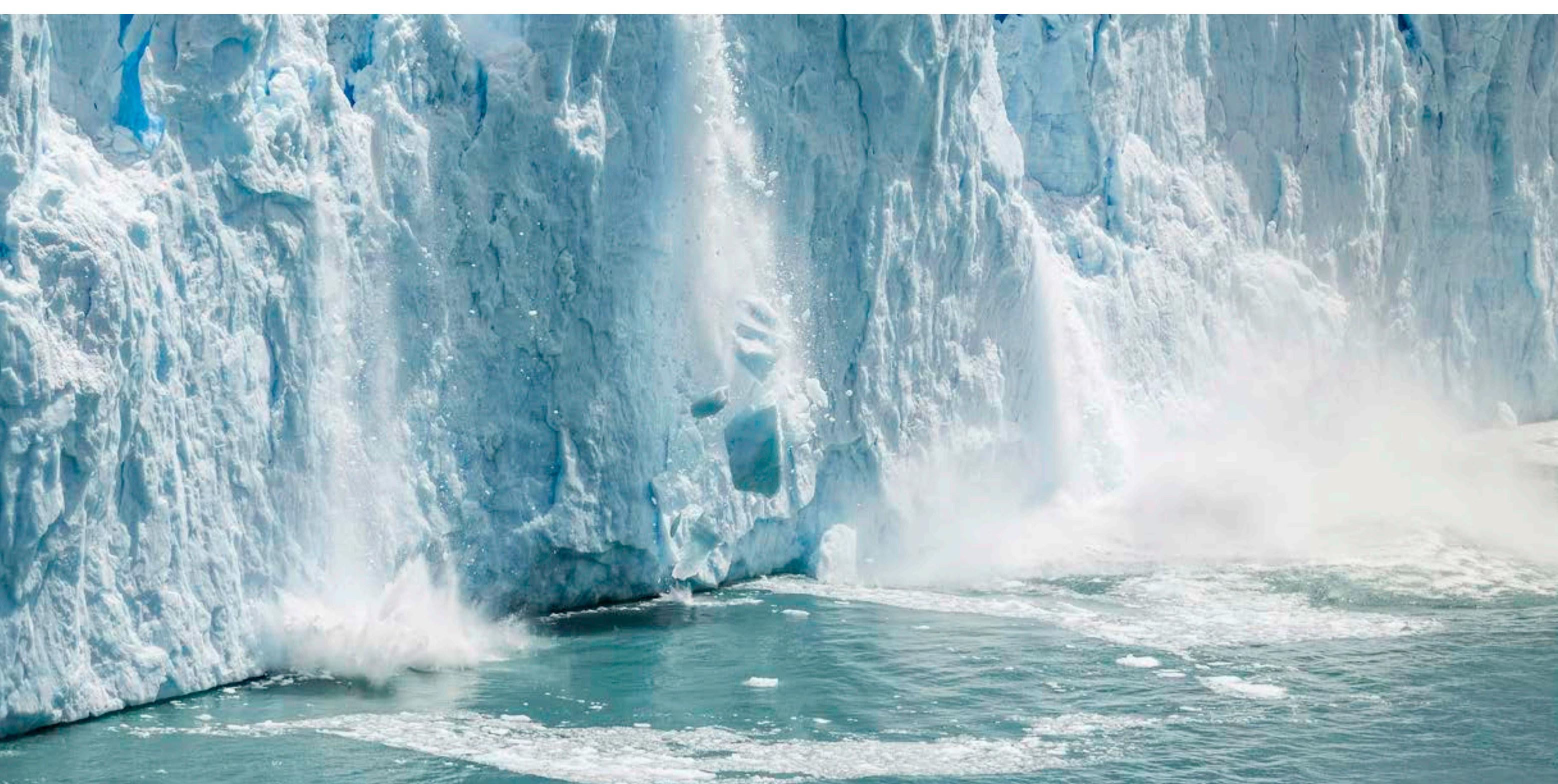
7 EMISSIONS AND CLIMATE IMPLICATIONS

The energy sector is the dominant source of greenhouse gas (GHG) emissions associated with human activities. The main contributor to these emissions is CO_2, which predominantly comes from combustion of fossil fuels. In this chapter, we describe how we estimate the extent of emissions and assess their climate implications.

We begin with the estimated energy-related CO_2 emissions associated with our forecast. Those, together with assumptions about other, non-energy-related GHG emissions, allow us to derive the associated temperature response. We do not assess climate implications beyond the likely global average temperature increase as part of our forecast.



7.1 EMISSIONS

It is estimated that 50% of energy-related emissions have been added to the atmosphere in the last 50 years (Buis, 2019). After staying virtually flat between 2014-2016, global energy-related CO_2 emissions grew to reach a peak of 34.4 Gt CO_2 in 2018 (IEA WEB, 2019). Preliminary reporting suggests a slight increase in 2019. We anticipate that the effects of COVID-19 will result in emissions dropping by approximately 8% in 2020, and then declining gradually to 31.2 Gt CO_2 in 2030. By 2050, energy-related emissions are expected to be 17.1 Gt CO_2, some 50% less than current levels (Figure 7.1).

COMBUSTION EMISSIONS

Coal is currently the main driver of energy-related CO_2 emissions, responsible for 44%, followed by oil and natural gas with 31% each. Emissions of CO_2 from coal will see the strongest decline towards 2050 (almost 75%) compared with 2018. Emissions from oil will halve by 2050 compared to 2018, whereas emissions from natural gas will grow towards 2030 and then drop back to today's level, as indicated in Figure 7.1.

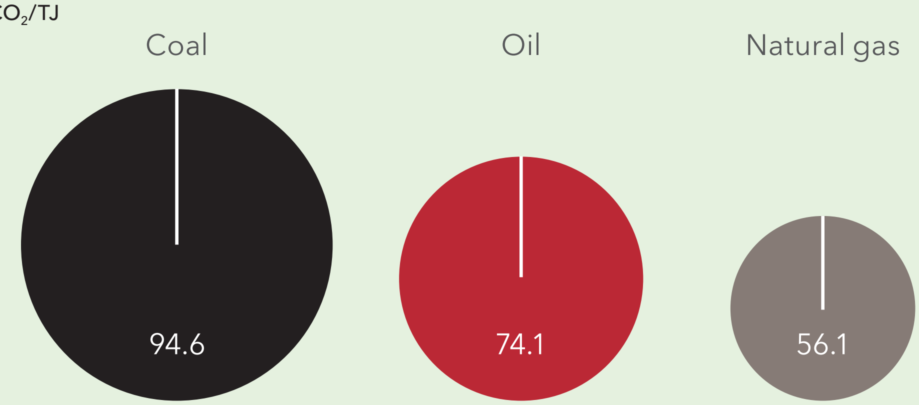
Thus, towards 2050, coal and natural gas shift places, with natural gas contributing 44%, while oil stays about the same at 30%. So, although in comparison with coal, natural gas contributes half the emissions per unit of energy produced, the growing amount of gas used for energy purposes will dominate the world's energy-related CO_2 emissions to 2050.

COMBUSTION-EMISSION INTENSITY

Energy-related CO_2 emissions originate primarily from burning fossil fuels. Each energy carrier generates different amounts of CO_2 emissions, but, collectively, they are referred to as combustion-emission intensity. Shown below are the comparative emissions from each fossil-fuel energy source per unit of energy generated as heat.

Emissions per unit of energy from fossil fuels

Units: tonne CO_2/TJ



SECTOR EMISSIONS

From a sectoral perspective, manufacturing is the main contributor to energy-related CO_2 emissions today. In 2050, we expect an equal split between manufacturing, transport, and buildings at almost 30% each (Figure 7.2).

During the forecast period, emissions from manufacturing will decline by 60%, while the transport and buildings sectors will see a reduction of almost 50%.

- **In manufacturing**, most of these changes will happen in the latter part of the forecast period, due to declining output in base materials and steel combined with a fuel switch to gas and electrification replacing coal.

- **The buildings sector** will see a steady decline in emissions, although we expect a significant increase in both number of commercial and residential buildings. Continuous improvements in energy efficiency and switching to cleaner sources of fuel for heating will be the main reasons for these reductions.

- **The transport sector** has experienced the earliest significant decline in emissions, due to changing travel patterns associated with the COVID-19 pandemic, which will reduce energy demand in the short term. However, the main trend is electrification of road transport, which will result in emissions declining markedly in the long term. This is not only because EVs use energy more efficiently, but also because electricity production from renewable sources will increase, supplying ever-more emission-free electricity to the transport sector.

As demand for energy peaks, CO_2 emissions start to decline, and the shift towards renewable energy sources intensifies the rate at which the system decarbonizes further. The carbon intensity of the energy system is used to measure decarbonization in tonne CO_2 per terajoule of primary energy consumption. Figure 7.3 shows the historical and forecast decarbonization for the three main demand sectors – transport, buildings, and manufacturing.

REGIONAL VARIATIONS

The ten Energy Transition Outlook (ETO) regions have different starting points and very differing emission trajectories during the forecast period. A growth of 0.7 Gt CO_2 in absolute emissions will occur in the Indian Subcontinent to 2050, whereas Sub-Saharan Africa will show an increase of 0.4 Gt CO_2. Greater China, currently the largest emitter by far, will reach peak emissions before 2030; emissions will then decline by almost 80% from 2030 levels. All other regions will reduce their emissions, with OECD Pacific, together with Europe, experiencing the biggest relative change with 83% less emissions in 2050 than today (Figure 7.4). North America and North East Eurasia will have the highest emissions per capita at 4.4 tonnes/person in 2050, followed by Middle East and North Africa at 3.4 tonnes/person (see infographic, Energy access).

> “In 2050, we expect an equal split between manufacturing, transport and buildings emissions at almost 30% each

FIGURE 7.1

World energy-related CO_2 emissions by fuel

Units: $GtCO_2$/yr

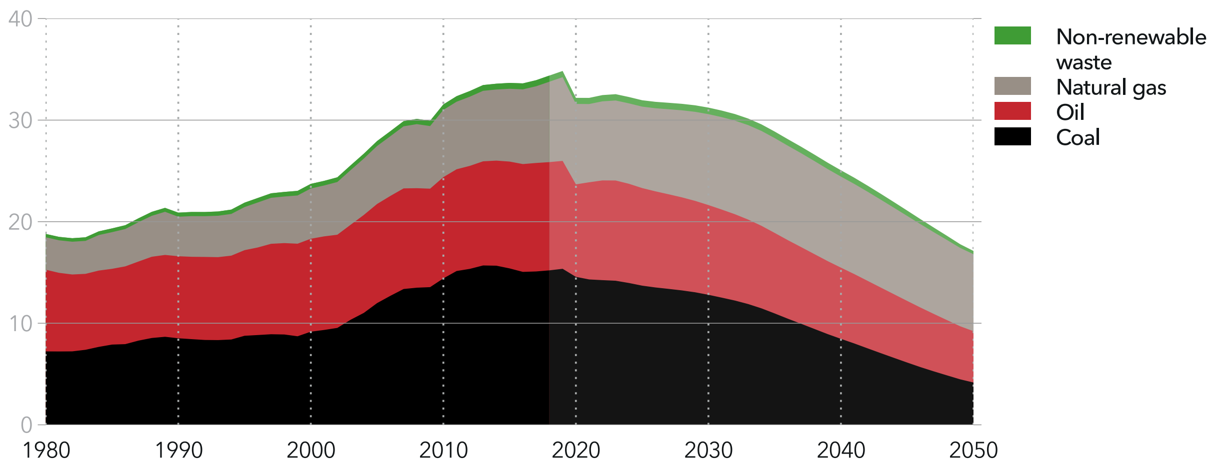
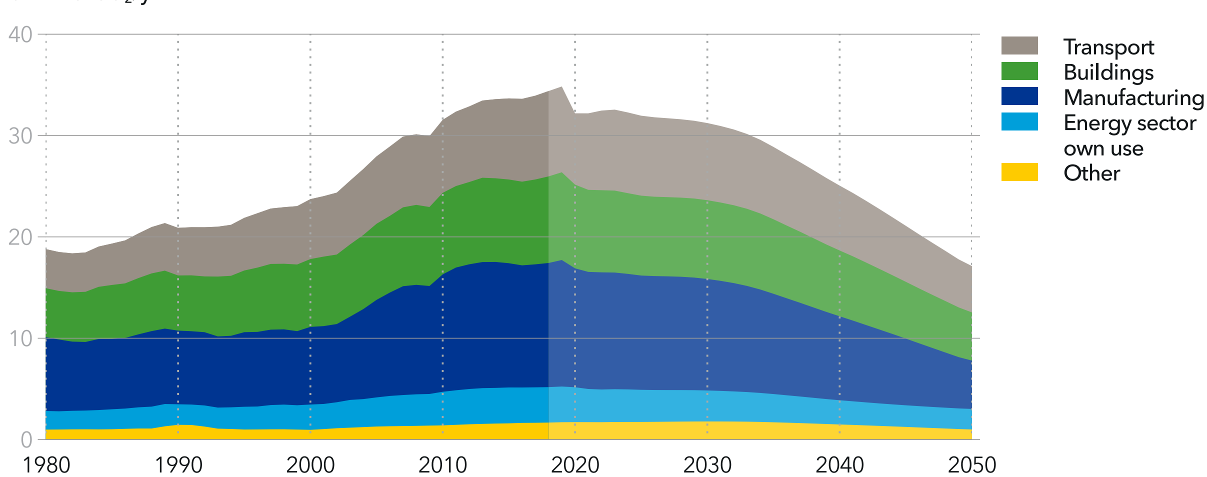


FIGURE 7.2

World energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Emissions from power and hydrogen generation are allocated to end-use sectors.

NON-ENERGY RELATED EMISSIONS

In addition to CO_2 emissions from combustion of fossil fuels, there are significant emissions from industrial processes that are not derived from fuel combustion alone. In our analysis, we include CO_2 emissions from industrial processes that consume fossil fuels as raw material for feedstock. In addition to these emissions from industrial feedstocks, there are also CO_2 emissions from other non-energy related activities. These emissions are not part of the ETOM, but are estimated to total 3.9 Gt CO_2 in 2018, of which approximately 40% are from calcination in the cement-production process. The remainder of the emissions are a split between coke ovens and production of lime or other chemicals (Olivier et al. 2020). These industrial emissions grew until 2016 but, based on recent trends, have since stabilized. We expect a slight growth in base-material output, which largely drives non-energy emissions, over the next 15 years and then stabilization. However, while base-material output might stabilize at a higher level than today's, improvements in production and technical efficiencies lead us to assume that non-energy industrial emissions will reduce linearly by a third through to 2050.

LAND-USE EMISSIONS

CO_2 emissions from AFOLU (agriculture, forestry, and other land use) are not included in our forecast model, but are substantial and should be factored into any calculation of global emissions. Emissions from land use have been growing slowly, averaging about 5 Gt CO_2/yr over the last 20 years, with large fluctuations between years. Prediction based on the latest figures estimate a peak of over 6 Gt CO_2/yr in 2019 (Fredrichlich et al., 2019) largely due to forest fires. There is currently considerable uncertainty about changes in future land use, as some countries with large forest areas are increasing deforestation, with rates of up to 140% gross tree loss annually (The Guardian, 2019). However, we expect that climate and sustainability concerns will eventually affect policy decisions, placing pressure on controlling land-use changes. Thus, for our emissions estimate, we assume CO_2 emissions from land use changes to stay at current levels of 5 Gt CO_2/yr until 2030, and then decline linearly by 50% to 2050.

> "There is currently considerable uncertainty about changes in future land use, as some countries with large forest areas are increasing deforestation

FIGURE 7.3

World carbon intensity by sector

Units: tCO_2/TJ

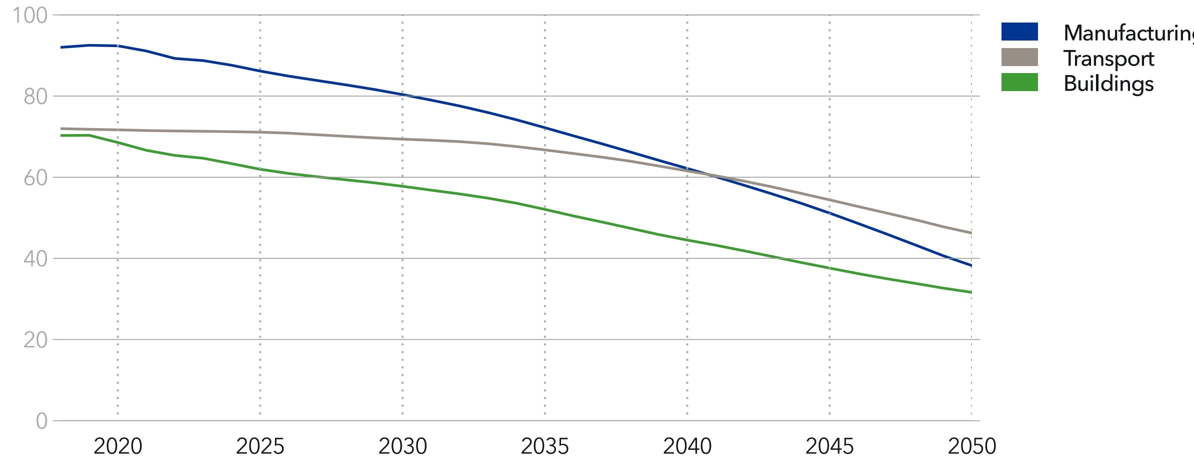
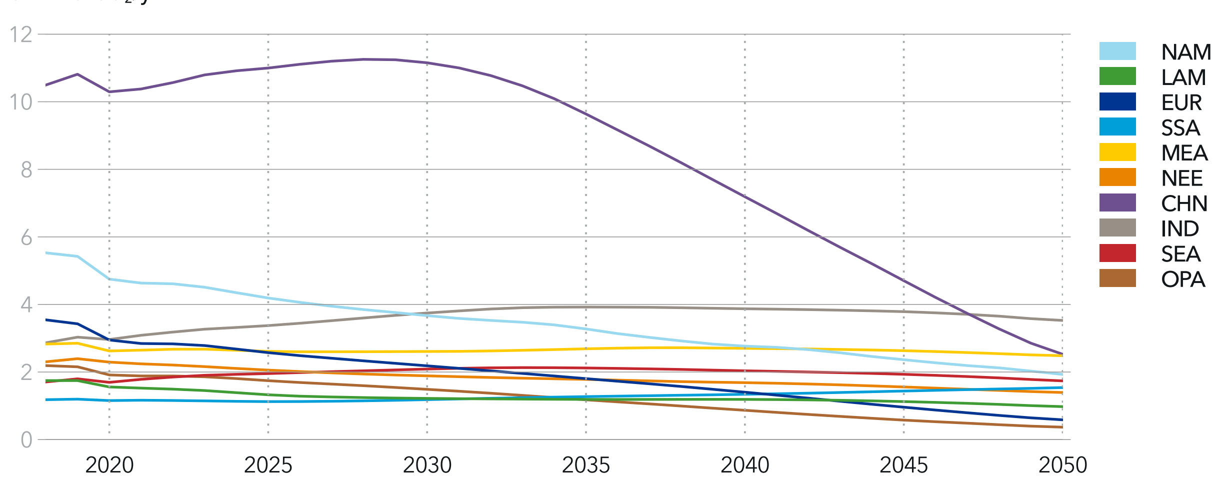


FIGURE 7.4

Energy-related CO_2 emissions by region

Units: $GtCO_2/yr$



CARBON CAPTURE

Carbon capture and storage (CCS) today is almost solely applied in enhanced oil recovery, where there is a viable business case. Looking forward, we predict large point sources in the power and manufacturing sectors to increase the capture of carbon from their waste streams. Additionally, we expect all carbon emissions from hydrogen production to be captured in the steam-methane reforming (SMR) process. Some capture is also expected when flaring occurs during natural-gas processing. However, collectively, these developments are not happening at sufficient speed or scale to make a significant impact in counteracting temperature increases and associated climate change. That picture is unlikely to alter.

Given existing and announced policy, CCS uptake will be very limited; it is only in the 2040s when carbon prices start to approach the cost of CCS that uptake accelerates, and deployment begins at scale. By 2050, we expect emissions captured by CCS to be 2.1 Gt CO_2. In combination with 0.9 Gt CO_2 captured from SMR as well as other point-source capture in power and manufacturing (Figure 7.5), the total carbon capture amounts to only 11% of all energy-related emissions in 2050. Over 60% of CCS capacity will be in Greater China and Europe.

Putting CCS on a faster deployment track is policy dependent, and policy will determine deployment rates until the point is reached where the cost of CCS has reduced as a result of the technology cost-learning curve associated with the cumulative increase in installed capacity. There is no doubt that an additional policy push will be needed to stimulate real-world experience, and to make projects and the CCS value chain commercially viable.

IMPACT OF COVID-19

One effect of the COVID-19 pandemic is a drop in energy-related emissions of approximately 8% (Chapter 1). Although the effect happens in the near term, it will also result in lower emissions throughout the entire forecast period. As economies rebound, emissions will follow; however, some activities, like air travel, will take years to return to pre-pandemic levels. The drop and recovery will reduce overall energy demand in the coming decades and the long-term effect can be seen in Figure 7.6.

The cumulative reduction in CO_2 emissions to 2050 is estimated to be 75 Gt CO_2, compared with a non-COVID situation. This seems like good news from a climate-goals perspective, however, this reduction represents about two years' worth of present emissions and will not significantly change the long-term temperature increase. Put differently, the world will need reductions in emissions equivalent to those associated with the pandemic to happen *every* single year, from now until 2050, to achieve the ambitions of the Paris Agreement.

> “The world will need reductions in emissions equivalent to those associated with the pandemic *every* year from now until 2050 in order to achieve the ambitions of the Paris Agreement

FIGURE 7.5

World CO_2 emissions captured

Units: $GtCO_2/yr$

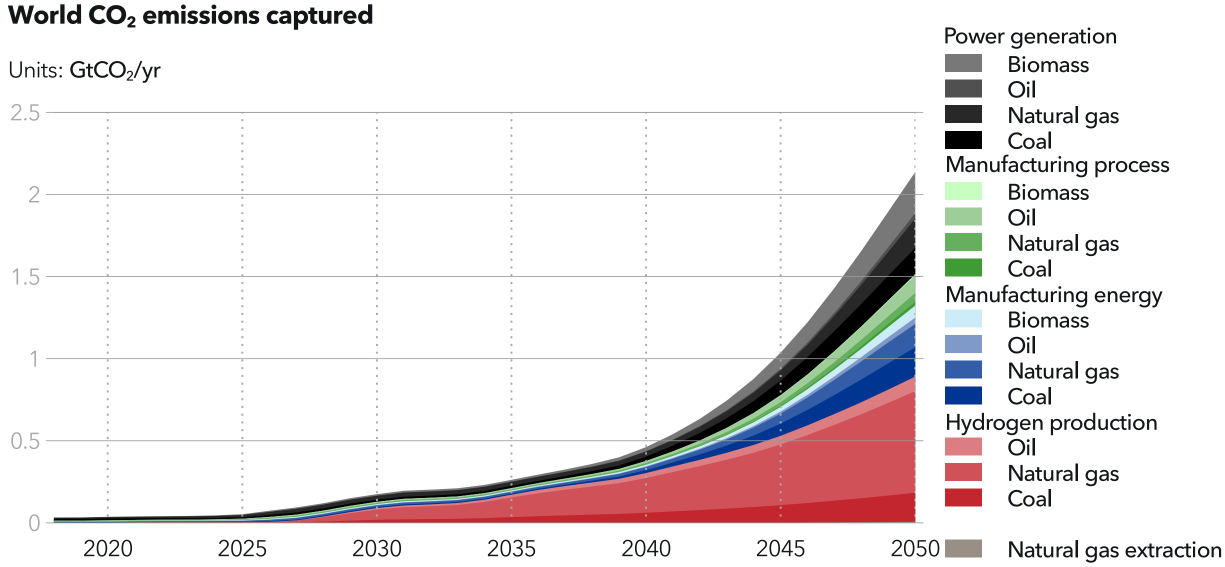
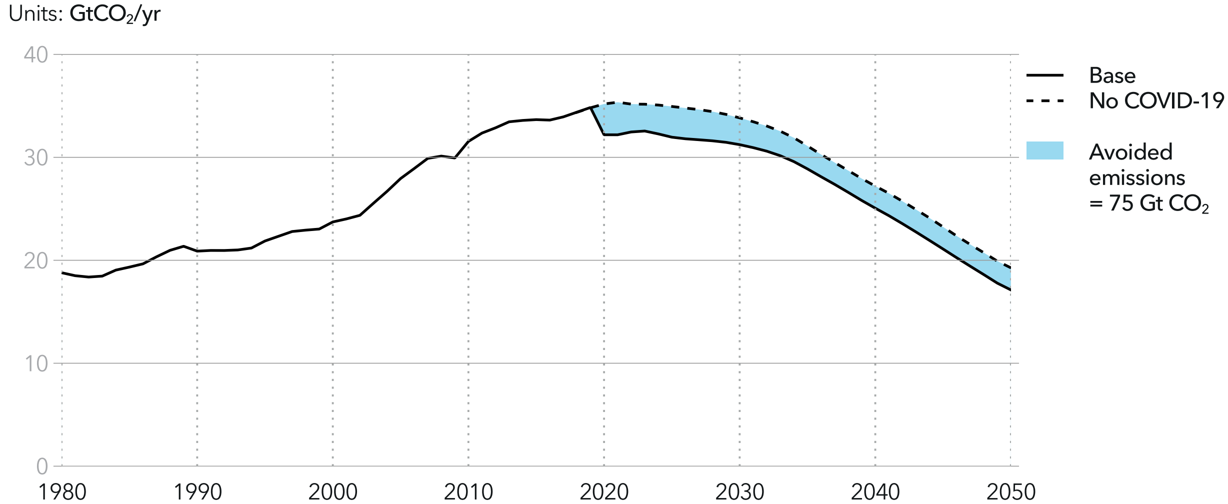


FIGURE 7.6

World energy-related CO_2 emissions - with and without COVID-19

Units: $GtCO_2/yr$



7.2 CLIMATE IMPLICATIONS

On the basis of predicted future emissions levels, we can determine the most likely climate response and the associated temperature increase. We focus only on first-order effects and do not include possible tipping points and feedback loops, such as melting permafrost and peat fires, that would accelerate global warming. Other climate implications, including those directly associated with emissions, e.g. acidification of the oceans, or indirect consequences, such as sea-level rise, are not assessed as part of our work.

CO_2 CONCENTRATIONS

The concentration of CO_2 in the atmosphere is measured as parts per million (ppm). Pre-industrial levels were around 280 ppm (Global Carbon Project, 2019), and emissions related to human activities, particularly burning fossil fuels, have resulted in a significant increase in atmospheric CO_2 concentration. The most recent reading, from June 2020, was a record level of 416.39 ppm (NOAA GML, 2020). The last time that Earth experienced this level of atmospheric CO_2 concentration was in the Pliocene era about 3 million years ago, a time pre-dating human existence (Jones, 2017). Over the last 60 years we have seen an increase in the concentration of over 100 ppm, which is of the same magnitude as the entirety of shifts observed over the previous 800,000 years.

> “We find that the 1.5°C carbon budget will be exhausted in 2028. It then takes a further 23 years to exhaust the 2°C carbon budget

Our forecast predicts a continuation of CO_2 emissions to the atmosphere linked to human activities, albeit at a decreasing rate. In contrast to methane which, on average, oxidizes after approximately 10 years (IPCC, 2001), it takes a long time before CO_2 naturally disappears from the atmosphere, a process measured in hundreds to thousands of years (Archer, 2009). The cumulative concentration of CO_2 in the atmosphere gives a direct indication of long-term global warming. As there is a causal link between concentration and long-term temperature increase (IPCC, 2014a), it is possible to calculate the expected temperature increase based on the accumulated amount of CO_2 in the atmosphere. Similarly, it is possible to estimate the amount of emissions that will result in reaching a certain temperature threshold; this quantity is often referred to as the carbon budget.

The carbon budget includes several uncertainties, including accuracy of data on historical emissions, accuracy of the predicted warming to date, the role of other GHG emissions on current warming, Earth system feedbacks, and, finally, the time delay between emissions having reached net zero and the additional amount of warming inherent in the system. The closer we get to the temperature increase that we wish to avoid (e.g., 1.5°C), the more these parameters contribute to uncertainty. Despite these uncertainties, the carbon budget has proved to be a robust method to indicate potential future warming levels based on different scenarios for energy-related emissions.

CARBON BUDGET

For our temperature estimates, we have used the ‘likely’ (meaning 66% probability) carbon budgets from the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018), which indicates a carbon budget with total emissions of 420 Gt CO_2 to stay below 1.5°C, and 1170 Gt CO_2 from 2018 to stay below 2.0°C. To avoid warming above these two warming levels, the accumulated amount of CO_2 emissions must be lower than these values, from 2018 to the time CO_2 emissions reach zero.

The IPCC carbon budgets have taken account of emissions from other GHGs. Methane emissions from fossil fuels or changes in agricultural practices, including fertilizer use, can have considerable influence on the size of the carbon budget.

Using the IPCC carbon budgets and the aggregated CO_2 emissions from our forecast, we find that the 1.5°C budget will be exhausted in 2028. It then takes a further 23 years (to 2051) to exhaust the remaining 750 Gt CO_2 budget associated with the 2.0°C threshold. It is clear from the data in Table 7.1 that the CO_2 emissions will still be considerable in 2050 and many years thereafter. Thus, the question arises, what temperature rise (to 2100) does our forecast suggest?

Our forecast predicts a continuation of CO_2 emissions to the atmosphere linked to human activities, albeit at a decreasing rate

TEMPERATURE

Our forecast stops at 2050, and emission levels have not been directly estimated for the latter part of this century. By 2050, the emissions' trajectory shows a steep decline, with increasing amounts captured by CCS. Eventually there will be some emissions that are increasingly difficult to abate. However, we think that it is likley to arrive at net-zero CO_2 emissions by the end of the century.

To estimate the warming by the end of the century, we assume a linear decline in emissions from 2050 to 2100. For simplicity and due to the uncertainties existing in the carbon-budget framework, the chosen approach allows us to estimate cumulative emissions of 527 Gt CO_2 between 2050 and 2100. This estimate does not include any large-scale negative-emissions technologies that may be able to reduce the atmospheric concentration significantly. Several interventions are possible, as discussed in Chapter 8, but we have not included them here. Directly interpolating between 2°C and 3°C using the 66% 'likely' overshoot of 527 Gt CO_2 suggests that the world will reach a level of warming in the second half of the century that is 2.3°C above pre-industrial levels.

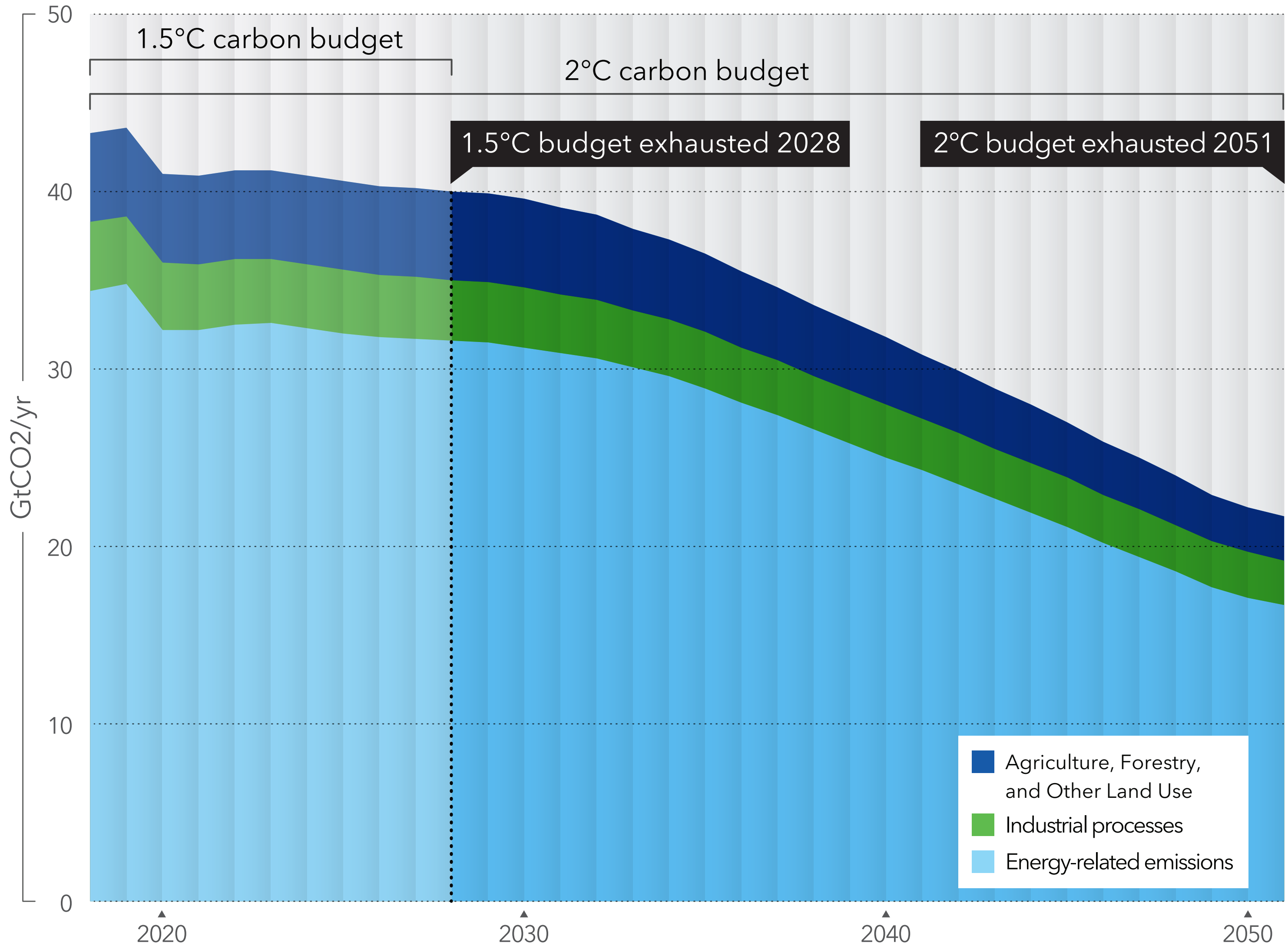
There are considerable uncertainties associated with this projected increase in temperature. These not only arise from our own work in estimating future emission pathways, but also, for instance, from how the availability and deployment of large-scale negative-emissions technologies will affect the outcome. Future AFOLU emissions are considered to continue in our forecast, but could be reversed and used as a carbon sink thereby increasing the room in the carbon budget. Other negative emission technologies could be developed, such as direct air capture. Climate scientists are working hard to reduce carbon budget uncertainties, such as climate sensitivity and Earth system feedbacks. We have included the default IPCC values for Earth systems feedbacks, mainly a limited release of methane from thawing permafrost and wetlands. This value represents warming of up to 0.05°C. However, we have not considered climate tipping points and other non-linear Earth-system reactions that are beyond the scope of this Outlook. The next IPCC Assessment Report will further refine the carbon budget estimates, and we will update our analysis based on the latest scientific consensus.

> "Our forecast suggests the world will reach a level of warming in the second half of the century that is 2.3°C above pre-industrial levels

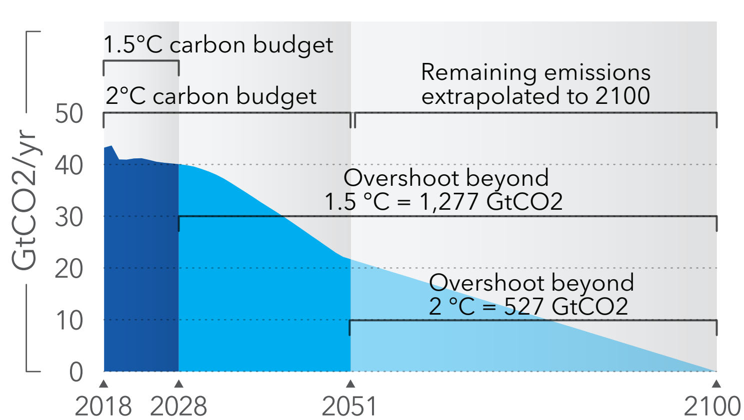
TABLE 7.1
Estimated anthropogenic CO_2 and remaining carbon budget in Gt/yr

	2018	2020	2030	2040	2050
Energy-related emissions (after CCS)	34	32	31	25	17
Captured and stored by CCS	-0.03	-0.04	-0.17	-0.46	-2.14
Industrial processes	3.9	3.8	3.4	3.0	2.6
AFLOU	5.0	5.0	5.0	3.8	2.5
Total Anthropogenic CO_2 emissions	43	41	39	32	22
Remaining Carbon Budget for 2°C	1130	1042	637	280	15

Carbon emissions and carbon budgets



Overshoots through to 2100



HIGHLIGHTS

We outline solutions for achieving an energy transition that limits global warming to safer levels.

According to our **forecast energy transition**, by the year 2100, the 1.5°C carbon budget will have been overshot by an estimated 1,280 Gt CO_2, while the 2°C budget overshoot will be a still-considerable 530 Gt CO_2 – which is equivalent to 15 years' of annual global energy-related emissions at today’s levels.

When considering how to close the emissions gap, two precepts are of importance:

- **No silver bullet exists** to close the gap on its own; a combination of many different solutions is needed.
- **There is no ideal way to close the gap**; several alternatives must be explored.

We explore technology solutions for the main demand subsectors: road transport; aviation; shipping; manufacturing; iron and steel; and heating in buildings. We also explore abatement solutions in power production; oil and gas production and in feedstock use (mainly plastics).

We sort the decarbonizing technologies for each of these subsectors into either a development track or an implementation track, and identify appropriate policy support and regulatory interventions to accelerate and scale the solutions.

CHAPTER

8

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8 CLOSING THE GAP TO 2°C — SOLUTIONS

This Outlook provides DNV GL's best estimate of the energy future. Alarmingly, that future does not meet the target of the COP 21 Paris Agreement 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". Here we outline how humanity can start closing that gap to achieve a transition that limits global warming to safer levels.

Climate change caused by anthropogenic carbon emissions is already visibly interfering with the world's climate system, and any further small increases in temperature will worsen the effects. The 2018 Special Report on Global Warming of 1.5°C (IPCC, 2018) highlights the urgent need to take action, emphasizes the challenges associated with even 1.5°C global warming, and points out the huge difference between 1.5°C and 2°C warming, in terms of climate-change impacts and irreversible alterations.

Every tenth of a degree of warming matters; risks and economic damage can be substantially lessened by limiting global warming to 1.5°C.

Those pathways that overshoot the 1.5°C threshold run a greater risk of triggering 'tipping points' where unknown, and potentially irreversible and unmanageable, Earth-system reactions may occur, even if temperatures should subsequently be reduced.

"Every tenth of a degree of warming matters; risks and economic damage can be substantially lessened by limiting global warming to 1.5°C

8.1 HOW BIG IS THE GAP?

Before we discuss what needs to be done, we need to outline the size of the problem. Our Outlook provides our best estimate of the energy future. This approach enables us to shed light on where energy-related greenhouse-gas (GHG) emissions are headed and describe the stark picture of just how far away the world is from achieving the goals of the Paris Agreement.

Our forecast gives a clear indication of the extent of our collective failure in limiting global GHG emissions, the size of the problem, and the magnitude of the gap that needs to be closed.

In Chapter 7, we explained how our forecast suggests that the world is heading towards warming to 2.3°C above preindustrial global average levels by the end of the century. Such a level of warming is considered to be associated with "very high risks of severe impacts" by the IPCC (IPCC, 2014a) and by the scientific community.

Our forecast indicates that we will overshoot the 1.5°C carbon budget in 2028, and will exhaust the 2°C budget in 2051. By mid-century, the overshoot of the 1.5°C budget will be 730 Gt CO_2 and there will be only 15 Gt CO_2 left of the 2°C budget. As illustrated in the carbon budget figure in Chapter 7 (Figure 7.7), the overshoot will continue beyond mid-century, and, by the year 2100, the 1.5°C budget will have been overshot by an estimated 1280 Gt CO_2, while the 2°C budget overshoot will be a still-considerable 530 Gt CO_2 – which is equivalent to 15 years of annual global energy-related emissions at today's levels.

Thus, the energy transition that we forecast is, unequivocally, not fast enough to limit warming to below 2°C. In other words, we need our forecast to be proven wrong. We want the future that we face not to be that of our forecast. We aspire to a future where global warming is limited to safer levels.

In order to do this, we need to close the gap between our forecast and future emission levels being kept within the bounds of the Paris-Agreement target. In the next sections, we look first at the uncertainties, then at detailed emissions of the various sectors, and finally highlight potential solutions, which, if implemented at scale, could close this gap.

UNCERTAINTIES

It is important to highlight that 'closing the gap' solutions are interlinked with emissions-reduction activities beyond the energy system. Reducing emissions from agriculture, forestry, other land use (AFOLU) is crucial if we are to have any chance of reaching the Paris-Agreement targets. However, we do not detail such emission characteristics and efforts in our analysis, as they are better addressed by AFOLU-domain experts. Non-energy related emissions (e.g., non-combustion emissions from processes in production of cement and fertilizer) are similarly critical for target achievement.

A combination of effective cross-sectoral measures is needed to reduce emissions and must be evaluated on the basis of cost and effectiveness for all solutions. These include reduction or capture of industrial emissions, as well as restricting deforestation, ensuring afforestation, and promotion of more-efficient land use. However, the palette of emissions and solutions that we focus upon here is directed towards the energy sector.

RECAP OF FORECAST ENERGY-SECTOR EMISSIONS

We forecast that energy-related CO_2 emissions will decline significantly, given the unfolding energy transition, but that the rate of decline is nowhere nearly fast enough to achieve the target of the Paris Agreement. Actions and solutions must be implemented to reduce emissions further, accelerating the decline, and hence the transition.

Table 8.1 provides an overview of today's emissions and those forecast for 2050 from our best estimate of the energy future.

> "We need our forecast to be proven wrong; we want the future that we face not to be that of our forecast

TABLE 8.1
Emissions by sector

Sector	Subsector	Emissions ($GtCO_2$/yr) 2018	Emissions ($GtCO_2$/yr) 2050	Forecast reduction (2018-2050)
Transport	Road	6.3	3.5	44%
	Aviation	1.1	0.7	36%
	Maritime	0.8	0.6	33%
	Rail	0.2	0.1	55%
	Total	**8.4**	**4.9**	**43%**
Buildings	Space heating	3.0	1.6	48%
	Space cooling	0.7	0.5	34%
	Water heating	1.4	0.9	36%
	Cooking	0.8	0.8	0%
	Appliances & lighting	2.8	1.0	64%
	Total	**8.7**	**4.7**	**46%**
Manufacturing	Base materials	4.6	1.3	73%
	Manufactured goods	4.5	2.4	47%
	Iron and steel	3.1	1.2	63%
	Total	**12.2**	**4.8**	**61%**
Energy sector own use		3.5	2.0	44%
Non-energy		1.7	1.0	45%
Other		1.5	0.9	43%
Total		**36.1**	**18.1**	**50%**


THERE IS
NO PLANET B
SAVE
MOTHER

8.2 SOLUTIONS TO CLOSE THE GAP

When considering how to close the emissions gap, two precepts are of importance:

- No silver bullet exists to close the gap on its own; a combination of many different solutions is needed.
- There is no ideal way to close the gap; several alternatives must be explored.

The suggestions that we make here are based on our assessment of which solutions currently appear to be the most promising, in terms of both costs and technical feasibility. However, as previously highlighted in Chapter 5 on policy, depending on the support provided to different solutions, those technologies that we may presently consider to seem most promising, might shift in the future owing to technological breakthroughs, changes in levels of support, and varying cost reductions.

Many 1.5°C and 2°C scenarios 'achieve' their GHG-reduction target by pushing mitigation actions into the future. These could involve large-scale net-negative emission technologies that are envisioned to be in place towards the latter half of the century. This is placing faith in those, or other, breakthrough solutions that do not exist now, to solve the problem in the future.

In our view, such approaches carry unacceptable risks. Climate impacts can be set in motion by kicking the can down the road, which will mean that the cost of addressing them later will be much more expensive than if we were to take immediate action. Although we accept that some form of net-negative emissions will likely be necessary, our main focus is on what can be done today, rather than leaving problematic areas for later. It is our opinion that to meet the ambitions of the Paris Agreement requires swift, urgent action; thus, much of the focus of this chapter is on near-term actions and solutions.

Because we look at the energy system of the entire world, with its multiple interdependencies and feedback loops, our ETO model is well suited for assessing the feasibility and impact of various alternative mitigation measures that can be initiated during our forecast period, i.e., before 2050.

However, there is - as we see it - no obvious and simple way to design a 'one likely pathway' to close the gap. Countries and regions have different starting points regarding available resources, existing energy-sector infrastructure, and political preferences. Thus, our ambition is to provide guidance on what we believe to be 'no-regret' solutions that would make sense in any pathway, and also to indicate the necessary tools and policy mechanisms required to realize their implementation.

Common to the solutions is that they fall within three main categories of emissions reduction, all of which must be addressed in any emissions-reduction plan. To achieve our climate goals we need solutions that:

- Reduce energy use by improving energy efficiency
- Increase the share of non-fossil energy supply
- Capture and store carbon

In addition to these technical solutions, we also need to consider behavioural changes. COVID-19 vividly illustrates the link between behaviour and energy emissions, as discussed in Chapter 1.

SOLUTIONS BY SECTOR

In order to narrow the range of combinations of decarbonization measures, we focus here on the most energy-intensive industries and those energy sectors that are responsible for the lion's share of emissions within our defined energy demand and supply sectors (Table 8.2).

Solutions with the potential to contribute towards 'closing the gap' require initiatives and action on many fronts, but we have made two clear distinctions for the route towards reducing emissions, and both tracks require near-term action to be realized:

– Implementation track – known and readily available solutions, but requiring full-scale implementation in the coming decade.
– Development track – possible solutions identified, but currently less mature and significantly more expensive than today's conventional technology. Hence the need for targeted policies, including incentives for additional R&D and funding for projects to trigger technology readiness and scaling-up.

In the next sections, we discuss each of the sectors individually for clarity. However, as discussed in Chapter 5, systemic innovation and sector coupling are increasingly important and should be retained as a front-of-mind issue. As decarbonization is based on renewable energy and electrification across sectors, solutions will often have a cross-sectoral dimension, where actions in one sector will significantly influence the decarbonization options and the cost of reducing emissions in other sectors.

In addition to the sector solutions, the key barriers, as they presently stand, are listed, as well as policy actions to address them (building on the policy toolbox discussed in Sections 5.5 and 5.6). Both the implementation and development tracks include the need for policy initiatives on both the energy-demand and the energy-supply sides.

In order to be successful, decarbonization and the transition need to be driven by the entire spectrum of policy mechanisms, with technology support, market activation, and economic signals.

TABLE 8.2
Energy efficiency improvements by sector

Demand sectors	Demand subsectors	Supply sectors
Transport	Road transport Aviation Shipping	**Power production**
Manufacturing	Manufacturing heating Iron and steel	**Oil and gas production**
Buildings	Heating in buildings	**Feedstock production**

ROAD TRANSPORT

Road transport decarbonization ranges from the relatively easy-to-abate passenger vehicles and rail industries to hard-to-abate heavy-road transport, and solutions cover a wide span.

Passenger vehicles today account for about 2.8 Gt CO_2 emissions, which is around 8% of global emissions, having increased steadily over the last decades. Our forecast predicts a reduction to slightly more than 1 Gt CO_2 emissions by mid-century, corresponding to about 6% of global emissions.

Efficiency improvements in the past were mostly outweighed by larger vehicle size, and thus heavier weight and more powerful engines. Measures to reduce road-transport sector emissions have been improvements in fuel economy and biofuel blends, as required by policies. However, substantial reductions in emissions will only be achieved through electrification of passenger vehicles and light transport. Currently, the low density of fast-charging stations is a major barrier to EV uptake in many parts of the world. This will become increasingly obsolete as EV utility improves through, e.g., bigger, lighter, and cheaper batteries, enabling most of the charging to be done at home. However, this development needs preferential treatment, as well as governmental frameworks, such as the European Green Deal, to support EV uptake.

Another measure to reduce road-transport emissions is decreasing the use of individual transport, particularly through improved urban planning and public-transit modes and systems. In addition, use of individual transport can be diminished through greater use of remote services, such as digitization of meetings and virtual conferences.

Global emissions from trucks and buses have been growing in recent decades, reaching approximately 3.3 Gt CO_2 in 2018, about 10% of global overall emissions. Emissions from heavy transport are forecast to halve, decreasing to about 1.6 Gt CO_2 by 2050, 9% of global emissions at that time. The main reasons for rising emissions in past decades are the rise in global GDP, resulting in increased freight demand, and only slow improvements in efficiency, especially for heavy trucks. In some countries, such as Germany, freight demand has been shifted from more-efficient rail transport to road transport, thereby increasing the number of heavy vehicles. In other countries, fossil-fuel subsidies have remained stubbornly high.

The momentum to reverse this trend is growing, with numerous cities worldwide fostering electric buses and large fleet operators switching to

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

- Improving utility for EVs, e.g., number of fast-charging stations and availability of renewable power.
- Policies to foster the further uptake of EVs and fuel-cell EVs in heavy transport, such as electric buses in cities and fuel-cell heavy trucks.
- Removing fossil-fuel subsidies to address externalities and for energy prices to reflect real costs.

electric commercial delivery vehicles. The use of hydrogen-fuelled fuel cells instead of fossil-energy carriers is considered a favourable option for heavy trucks and long-distance transport. As road transport is responsible for a large share of global emissions, encouraging the switch to low-carbon fuel alternatives and increasing the uptake momentum is vital.

> "Substantial reductions in emissions will be achieved through the electrification of both the passenger and commercial vehicle fleets worldwide

TABLE 8.3
Road transport

Track	Solution/technology	Barriers	Policy instrument
Implementation	Higher market share of electric vehicles	Insufficient charging infrastructure	Broad EV incentives (incl. charging infrastructure); stringent fleet-wide average emission standards; zero-emission vehicle fractions on car-manufacturer total sales
		Higher CAPEX compared to ICE	CAPEX reducing instruments such as tax exemptions, reduced import duties
	Improve transport demand management	Lack of cost competitiveness due to fossil-fuel subsidies	Removal of fossil-fuel subsidies
		Individual behavioural change	Steer behaviour through 'feebates' and measures such as congestion pricing, city taxes, or parking pricing
	Modal transport shift towards more energy efficient transportation modes such as rail freight transport	Lack of needed infrastructure	Regulations supporting modes of higher energy efficiency in freight transport
		Lack of cost competitiveness	Removal of fossil-fuel subsidies
Development	Electric heavy-duty vehicles	Technology maturity, especially power density of batteries and thus range	R&D on energy density of batteries
		Fast charging infrastructure along main transport routes	R&D and incentives on buildup of fast-charing infrastructure with supportive regulation
	Fuel-cell heavy vehicles	Availablity of green hydrogen along main transport routes	R&D on value chain of green hydrogen production/supply and incentives for pilot projects

AVIATION

The aviation industry currently emits 1.1 Gt CO_2, or 3% of global emissions, and we forecast that this will drop by some 40%, down to 650 Mt by 2050, but will still account for about 3% of global emissions. As electrification appears feasible for short-haul flights only, and few low- and zero-carbon fuel alternatives are available and practical at scale, aviation is a hard-to-abate sector. Solutions that, in concert, could contribute to reducing aviation emissions are: sustainable aviation fuels (SAF: biofuels, hydrogen, and ammonia appear promising), efficiency improvements, and offsetting within or outside the aviation sector.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

» Continued support to R&D on sustainable aviation fuel (SAF) alternatives, their commercial-scale production and mandated uptake.

TABLE 8.4
Aviation

Track	Solution/technology	Barriers	Policy instrument
Implementation	Efficiency improvements	Cost and ROI for efficiency upgrades	Investment support on tech upgrades
			Carbon price
			Emission limit regulations
	Change high-emitting lifestyles by reducing travel	Public acceptance of air-travel regulation; individual behavioural change	Increasing fees and taxes
Development	Biofuel, hydrogen and other sustainable aviation fuels (SAF)	Technology maturity	R&D; technology roadmaps prioritizing fuel alternatives
		Fuel availability (lack of fuel-production capacity and widespread SAF infrastructure)	Investment support to fuel production infrastructure
		Scaling; high CAPEX	Financing of (technology) pilots and demonstration
			Mandates on fuel targets and blend-ins
	Electrification	Technology maturity; technology limits (range limitations, charging time)	R&D
		Cost level; lack of charging infrastructure	Financing of (technology) pilots and demonstration

MARITIME

Maritime transport sector currently emits 820 Mt CO_2, some 2.3% of global emissions. We forecast that this will be decreased to around 600 Mt by 2050, accounting then for about 3.5% of global emissions. As direct electrification is expected to be viable only in the shortsea segment and few low- and zero-carbon fuel alternatives are available and practical today, maritime transport is considered a hard-to-abate sector. We forecast a high share of natural gas, ammonia, and other low- and zero-carbon fuels in 2050, but additional action is needed in order to reduce emissions to a lower level than we currently forecast. The Maritime ETO report (DNV GL, 2020c) details decarbonization pathways for shipping.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

» Continued support to R&D in carbon-neutral fuel alternatives, and their commercialization in terms of supply-chain buildout and mandated uptake.

TABLE 8.5
Maritime

Track	Solution/technology	Barriers	Policy instrument
Implementation	Efficiency improvements incl. logistics	Limited reduction potential	Investment support on technology upgrades
			Emission limit regulations
			Speed regulations
	Fuel switch	Fuel price	Fuel levy; removal of fossil-fuel subsidies; carbon price
		Fuel availability (scale-up and lack of widespread /global bunkering infrastructure)	Investment support on fuel production infrastructure
Development	Carbon-neutral fuels	Technology maturity	R&D
		High cost level	Investment support on fuel production infrastructure
		Required machinery and fuel-storage systems on vessels	Emission limit regulations
		Fuel price	Fuel levy; removal of fossil-fuel subsidies; carbon price
		Fuel availability (scale-up and lack of widespread /global bunkering infrastructure)	Investment support to fuel production infrastructure
	Electrification	Technology limits (battery sizes etc)	R&D
		High cost level	Financing of (technology) pilots

HEATING IN BUILDINGS

In 2018, the buildings sector emitted 8.7 Gt CO_2, representing around one quarter of total global emissions. This sector will see a steady decline in emissions, dropping to 4.7 Gt in 2050, by then accounting for 27% of total global emissions. Continuous improvements in energy efficiency and switching to low- or zero-carbon fuels for heating applications will be the main drivers of these reductions. Nevertheless, despite improvements in end-use conversion efficiencies, the final-energy consumption will stay relatively stable to meet the growing demand for heating of buildings.

With continued improvements in heating solutions and widespread use of more-efficient technologies, such as condensing gas boilers and electric heat pumps for space- and water-heating applications, the average efficiency of heating will increase significantly. Reductions in the cost of heat pumps, together with improvements in performance, will boost their market share significantly, bringing large mitigation potential. Decreasing heating demand by insulation and retrofitting of buildings will be an effective strategy that complements improvements in energy efficiency.

Scaling up the share of renewable sources, such as solar-thermal heating and renewables-based district-heating systems, will result in emissions dropping in the buildings sector. Another important step in decarbonizing the buildings sector, will be to reduce use of traditional biomass combustion in less-developed regions by enhancing energy access and utilizing modern heating technologies.

In addition to efficiency improvements and technology replacement, biomethane and hydrogen, in pure or fuel blends, can play an important role in decarbonizing the buildings sector. Hydrogen will become a new energy source for heat-related end uses as a direct alternative to natural gas. In the three OECD regions and in China, the current and planned gas grids will accommodate both pure and fuel-blend hydrogen piping at a low additional cost, although upgrading heating appliances will be required for utilizing pure hydrogen.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

» Replacing traditional biomass combustion and scaling up high-efficiency heat pumps.

TABLE 8.6
Heating buildings

Track	Solution/technology	Barriers	Policy instrument
Implementation	Insulation and building retrofits	Cost and ROI on investment	Investment support on technology upgrades; building codes; carbon price
	Replace traditional biomass combustion	Technical maturity	Regulation of building codes; financial support to convert from traditional biomass to modern heating
	Smart control systems	High CAPEX; lack of net metering; privacy, trust and cyber security concerns	Financial support to building upgrades/retrofitting
	Condensing gas boilers	Cost level	Mandates on fuel mix and minimum requirements
	Solar thermal heating	High CAPEX; lack of local competence; awareness	Investment support; demonstration projects helping increase awareness
Development	High efficiency heat pumps	High CAPEX	Financial support for R&D and pilot projects; carbon price
	Hydrogen blending in gas grids	Technology maturity	Support scheme such as tax reductions, feed-in tariff; clarity on access to infra-structure; quality standards and safety measures
	Biomethane in gas grids	Technology maturity; production capacity; access to infrastructure	Investment support on fuel production infrastructure; clarity on access to infra-structure; quality standards and safety measures

MANUFACTURING

Currently, about 35% of total global CO_2 emissions originate from this energy- and heat-intensive sector. In 2018, the emissions from this sector were about 12.2 Gt CO_2 and this is forecast to more than halve to 4.8 Gt CO_2 in 2050, when accounting for a third of total global emissions. Our analysis of focuses on three subsectors: manufactured goods, production and extraction of base materials, and production of iron and steel. Heat is the end use that is responsible for most of the emissions by far, with 70% of all manufacturing emissions.

Several technologies can be used for low-grade heat processes, with industrial heat-pumps being a promising low-carbon solution. High-grade industrial heat processes, however, need a dense energy carrier, either in the form of fossil fuels or energy-intensive electric heating. Common to hard-to-abate sectors and processes is the difficulty in competing with existing technology and supply chains based on fossil fuels regarding cost and efficiency. Electrification and hydrogen from electrolysis are technologies that can solve the decarbonization challenge, but most electricity today is based on fossil fuels and therefore, compared with direct-heat technologies, suffers from heat losses.

The current annual production of about 1.3 bn tonnes of steel is a carbon-intensive process requiring fossil fuels for both feedstock and for provision of energy as heat. In 2018, around 3.1 Gt CO_2, equivalent to 9% of total global emissions, originated from this energy-intensive process. We forecast this subsector to halve its emissions to 1.2 Gt CO_2 by 2050, still accounting for 7% of total global emissions. This reduction in emissions is mainly due to a higher share of electric arc furnace-based steelmaking and the uptake of low-carbon energy carriers, such as hydrogen, as well as capture of process emissions via CCS. The iron and steel industry has already reduced emissions per tonne product in recent decades, and therefore further simple solutions are not readily available.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

- Increase recycling and availability of scrap that requires much-less energy for processing, e.g., steel, aluminium.
- Support on-site renewable electricity production, and/or relocation of manufacturing to production areas with a low-carbon electricity mix (for electricity-based heating).
- Facilitate growth in electric arc furnace usage based on renewable electricity.
- Where appropriate, deploy CCS-application in the production process.

TABLE 8.7
Manufacturing

Track	Solution/technology	Barriers	Policy instrument
Implementation	Recycling	Cost and ROI on investment	Mandates on recycling; investment support on tech upgrades
	Heat pumps for low heat applications	Technical production capacity	Investment support on equipment/tech upgrades
			Minimum energy performance standards for industrial equipment
			Carbon price; emission limits regulation
			Bans on polluting technologies. e.g. coal for heating
Development	Higher share of arc furnace steelmaking	Availability of scrap metal	Improvement of circular economy regulation e.g. mandates on recycling, extended-producer responsibilities; financial incentives
		Supply of low- and/or zero-carbon power	Carbon price
	Hydrogen	Process maturity	Financial support for R&D and pilot projects; carbon price
	CCS	Technology maturity, location and capacity of storage sites	Financial support for R&D and pilot projects; carbon price

POWER PRODUCTION

Power generation was responsible for 13.2 Gt CO_2 emissions in 2018. By 2050, we forecast this to decline to 5.5 Gt, reducing its share in total energy-related CO_2 emissions from 38% to 32%.

Energy-efficiency improvements can reduce power-sector emissions by decreasing electricity demand. Such solutions are discussed elsewhere in this section. Here, we focus on the power sector itself, and investigate options for reducing the emission intensity of the electricity.

Utility-scale solar PV and wind are becoming cost competitive in most regions, but still require support in many countries where the cost of fossil fuels is low. Expanding solar PV and wind to floating offshore locations and to final consumers is also in need of incentives. Furthermore, for higher uptake of variable renewables, governments should focus on supporting complementary flexibility technologies, like batteries and interconnections, and redesigning the power market to allow continued profitability for investors. Other renewables, such as hydropower, biomass, and waste, have their own challenges in terms of resources and public perception. These can be helped in being overcome, at least partially, by policy measures.

Decommissioning old fossil-fuel power plants that are less profitable and applying CCS to the remaining ones is the only viable way for conventional thermal generation to survive. Both actions need policy support to kickstart the cost reductions.

Further decarbonization of power can be achieved by expanding the menu of decarbonized power options by supporting immature technologies like small modular nuclear reactors, nuclear fusion, and ocean energy. These solutions can complement variable renewables where they are expensive or unavailable.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

» Making renewables cost-competitive in all parts of the world, so that developing countries are not locked into fossil-fired power to meet their growing power needs.

TABLE 8.8
Power sector

Track	Solution/technology	Barriers	Policy instrument
Implementation	Solar PV	Lower profits with higher vRES penetration; reliance on advances in storage	Feed-in tariffs, or other mechanisms for long term profitability
	Wind	Noise & environmental concerns; non-standardized regulatory processes; lack of skilled labour in developing countries	Long-term vRES targets; tax incentives for investments and turbine production; stable and predictable policy
	Hydropower	Human & environmental impacts; geopolitical rivalry on international rivers; lengthy approval; construction & payback	Simplified admin; R&D support for equipment design; materials and control systems
	Biomass, waste	Scalability vs sustainability; local availability; cost of collection, handling, prep and transport	Carbon prices; financial support for power plants; mandated biomass quotas
	Early retirement of fossil fired plants	Job destruction; need to replace retiring capacity	Bans; financial compensation to operators for early closures
	Residential and commercial renewables	High up-front cost for consumers; technology scaling	Direct subsidies; net metering systems; local demonstration projects
	Grid interconnections	Long planning processes; incompatibility of grids; national rivalries	Interconnection standards; transparency of legal processes; stronger international cooperation
Development	CCS	Technology maturity; location and capacity of storage sites	Financial support for R&D and pilot projects; carbon price
	Floating renewables	High CAPEX; conflict with fishing and shipping areas; lack of well-established construction methods	Stable policy regime; renewable energy targets; tax breaks; direct government subsidies
	Small modular nuclear reactors	High CAPEX; unsolved waste problem; social opposition to nuclear energy	Setting targets; expanding renewable goal definitions to include nuclear; financial support for design studies

OIL & GAS SUPPLY

The oil and gas sector's own use of energy from exploration, development, production, and refining/processing currently results in about 1.5 Gt of CO_2 emissions annually, equalling 4% of global CO_2 emissions. This is forecast to slightly decrease to 1.3 Gt in 2050, by then accounting for about 7% of global emissions. Most of the energy used could be transferred to electricity by implementing relatively simple, albeit sometimes expensive, measures.

The Oil & Gas ETO report (DNV GL, 2020b) provides a comprehensive overview of further decarbonization options for the oil and gas industry, and therefore extensive details are not included here.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

» Harvest low-hanging fruits within energy efficiency and take urgent action to curb methane emissions from natural-gas production.

TABLE 8.9
Oil and Gas supply

Track	Solution/technology	Barriers	Policy instrument
Implementation	Energy efficiency	Profitability	Financial support on investment
	Remote sensing to detect and manage methane	High upfront investment	Financial support for remote sensing Methane emission regulations
	Behavioural change to reduce flaring	Environmental concerns	Ban on flaring Methane emission limits regulations
Development	CCS	Technology maturity Cost level	R&D Government funding of CCS pilots Mandatory CCS
	Electrification of oil & gas production	High CAPEX cost	Mandates on electrification Financial support to new projects

FOSSIL-FEEDSTOCK PRODUCTION

Use of fossil-fuel based feedstock to produce plastics and petrochemicals was the source of 1.7 Gt CO_2 emissions in 2018, accounting for about 5% of total emissions. By mid-century, these emissions are estimated to be reduced to 1 Gt CO_2, by then representing about 5% of total emissions.

Currently, nearly half of the global fossil-fuel feedstock is used for plastic production, with the potential of being expanded to over 60% by 2050. Upstream efficiency gains through substitution, design, and light weighting can save some plastics from being produced. Currently, the rate of growth in plastic demand is greater than that of the growth in plastic recycling, calling for national and regional policy interventions to support recycling industries, decrease waste, and reduce virgin-plastic demand. Both mechanical- and chemical-recycling processes are required to fulfil the circular-economy potential of plastics. Technological developments and the rapid growth of chemical recycling will accelerate the growth of plastic recycling.

Bio-based or low-carbon electrofuels are alternatives to fossil-fuel feedstock. Bioplastics currently represent only a very small share of the global plastic market, due to their high production cost. However, increasing the use of bioplastics could be an effective mitigation option, especially if less energy-intensive production processes are developed. Chemical recycling applied to bio-derived plastics could eventually become a significant form of carbon capture.

MOST IMPORTANT PRIORITIES OVER THE NEXT FIVE YEARS

- Government incentives to support the systems for plastics recycling.
- R&D and deployment (RD&D) for chemical recycling.

TABLE 8.10
Feedstocks

Track	Solution/technology	Barriers	Policy instrument
Implementation	Lower plastic demand	Lack of collection and recycling infrastructure	Extended producer responsibilities; official support for informal waste collectors
	Upstream efficiency gain	Multiple types of plastics complicating recycling	Mandates on recycling; promotion of chemical recycling
	Mechanical recycling	High investment cost and low ROI; cheap virgin resin	Single-use plastics ban; public incentives for recycling (e.g. deposit returns); tax on plastic
Development	Chemical recycling	Technology maturity and scaling; high CAPEX; cheap virgin resin	Tax on virgin resin; R&D and investment support; market activation e.g. local authority demonstrator projects; setting targets for feedstock recycling
	Bio-based plastics	Technology scaling	R&D and investment support; target recycling of bio-derived plastic as a decarbonization mechanism

8.3 BRINGING IT ALL TOGETHER

In this edition of our Outlook, we have chosen to structure our presentation of potential solutions using a sector and technology focus. Thus, we consider and present, in turn, the main energy sectors responsible for the emissions, and discuss relevant mitigating technologies within each of them. It is clear that there are a number of possible solutions within the various energy sectors that could be implemented to close the gap, and, collectively, they hold the potential for achieving the sizeable reductions needed.

POLICIES AND REGULATIONS

To ensure the necessary reductions are achieved, various policy actions are also needed within each of the sectors. This aspect is critical, and without enabling governmental policies and regulatory measures at international, national, and sub-national levels, the solutions and technologies are unlikely to scale, and the technologies will not deliver on their potential. Furthermore, the contributions and shifts in investments, from both the financial sector and the private sector in general, will be instrumental in accomplishing implementation of the various solutions.

BEHAVIOURAL CHANGES

Finally, we have alluded to behavioural changes. Encouraging progress has been made in the last eight months on discussion about behavioural changes, promoted by actual behavioural changes – both enforced and voluntary – that have been sharply in focus during the ongoing COVID-19 crisis. Although this topic has not been addressed in any depth in previous forecasts, how we behave is clearly an important element in the energy transition and the solutions to close the gap to 1.5°C. From now on it may be easier to discuss the relevance of behavioural changes and incorporate them in future solutions. These changes include e.g. reducing demand for air travel and commuting, increasing the use of digital technology in everyday life, modal transport shifts and, critically, consumer choices that proceed from questioning the need for non-essential consumption and selecting sustainable products and services.

Our Outlook and analysis address the energy transition. Solutions for transforming the energy system are the most important step for success in achieving the goals of the Paris Agreement, but energy-related solutions alone are not sufficient. Because we have limited our focus to the energy transition, relevant technologies, policies, financial instruments, and behavioural changes for areas other than energy are not detailed in this Outlook. However, as shown by, e.g., IPCC (2014a,b) and, more recently, Drawdown (2020), solutions within all economic areas must play a role if we are to reach net-zero or other ambitious climate targets.

PRIORITIZING SOLUTIONS

Among the long list of potential technical solutions, it is relevant to question whether we need them all, or which of them should be selected for prioritization. Clearly, some of the solutions are also partly overlapping, and there is no single way to close the gap, but various alternatives. In choosing the optimal approach, cost-efficiency considerations are important and also ease of implementation, in terms of political feasibility and public acceptability. In many sectors, the industry and the appropriate authorities need to work in tandem, developing parallel solutions, and then, when the technologies have matured further, prioritizing those that appear most promising.

As highlighted in Chapter 7, the 1.5°C carbon budget is likely to be exhausted in 2028, and our challenge to avoid this is daunting. However, technological solutions exist, although it is difficult to envisage a realistic scale-up of solutions that will keep us within this emissions' budget. The options for mitigation need to be implemented at massive scale and speed, with immediate political attention and action as the most important lever. Given the urgency and the importance, such implementation is something that DNV GL supports, encourages, and works to achieve.

A temporary overshoot of the 1.5°C budget, with large-scale net-negative emissions planned for later in the century, preferably before 2050, is an alternative approach to staying within the 1.5°C threshold; further details on negative-emissions technologies are listed in the fact box. However, this route to reductions in emissions will also require focus and near-term action to ready the technologies for later implementation. Although the temporary overshoot is a high-risk approach, a permanent overshoot would be far worse.

NEGATIVE-EMISSION TECHNOLOGIES

"Negative emissions" is the term that describes removing CO_2 from the atmosphere beyond the natural cycle. Prime examples are afforestation and reforestation, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). Other examples include soil carbon, biochar, and enhanced weathering. Both the maturity and costs of these various options differ significantly.

Afforestation/reforestation: in simple terms this means planting trees in new areas and/or replacing felled trees with as much forest as possible. The additional trees will store CO_2. This solution is a mandatory part of all future 1.5°C or 2°C scenarios. The risk is low, but there is fierce competition for arable land for agriculture and other uses. The solution is easy to scale, but cannot be scaled sufficiently for this to be the only solution.

BECCS: as discussed in Chapter 4, burning wood is considered carbon neutral, because only the CO_2 that was captured when the plant was growing is released. If, in addition, CO_2 is captured from the burned wood and stored safely underground, then we remove carbon from the atmosphere. The technology exists, but only at the pilot stage, and the magnitude suggested for this solution in many 1.5°C and 2°C scenarios is alarmingly high. Enormous investments are required and there are considerable challenges with CO_2-transport infrastructure and finding enough storage sites. In addition, there are always timescale challenges when biomass is burned and the acreage then replanted.

DACCS: removes CO_2 directly from the air and subsequently stores it underground. DACCS facilities can be located close to where the CO_2 is to be stored, thereby eliminating transport needs. The technology is unproven for all but laboratory-scale plants, and has the same challenges as BECCS regarding storage of CO_2.

A.1 TEN REGIONS

In this Outlook, we have divided the world into 10 regions chosen on the basis of geographical location, extent of economic development, and energy characteristics. Each region's input and results are the sum of all the countries in that region. Where relevant, weighted averages are used, such that countries are assigned weights relative to population, energy use, or other relevant parameters. Distinctive characteristics of certain countries, for example, nuclear dominance in France, are thus averaged over the entire region. In some cases, we comment on this.

In a few places in the Outlook, we refer to "OECD regions". This designation refers to the following three regions: North America, Europe, and OECD Pacific (OPA).

Detailed characteristics, results, and discussions regarding the regional energy transitions are included in Chapter 6 of this Outlook. These are used to provide an analysis of, and a forecast for, the energy transitions in each of the regions.

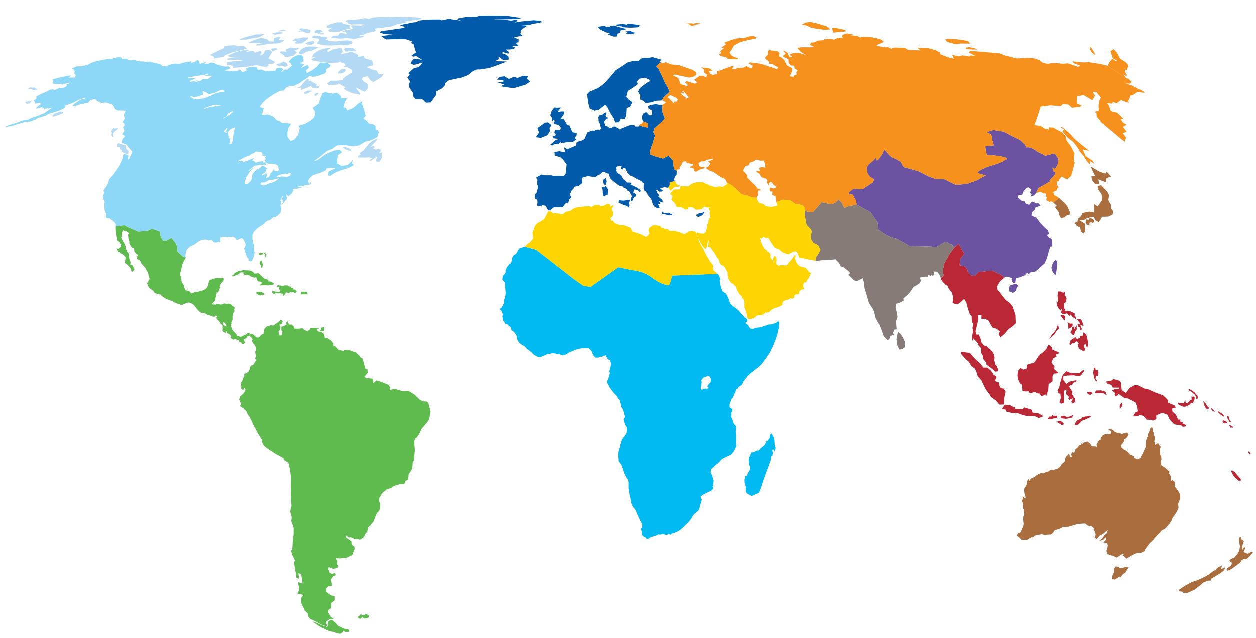


FIGURE A.1

- 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)

A.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 requires access to energy in one form or another.

The source most frequently used for population data and projections is the UN Department of Economic and Social Affairs, which publishes its *World Population Prospects* every other year. The forecast in the latest update, published in June 2019, runs to 2100. Other 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 places more emphasis than the UN on considering how future education levels, particularly among women, will influence fertility. As noted by Lutz (2014), urbanization in developing countries will result in fertility rates falling; having many children is a greater economic burden and less of a necessity in cities than in traditional, rural settings. Furthermore,

Rooftop solar PV at Enkanini, an informal settlement outside Stellenbosch, South Africa evidence indicates that higher levels of education among women are associated with a lower fertility rate (Canning et al., 2015). Sustainable Development Goal (SDG) #4 Quality Education and SDG #5 Gender Equality are providing further impetus to improving female education.

Fertility is low in both the OECD and China, and in non-OECD regions it is falling considerably. In Sub-Saharan Africa (SSA), the reduction in fertility has been slower than in other parts of the world, and the total fertility rate is still at about 4.5 births per woman, falling by about 0.6 births per woman per decade. SSA, where many of the least-developed countries are located, also lags behind other regions in the expansion of education. However, we assume that urbanization and improved education levels among women will, eventually, also accelerate the decline in fertility rates in Africa.

The Wittgenstein Centre also uses several scenarios related to the five different 'storylines' that were developed in the context of the Intergovernmental Panel on Climate Change, IPCC (van Vuuren et al., 2011). The IPCC calls these storylines "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 inputs.

Using the Wittgenstein population projections for SSP2, we arrive at our 2050 population forecast of 9.4 billion, which is an increase of 25% from the most recent UN (2017) population estimate of 7.5 billion. By mid-century, the global population will still be growing, but the rate is reduced to 0.3% per year, and with SSA as the only region with notable growth, as illustrated in Figure A.2.

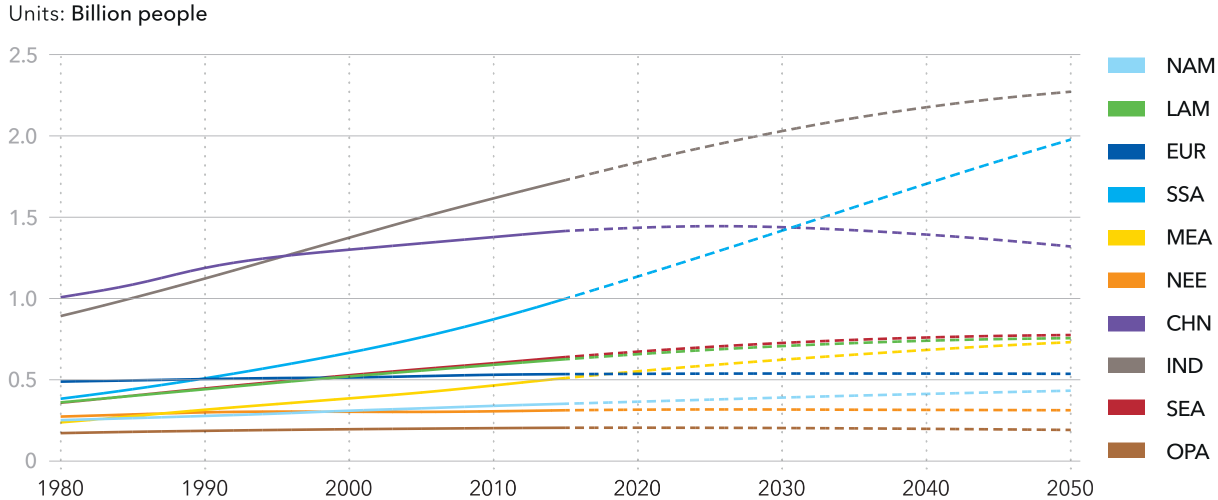
Our 2050 figure of 9.4 billion is 4% lower than the latest UN median estimate of 9.7 billion. If we had used the UN median population projection, most of our energy demand figures would increase commensurately, but with regional variations.

> "We forecast a global population of 9.4 billion in 2050 , an increase of 25% above the most recent (2017) UN population estimate of 7.5 billion

FIGURE A.2

Population by region

Units: Billion people



Historical data source: UN (2017), Forecast: Wittgenstein Centre for Demography and Human Capital (2018)

A.3 PRODUCTIVITY AND GDP

GDP per capita is a measure of the standard of living in a country and is a major driver of energy consumption in our model. From a production point of view, it is also a good proxy for labour productivity, as it reflects the amount of economic output per person.

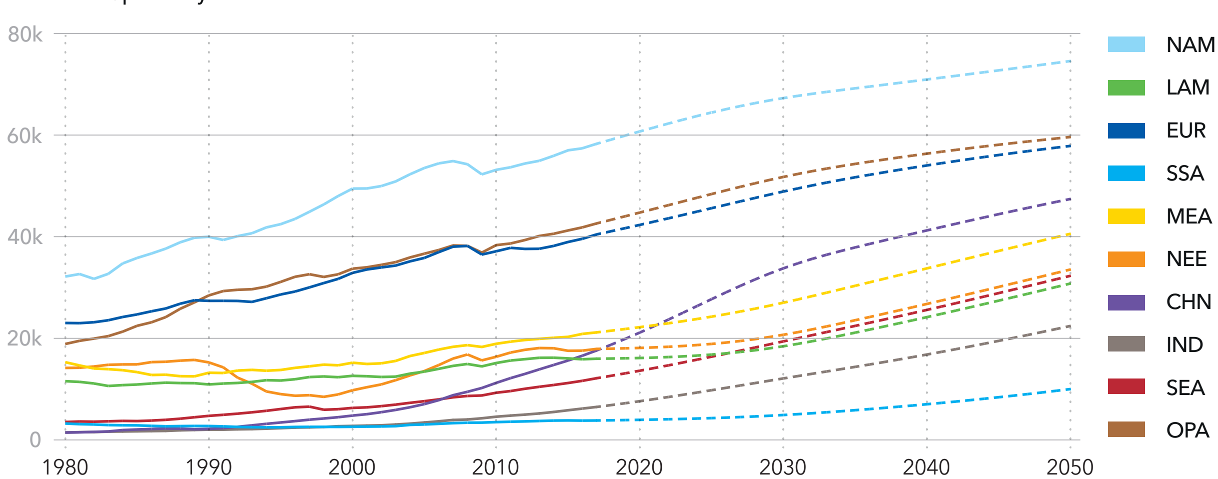
We base our GDP per capita growth forecast on the inverse relationship between GDP per capita level and its growth rate. This relationship is a result of sectoral transitions that an economy experiences as it becomes more affluent. An increase in the standard of living in a poor country initially arises from productivity improvements in the primary sector, and, thereafter, from productivity improvements in the secondary sector. In both sectors, the move from manual to industrial processes carries vast potential for productivity improvements. Mature economies employ increasing shares of their GDP in the tertiary (service) sector. Although services such as financial services and healthcare also benefit from technology uptake, productivity improvements tend to increase the quality, rather than the amount, of output. This implies that productivity growth will slow down as economies approach maturity, and, indeed, this has been demonstrated empirically time and again.

At infrequent intervals, major events cause an extraordinary productivity change. The 2020 COVID-19 pandemic is one such event and will result in negative growth figures. At the time of writing, the medium-term effect of this is highly uncertain, but a global growth figure of -5.9%, and regional 2020 growth figures of between -7% and -1% are included in the forecast, with further adjustments for the following years.

FIGURE A.3

GDP per capita by region

Units: USD/person-yr



Historical data source: World Bank (2018), Gapminder (2018)

The fact box at the start of Chapter 1 describes more fully how we have incorporated the effects of the pandemic into our forecast.

Measured in purchasing-power-adjusted constant (2017) USD, historical GDP per capita developments from 1980 to today, along with forecast developments towards 2050, can be seen in Figure A.3. On a world-average level, a compound annual growth rate (CAGR) of only 1.3%/yr is expected in the 2018-2030 period, due to COVID-19. This is 1.1% lower than forecast a year ago, illustrating both the impact, but also the uncertainty, associated with COVID-19.

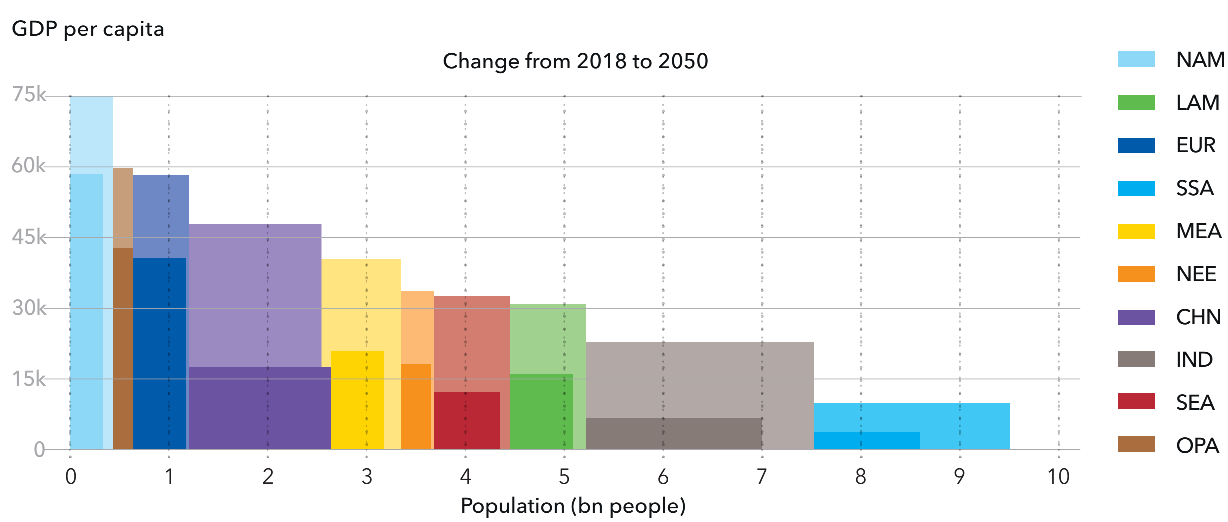
With or without COVID-19, the fastest growth in GDP per capita, leading up to 2030, will be in Asia. Greater China (CHN) will have highest growth rate, at an average of 4.5%/yr, followed by the Indian Subcontinent (IND) at 3.9%/yr, as shown in Figure A.3.

As the Chinese economy matures, growth in GDP per capita will slow down after 2030. The period between 2030-2050 will be characterized by a more-even spread of prosperity improvements globally, with highest growth in the least-developed regions. The region with the fastest GDP per capita growth will therefore be SSA, with a CAGR of 3.6%/yr. Improvements in the standard of living in economically developed regions will reduce to under 1%/yr in the 2030-2050 period. The forecast beyond 2030 does not include any larger changes in the relative positions among the productivity of the different regions.

World GDP is expected to grow from USD 134 trn/yr in 2018 to USD 269 trn/yr in 2050, measured in constant 2017 purchasing-power-adjusted USD. This doubling over the 32-year period is a result of a 23% increase in population and a 63% increase in average GDP per capita, with large regional differences. Figure A.4 illustrates the

FIGURE A.4

Population and GDP per capita by region



Historical data source: World Bank (2018), Gapminder (2018), UN (2017)

TABLE A.1
Compound annual GDP growth rate by region

		2000-2018	2018-2030	2030-2040	2040-2050	2018-2050
NAM	North America	2.0%	1.0%	1.1%	1.0%	1.1%
LAM	Latin America	2.5%	0.2%	3.2%	3.3%	2.0%
EUR	Europe	1.5%	1.0%	0.9%	0.5%	0.7%
SSA	Sub-Saharan Africa	4.7%	2.5%	5.5%	5.2%	4.2%
MEA	Middle East and North Africa	3.8%	1.5%	3.3%	2.8%	2.5%
NEE	North East Eurasia	3.8%	0.7%	2.4%	2.1%	1.7%
CHN	Greater China	8.6%	4.4%	1.8%	0.8%	2.4%
IND	Indian Subcontinent	6.4%	4.9%	4.1%	3.3%	4.2%
SEA	South East Asia	5.3%	3.7%	3.2%	2.5%	3.2%
OPA	OECD Pacific	1.7%	0.5%	0.6%	0.2%	0.4%
	World	3.7%	2.4%	2.4%	2.0%	2.2%

combined effect of population change (x-axis) and GDP per capita growth (y-axis); the decadal growth figures are included in Table A.1.

As Table A.1 shows, the world experienced a 3.7% compound annual GDP growth from 2000 to 2018. In the 2040s this will gradually slow to 2%/yr, combining the effect of slowdown in population growth with the economies of more and more countries become service orientated. Nonetheless, most economies around the world will continue to grow, albeit at varying rates, with likely exceptions only in mature economies that are experiencing marked population decline, such as Japan.

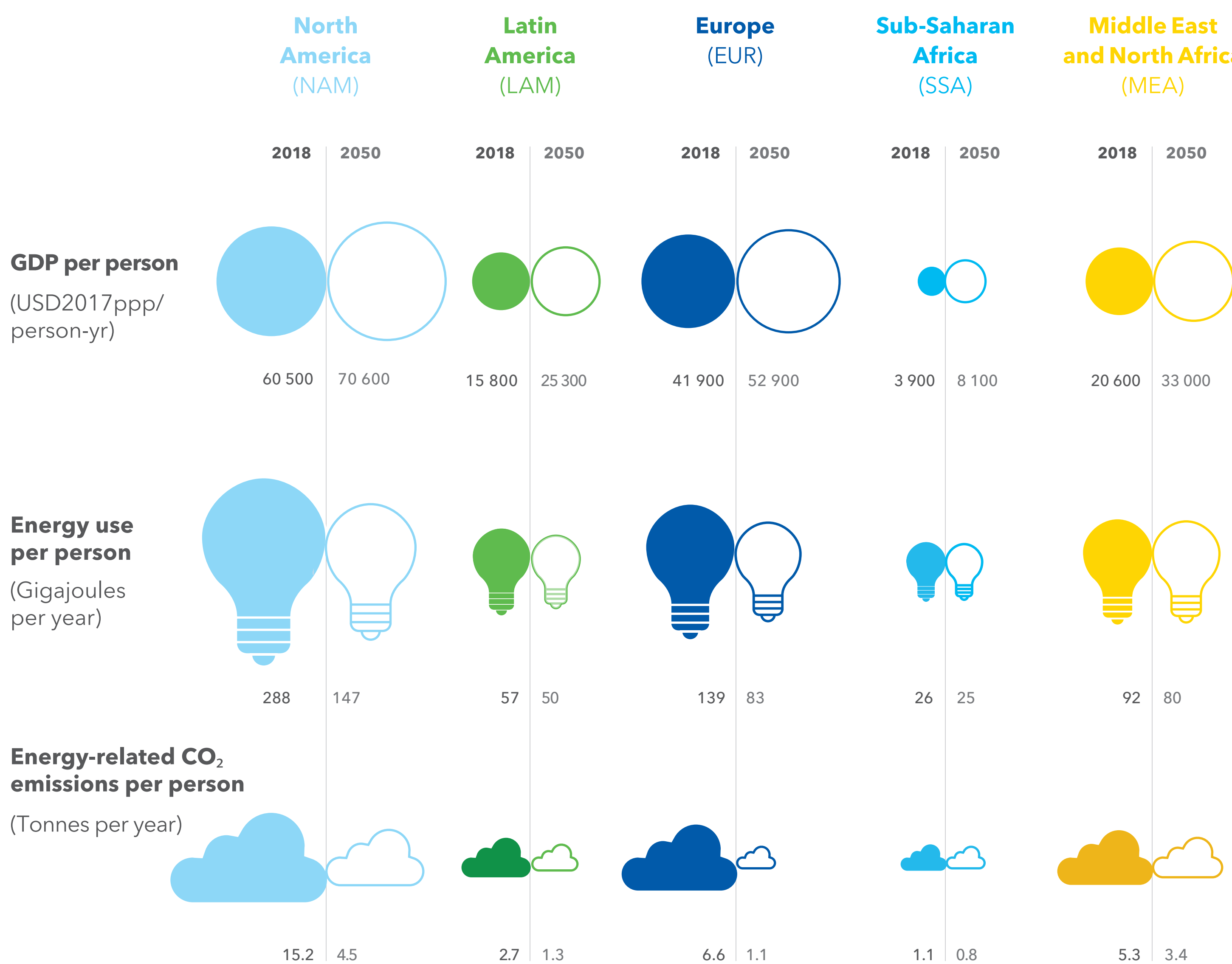
Compared with last year's forecast, ETO 2020 has estimated a lower GDP due to COVID-19. Of the 10% difference in the predicted 2050 global GDP of 269 trillion, compared with the 299 trillion forecast last year, 9% is due to COVID-19. However, more important in the long term is our belief that we will not see any reversal of the well-established productivity-growth decline rates as regions' populations become more prosperous, especially in the OECD regions.

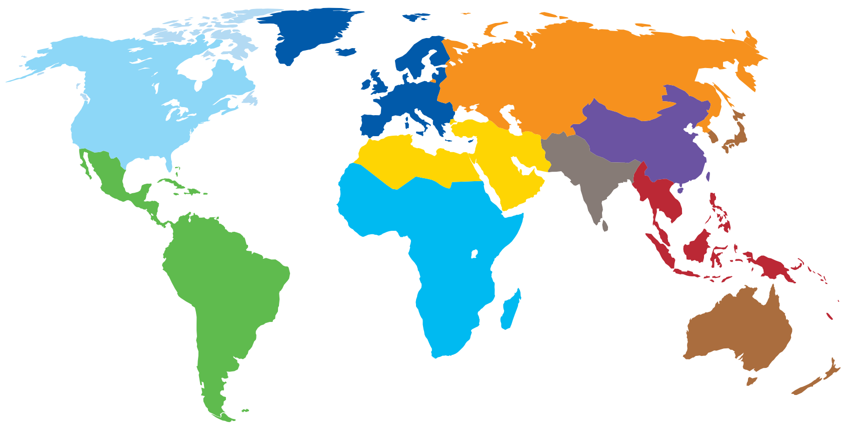
“World GDP is expected to grow from USD 134 trn/yr in 2018 to USD 269 trn/yr in 2050, measured in constant 2017 purchasing-power-adjusted USD.

GDP, ENERGY USE AND EMISSIONS ACROSS OUR 10 OUTLOOK REGIONS

2018-2050 OVERVIEW

This illustration shows, for each region considered in this Outlook, a comparison between per capita GDP, primary energy use and energy-related CO_2 emissions (2018 and forecast figures for 2050)





North East Eurasia (NEE)		Greater China (CHN)		Indian Subcontinent (IND)		South East Asia (SEA)		OECD Pacific (OPA)		World	
2018	2050	20188	2050	2018	2050	2018	2050	2018	2050	2018	2050
17 400	29 900	20 100	47 200	6 600	19 400	12 900	30 200	40 900	50 900	17 600	28 700
139	107	101	96	27	39	48	59	182	102	79	61
7.2	4.4	7.3	1.9	1.6	1.5	2.6	2.2	10.6	2.0	4.5	1.8

A.4 TECHNOLOGY AND COST LEARNING CURVES

The proliferation of new technologies, along with the continued development of existing technologies, exerts a strong influence on the energy transition. Experience shows that the costs of any technology tend to follow a pattern that can be explained by a single factor: the cost learning rate (CLR). This factor, which can be measured (after the fact), establishes a constant relationship between doubling of accumulated unit production numbers and the cost decline.

The logic behind the CLR is that a host of factors improve with experience. First, R&D becomes less important as the product matures and is fine-tuned, economies of scale then increase – both at individual manufacturing facilities and also through improving supply chains. Moreover, skill sets at all levels improve with experience – in government, management, and labour - and also as schools and universities transmit better practices to new generations of workers.

> “Cost learning tends to be self-reinforcing: cost decline both causes and is caused by the growing number of unit installations

For technologies still in their infancy, CLRs cannot easily be established with reference to that technology, and calculations rely on insights from similar technologies. Both carbon capture and storage (CCS), other than used in enhanced oil recovery (EOR), and next generation electrolysis are examples of this. Current experience is limited to lab versions and pilot plants with extremely high costs. Similar technologies are then identified and their CLR used. In contrast, solar PV, batteries, and wind turbines are well established 'newcomers' with significant grounds for establishing CLRs with more confidence. At the other end of the experience spectrum are oil and gas extraction. But with these another challenge arises: although unit production costs and accumulated production levels are high and easy to establish, CLR frequently drives costs down at the same time as resource scarcity and less-hospitable environments push costs up – the easy oil is taken first. It is virtually impossible to disentangle these two effects using costs and volumes alone, but, again, we can use datasets to estimate CLR and depletion effects separately.

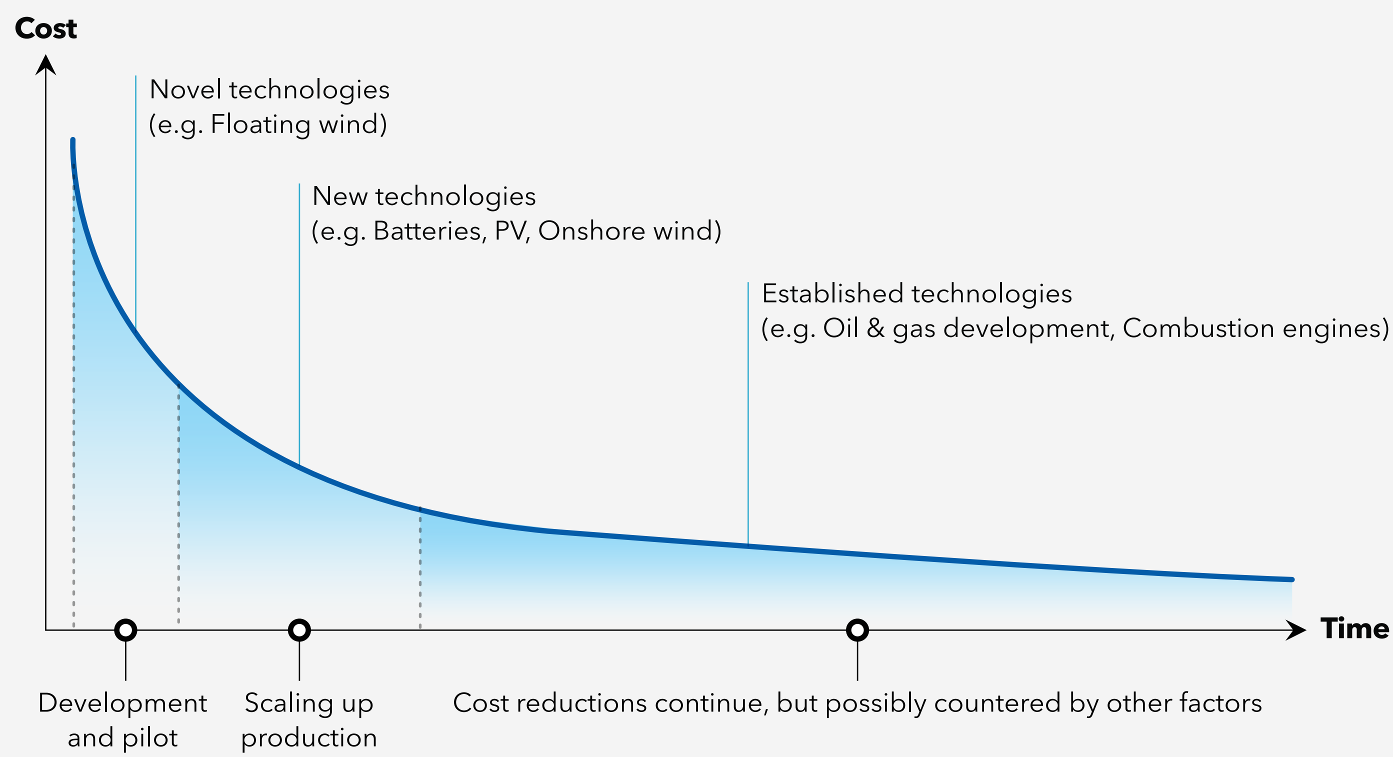
Extensive research has been conducted on which factors determine CLR, but clearly manufacturability is important. Technologies where manufacturing requires a strong manual component in development or deployment, i.e., where economies of scale are hard to establish, will receive weaker CLRs.

We are therefore less confident about our cost estimates for emerging technologies. Technologies in even earlier – gestation – stages cannot be ruled out, but we do not include them in our forecast. Examples of these include cold nuclear fusion and wave & tidal ocean energy.

In all technologies, the cost of the core technology must be separated out from supporting technologies; for example, photovoltaic panels from control systems and installation kits. The latter typically have a lower CLR. For PV, core technologies have CLR of 28%, while balance of supply (BOS) has only 9%. For some technologies, like batteries, the core technology is almost all that there is, and so the highest CLR dominates. For other technologies, like unconventional gas fracking, other cost components dominate.

Water-Go-Round hydrogen powered ferry, San Francisco. For hydrogen to take off as an energy carrier, signficant cost-learning is required across many value chains, but most critically in electrolysis powered by renewable energy. Image courtesy Golden Gate Zero Emission Marine

TECHNOLOGY COST LEARNING RATES



Cost Learning Rates (CLR)

For any given technology, costs tend to decline at a constant rate with each doubling of accumulated capacity additions. Each doubling of the installed base of a technology takes a progressively longer time, and consequently the rate at which costs will decline will also slow – as shown opposite.

Cost learning arises from:
a.) Technology improvements -
- R&D
- Innovation – e.g. around materials choices

b.) More effective production -
- 'Learning by doing' – experience from deployment
- Scale economies and broader supply chain efficiencies

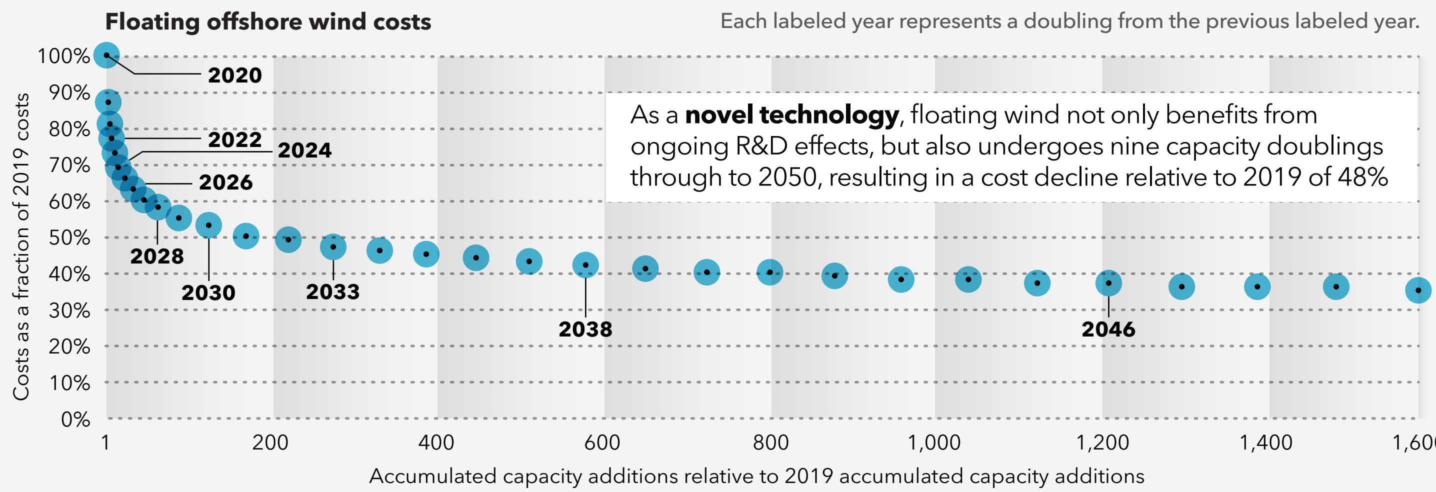
Cost learning tends to be self-reinforcing: cost decline both causes and is caused by the growing number of unit installations.

CLRs for core and supporting technologies

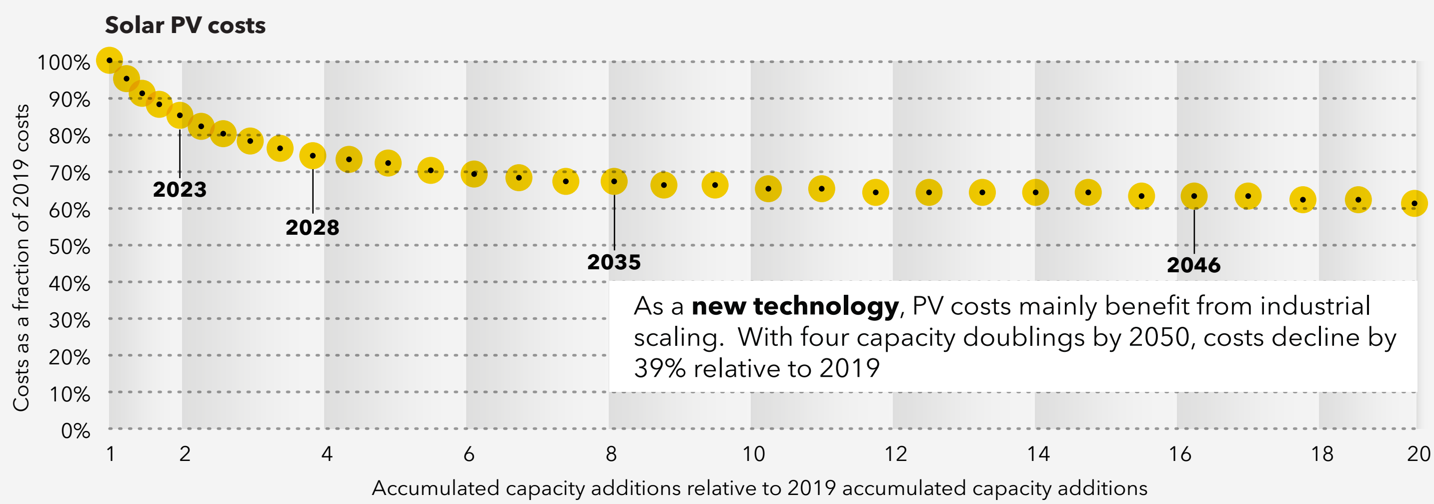
The cost learning rates (CLRs) associated with core technologies tend to be higher than supporting technologies. For example, PV panels – core technology – have a CLR of 28%, while the balance of supply (BOS) has only 9%. Thus, technologies that mainly comprise 'core' technology (e.g. batteries) tend to have higher learning rates.

Although technology costs tend to fall at constant rates relative to deployment, other costs – notably labour – do not. Thus, the operation and maintenance cost curves for wind and solar PV are around half, at best, of the technology learning rate, with installation costs falling at a lower rate still in relation to market growth.

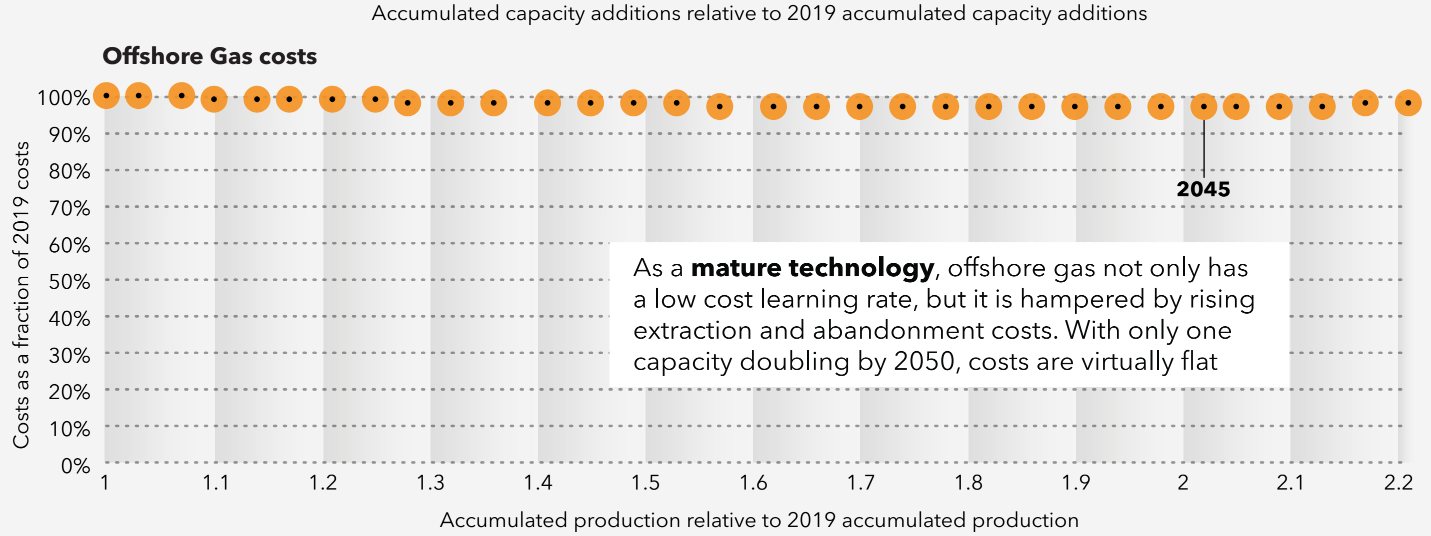
In some industries, costs rise with time – for example in extractive industries, the easy deposits tend to be accessed first.



Floating offshore wind costs
Each labeled year represents a doubling from the previous labeled year.
As a **novel technology**, floating wind not only benefits from ongoing R&D effects, but also undergoes nine capacity doublings through to 2050, resulting in a cost decline relative to 2019 of 48%
2020
2022
2024
2026
2028
2030
2033
2038
2046
Costs as a fraction of 2019 costs
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
200
400
600
800
1,000
1,200
1,400
1,600
Accumulated capacity additions relative to 2019 accumulated capacity additions



Solar PV costs
As a **new technology**, PV costs mainly benefit from industrial scaling. With four capacity doublings by 2050, costs decline by 39% relative to 2019
2023
2028
2035
2046
Costs as a fraction of 2019 costs
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
2
4
6
8
10
12
14
16
18
20
Accumulated capacity additions relative to 2019 accumulated capacity additions



Offshore Gas costs
As a **mature technology**, offshore gas not only has a low cost learning rate, but it is hampered by rising extraction and abandonment costs. With only one capacity doubling by 2050, costs are virtually flat
2045
Costs as a fraction of 2019 costs
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
Accumulated production relative to 2019 accumulated production

A.5 RESOURCE LIMITATIONS

One central feature of our Outlook concerns the rapid electrification of the world's energy system. For example, electrification of road transport will increase by between 10 to 60 times (depending on world region) as growth in fossil-fuel use stagnates and then declines. Transitions on this scale require sufficient raw materials and land area. Supply of these resources must be capable of expanding at rates that can support demand, both sustainably and cumulatively, between now and 2050. Although this will cause local challenges and price volatility in the future, the overall picture is that there will be enough materials and land to support the transition. Technologies, materials choices, and greater recycling and re-use of resources will be important for ensuring that major disruptions are avoided.

> "Supply of resources must be capable of expanding at rates that can support demand, both sustainably and cumulativly, between now and 2050

LAND AND SEA TO SUPPORT RENEWABLE GROWTH

We forecast a 21-fold increase in solar PV by 2050, with sufficient land and building area a prerequisite. In our model, solar PV is installed at utility scale, in microgrids, and on the roofs of residential or commercial buildings. The first two of these categories compete with other uses for land. Applying an estimated average 50 MW/km^2 for non-rooftop solar-PV installations indicates a requirement for 0.1% of total land area globally in 2050. Even for regions with large shares of solar PV, the land area requirement is not unmanageable; for example, 0.6% of land area in Greater China and 0.5% in the Indian Subcontinent will be needed in 2050. Co-use of land for grazing or for certain types of agriculture is possible, and therefore it seems unlikely that the expansion of solar PV will encounter space limitations overall.

We predict a 10-fold capacity rise in wind energy, and the question arises as to whether there will be sufficient land and ocean-surface areas. Onshore wind has a relatively small footprint, effectively just the base of the tower, so there will be no lack of land area. However, the siting of tall, rotating structures in densely populated areas could be a growing concern. In contrast, offshore wind is generally located far from populations and provides abundant energy in our Outlook. Our model includes fixed offshore wind and, in water deeper than 50 m, floating offshore wind.

Globally, there will be enough water and coastline to accommodate the estimated amount of offshore wind. Europe and the North Sea basin are expected to utilize fixed and floating offshore wind. Greater China will install the largest amount of offshore wind. The mean water depth of 44 m off the region's coastline and in the Yellow Sea is well suited for this purpose. We estimate that the Greater China (including Taiwan) coastal offshore areas would utilize 25% and 5% of the technical potential, respectively, for fixed and floating offshore wind in the region in 2050, which should allow for further growth.

DEMAND FOR RAW MATERIAL

We have considered the energy transition's footprint on demand for materials. For example, solar PV panels are expected to consist mainly of crystalline silicon cells (TO2030_web, 2020), where the main component is silicon, which is considered an abundant material (USGS, 2020). New, thin-film technologies, which are not yet prevalent but are showing potential, will reduce the demand for materials further. Wind turbines use common building materials, but there could be supply-chain challenges for rare earth elements, especially for neodymium used for permanent magnets in the turbines.

Growth in EVs and vehicle battery size will drive a 1400-fold increase in global battery capacity. This will spur the demand for minerals (lithium and cobalt) currently used in lithium-ion Batteries (LIBs) unless new battery chemistries are developed. The forecast growth in battery capacity is by far the largest driver of demand for lithium and cobalt used in battery cathodes and is where we expect the biggest supply challenges. There are several plans and mining initiatives to increase supply for lithium, while for cobalt the supply chain is hampered to demand surges, we therefore identify cobalt as the main raw material for further investigation.

COBALT

Cobalt is primarily used for wear-resistant and high-strength alloys and as a component in LIBs. Batteries account for about half the demand for cobalt, which are used in portable electronics, EVs, energy-storage systems, medical equipment, and increasingly in military and space applications.

Of cobalt extracted today, around 70% comes from the Democratic Republic of Congo (DRC), with Australia and Russia in second place, each providing about 4%, and the remainder coming from about 10 other countries. Most of this cobalt is a by-product of copper and nickel mining, except for artisanal mining in DRC and 1.5% directly mined in Morocco; thus, the demand for nickel and copper affects cobalt supply. Two of the largest mining stakes in DRC derive only approximately 30% of their revenues from cobalt (MDO, 2020). As most mined cobalt goes to China for refining, just two countries control much of the cobalt supply chain, thus increasing the risks of bottlenecks and price volatility. Focus on environmental and social conditions will further challenge this supply chain and the use of cobalt. In 2018, 15% was used in EVs and storage (BNEF EVO, 202), while the last two years (2018/2019) annual mining volumes are 0.14 Mt compared to the identified terrestrial resources of 25 Mt and another 120 Mt in manganese nodules and crusts on the ocean floor (USGS, 2020).

The nickel-manganese-cobalt (NMC) battery in Nissan, Audi e-tron, and Chevy Bolt vehicles is the most common LIB type. Tesla uses a nickel-cobalt-aluminium (NCA) battery. Battery manufacturers are seeking to reduce cobalt use. Originally equal proportions (one-third) of nickel, manganese, and cobalt were used in the NMC111 battery, but the updated NMC532 or NMC622 versions have only 20% cobalt, and there are high hopes that the NMC811 will contain only 10% cobalt, although its production is not yet confirmed.

> Growth in EVs and vehicle battery size will drive a 1400-fold increase in global battery capacity and spur the demand for metals, mainly lithium and cobalt

Commercial vehicles sometimes use the more expensive lithium-titanite oxide (LTO) battery and the cheaper lithium-ferrous phosphate (LFP) chemistry, neither of which contains cobalt. The world’s top EV manufacturer, BYD, focuses solely on LFP; 95% of commercial vehicles in China, and many of those exported, use LFP chemistry (Campbell, 2019).

The various battery chemistries have different advantages and disadvantages regarding optimization of energy density, cost per kWh, number of charge cycles, degradation, and safety against thermal runaway causing fires.

Market conditions and availability influence vehicle manufacturers' decisions on battery choice in each EV segment. We looked at historic and currently produced EVs to develop a forecast for the type, size, and total capacity of EV storage in each segment. Recent sales figures for EVs, where available, combined with estimates in emerging markets, provided an understanding of the most common vehicles and battery chemistries per region. Scientific literature provided an estimate of the amount of cobalt in each chemistry. Many segments and regions use little cobalt due to widespread use of LFP.

> "In our view, the energy transition will not be significantly constrained globally by the availability of either raw materials or land/sea area

Among the most common battery chemistries – NCA, NMC, and LFP – the first two contain 0.14 kg to 0.38 kg per kWh of battery pack (Olivetti et al., 2017). Factoring in a transition towards chemistries using less cobalt, we assumed a future battery chemistry to use half the estimated 0.09 kg/kWh for NMC811 and will be introduced increasingly towards 2030. We foresee only very-low-cobalt and cobalt-free chemistries existing beyond 2030. Based on our EV-growth forecasts, we estimate the global demand for cobalt to be 350 kt/yr in 2030. Current annual extraction needs to increase 2.5 times to support this demand; 58% of this demand is for passenger vehicles, 37% for commercial vehicles, and 5% for two- and three-wheelers.

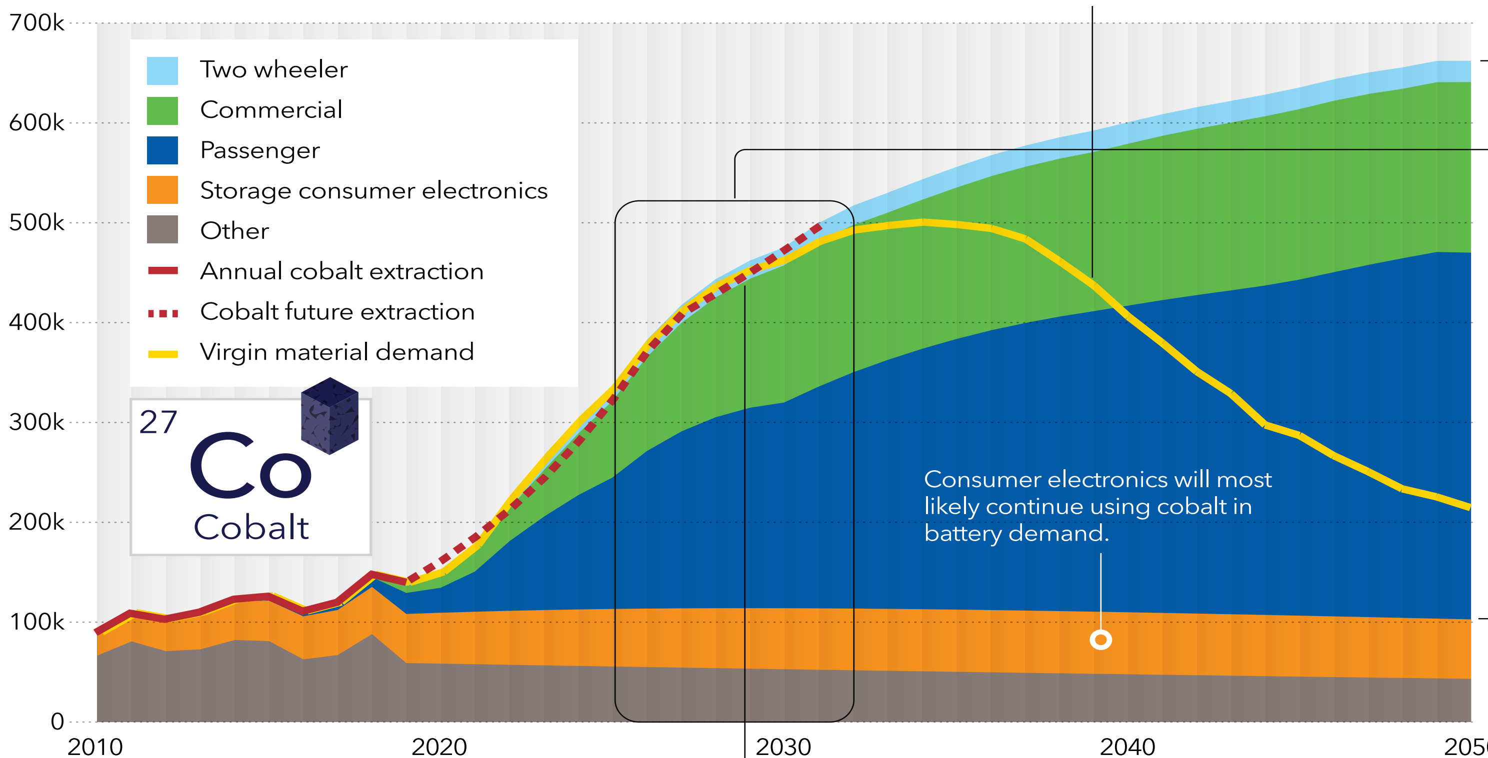
The structural integrity of cobalt does not degrade through use or in recycling. Very little recycled cobalt comes from EV batteries today, but growing EV sales will eventually result in a significant number being scrapped and available for recycling. Increasing demand and higher prices suggest the potential for recycling rates of more than 90% (NAR, 2019; Recycling International, 2019). By introducing recycling as a supply source, we find the annual demand for virgin cobalt peaking in the mid-2030s at 2.7 times today's extraction rate. If mining can increase output at a CAGR of initially 15% to 2025 and then taper to 5% through to 2030, cobalt supply seems to match demand, although the fragile supply chain makes it unclear if such growth is sustainable. Disregarding other sources of demand growth from portable electronics, aerospace, and energy storage then annual demand from EVs for virgin cobalt peaks at 385 kt in 2035 and supply from recycling takes over, reducing demand for mined cobalt. In 2050, most cobalt demand will be met from recycled material.

Rapid advances have been made in research into new chemistries promising zero- or much-less cobalt use in batteries (Reuters, 2020). Recent research even questions whether cobalt brings "little or no value at all to NCA-type materials with high nickel content" (Hongyang et al, 2019). One sign that rapid changes in battery chemistries are already affecting demand is that cobalt prices have dropped a third from record levels in 2018 (LME, 2020). Future developments in battery chemistries will determine the criticality of cobalt, but it already appears that sustaining its supply will be manageable, albeit not without challenges.

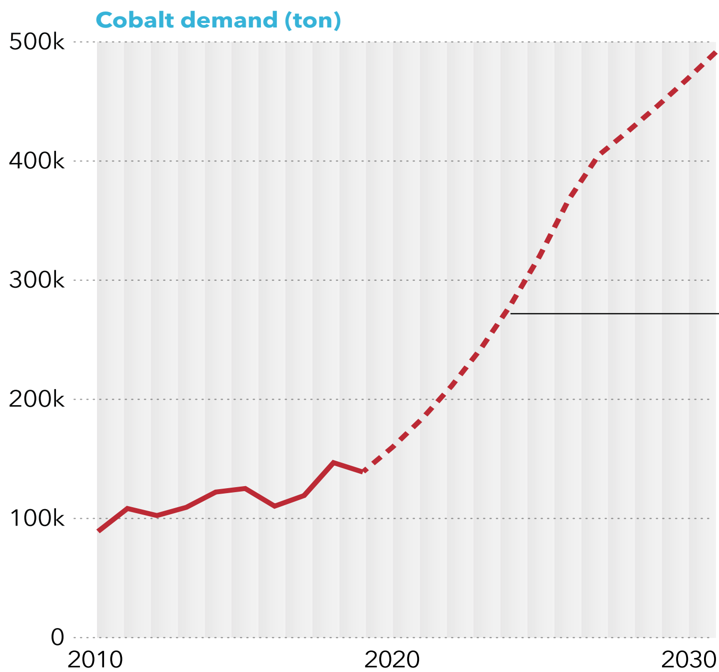
In our view, the energy transition will not be significantly constrained globally by the availability of either raw materials or land/sea area. Narrowing the perspective, some regions may struggle to find raw materials and land/sea area will be in short supply, while others will enjoy an abundance. Historically, such imbalances would be solved by global collaboration and trade. However, it remains to be seen whether multilateralism will advance or stall in the 'next normal' after the present pandemic.

Northvolt Ett lithium-ion battery gigafactory, Skellefteå, Sweden – August 2020. Currently under construction, the gigafactory is scheduled for start of production in 2021, with a potential annual output of 40 GWh. Image, courtesy Northvolt

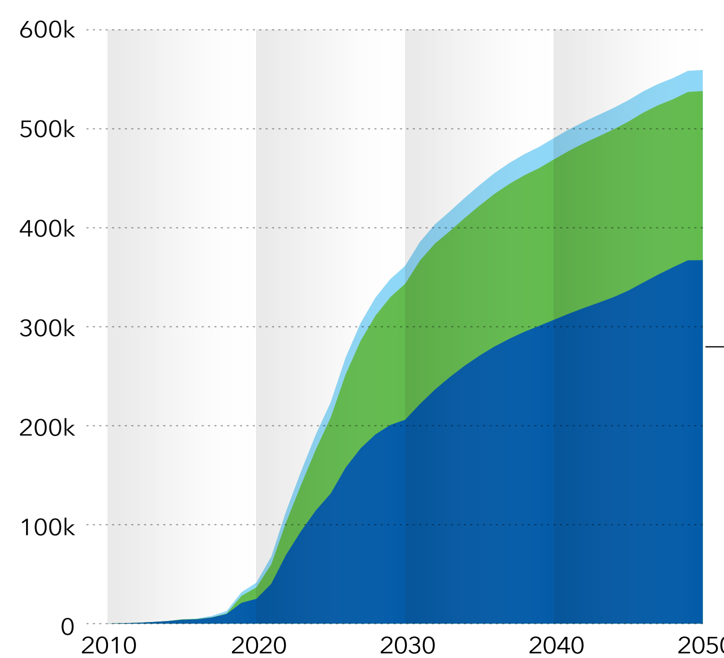
COBOLT SUPPLY AND USE



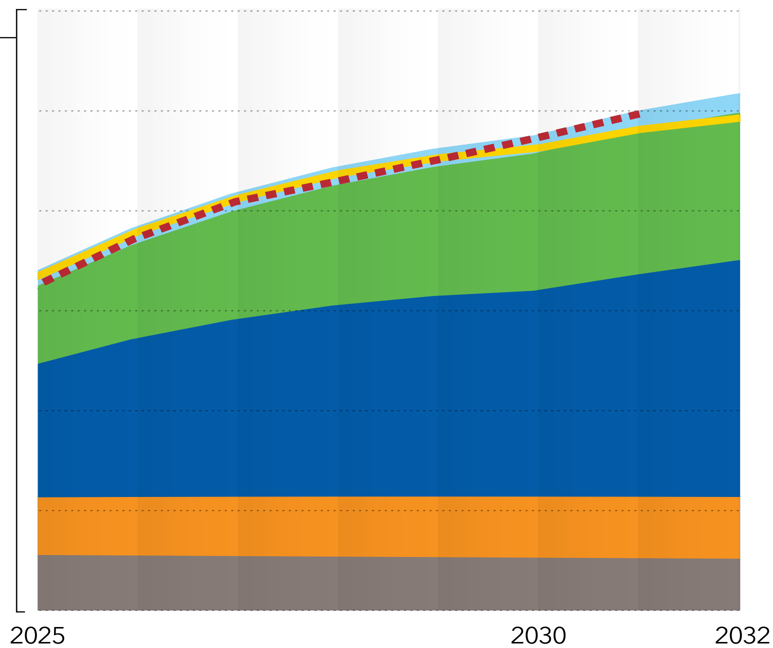
Annual extraction of cobalt is currently at 140kton per year. Using an estimated ramp-up of initially 15% CAGR per year to 2025 declining to 5% by 2030 would make it possible to supply enough cobalt.



Demand for cobalt will be driven by passenger vehicles followed by commercial vehicles. The size of the batteries combined with chemistries drives demand.

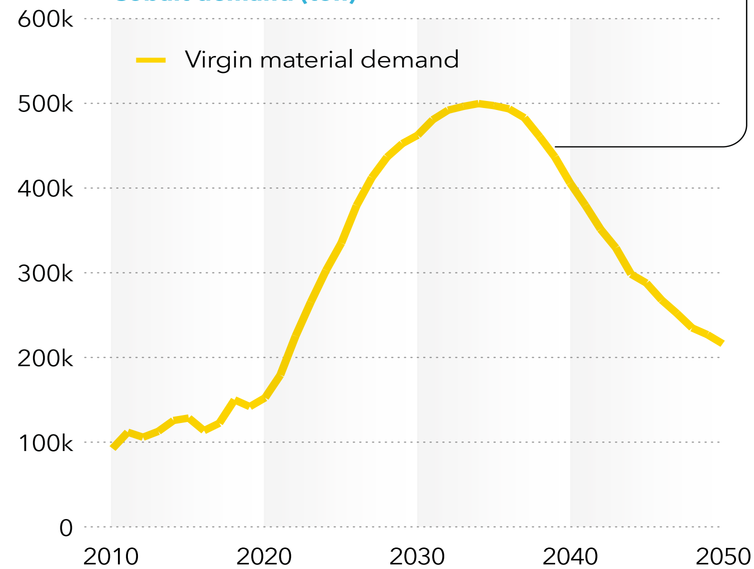


It is possible that a **supply squeeze** emerges in the late 2020s, dependent on ramp-up in production, EV demand and new battery chemistries.



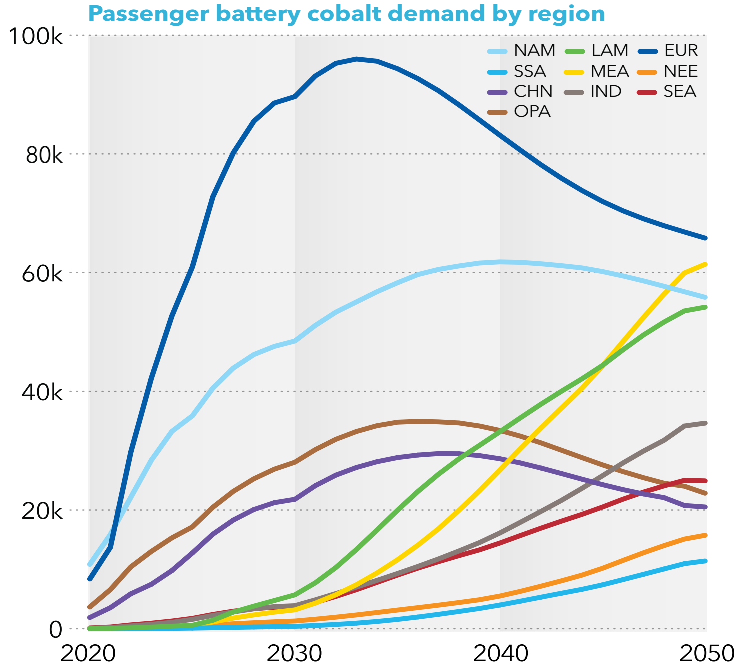
Virgin raw material demand is an estimate of the actual demand combined with recycled cobalt becoming available. Lifetimes of EV batteries combined with limited volumes of scrapped batteries makes recycling volumes impact virgin demand from 2030.

Cobalt demand (ton)



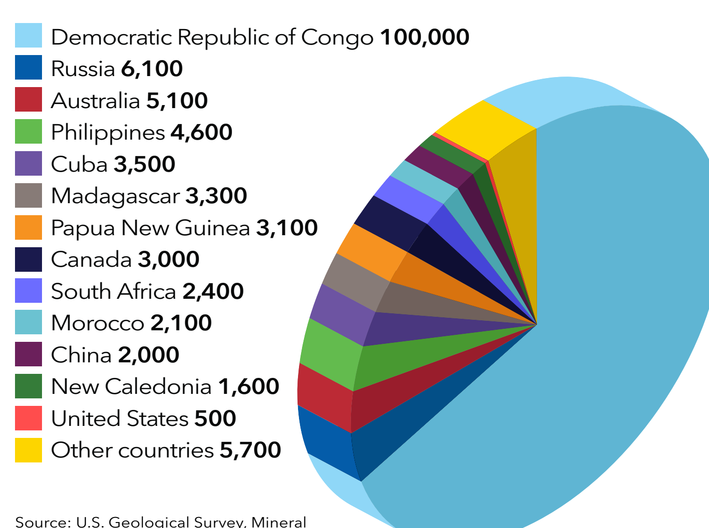
Cobalt demand is primarily driven by Europe(EUR) followed by North America (NAM). Both these regions have EVs based on cobalt intensive chemistries. These will be improved over time and cobalt demand will start to decline.

Passenger battery cobalt demand by region



World mine production: 70% of cobalt extracted today comes from the DRC. Up to one fifth of that comes from artisanal mines, many of which use child labour. Most cobalt is a by-product of copper and nickel mining. Of the identified production, 73% comes from Sub-Saharan Africa, 11% OECD Pacific, 6% Latin America, 5% North America, and 5% other.

Metric tons production 2019e



Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2020

A.6 MODEL DESCRIPTION

The basis for our forecast is our Energy Transition Outlook Model (ETOM) – an integrated system-dynamics simulation model that reflects relationships between demand and supply in several interconnected modules.

Each sector of the energy system (see figure A.6) is modelled by modules representing:

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

These modules exchange information regarding demand, cost, trade volumes, and other parameters to provide a coherent forecast.

MODELLING PROCESS

The equations and parameters in the ETOM are based on academic papers, external databases, commercial reports, and expert judgement from both within and outside DNV GL. Examples of external databases used include IEA World Energy Balances, IRENA Capacity & Generation Database, Platts World Electric Power Plants Database, GlobalData Power and O&G Databases, Rystad Upstream Database, UN Comtrade Database, and Clarksons 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, as quality assurers of model sectors and interrelationships, and as expert assessors of end results.

TIMESCALE

This ETOM covers the period 1980–2050. Historical simulation outputs have been used to test the model's ability to replicate historical developments, and hence validate our forecast.

The ETOM is a continuous-time model, with years as the base time unit: it is designed to reflect dynamics that are happening only at the yearly scale or longer. Shorter-scale dynamics, such as within-year seasonality of oil demand, are implied in annual parameters and are not directly reflected in the model. An exception is the power-market module, which balances supply and demand at an hourly resolution.

With the ETOM deliberately ignoring short-term fluctuations occurring over months or even a few years, the Outlook has less reliability over shorter time periods. For example, although the average growth rate of gas demand over 10-year intervals can be compared with confidence, analysing the rate for a particular year in isolation would not necessarily yield meaningful insights. We depart from this approach to incorporate the expected short-term, as well as long-term, impact from the COVID-19 pandemic on social behaviour, economic activity, and energy consumption.

Hoover Dam.
Arizona/ Nevada

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. For example, the investment cost of a particular power-station type 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.

> “Our model captures three key characteristics of the world energy system: interconnectedness, inertia, and non-linearity

MODELLING PRINCIPLES

Our main priorities when designing the ETOM were to include three key characteristics of the world energy system: interconnectedness, inertia, and non-linearity. The whole energy supply chain, from demand to supply, is one huge interconnected system. 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 one factor does not always have the same effect on another variable. Our model reflects these key characteristics.

Whereas many energy models are econometric and assume equilibrium conditions, the ETOM is not. Instead, it simply simulates the consequences of its assumed goals, parameters, and interrelationships. The ETOM explicitly reflects the delays in reaching a desired state and, consequently, is 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 situation, decision making can be predicted (Thaler, 2015). However, the decisions themselves are not necessarily rational, in the utility-maximizing sense of the term. For example, we reflect the fact that more emphasis is placed on the initial purchase price of a vehicle by private buyers than by commercial purchasers. Thus, private buyers may choose a technology that has a lower upfront cost, although it may be more expensive from the perspective of total cost of ownership.

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. However, there are, of course, multiple sources of uncertainty in the outputs, and the ETOM cannot provide confidence levels for these. In order to address this to some extent, sensitivity tests have been run to help us understand how the model results change when selected input parameters are adjusted. Furthermore, some assumptions that we make may be controversial, or differ from those presented in other forecasts. In such cases, we discuss the associated sensitivities.

Our aim is to present a transparent model, not a black box. This is because we believe that this makes it easier to discuss the results. Furthermore, if it is of interest to test the consequences of an alternative assumption or to try a different value, perhaps due to disagreement with a value chosen, then that is easily accomplished. Although the exact calculations emerge from a complex model and are therefore not amenable to simple checking with a pocket calculator, we are clear about the parameters that have been used and how they are related. Detailed documentation of the model is provided elsewhere (DNV GL, 2020d).

CONTINUOUS IMPROVEMENT

The structure and input data of the ETOM are continually updated in order to:

- provide a more complete and accurate representation of the world energy system;
- generate new outputs relevant to our stakeholders;
- reflect recent changes in the energy sector.

The most significant changes to the ETOM since our 2019 Outlook are:

- the inclusion of a separate iron and steel sub-sector in manufacturing, splitting floating and bottom-fixed offshore wind power,
- recalibration of energy demand for end uses in buildings, reflecting the impact of breakeven prices on regional oil and gas production,
- improvements in electric vehicle (EV)-uptake logic,
- updating fuel efficiency of passenger and commercial vehicles regarding real-world consumptions and vehicle-size trends,
- updating the inputs related to hydrogen production resulting in an expansion of hydrogen use in buildings and roads in all ten regions, and
- revision of feedstock sub-sector parameters, particularly on plastics.

ENERGY DEMAND

We use policy and behavioural effects, either explicitly, as in the effect of increased recycling on plastics demand, or 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 energy services provided, such as passenger-kilometres of transport, tonnes of manufacturing, or 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.

We use non-linear econometric models to estimate regional demand for energy services. Population and GDP per capita are the main drivers, but we also incorporate other technological, economic, social, and natural drivers, as necessary.

In road transport, the number of vehicles required rises as regional GDP increases. This is a non-linear effect that reaches saturation at different levels for each region. Vehicle demand is also affected by driving distance and vehicle lifetime, both of which are influenced by the uptake of autonomous and shared vehicles. The link between maritime trade and production/consumption balance of energy and non-energy commodities is explicitly modelled. For non-cargo vessels, air travel and rail passengers, and freight demand, GDP is used as the driving factor.

In the buildings sector, we estimate the energy required for residential and commercial buildings for five end uses. Together with insulation and climate, the floor area of buildings is the major determinant for regional space-heating and cooling demand. Hot-water demand is linked to standard of living and population. For cooking, we use the useful heat delivered as the energy service, and estimate it by household size and population. GDP from the tertiary sector, which increases with GDP per capita, is a major factor for commercial buildings, driving both the floor area and the demand for various energy services.

The energy service we use for manufacturing is the output in tonnes, estimated separately for base materials, manufactured goods, and iron and steel. The demand for manufactured goods in each of our world regions is driven by GDP. The regional split of production is estimated by each region's GDP share from the secondary sector.

This is converted to manufacturing output using historical trends. Demand for base materials is derived from the production of manufactured goods. Demand for iron and steel is linked to building construction, vehicle production, shipbuilding, and economic activity. In terms of energy services, we distinguish between process and non-process heating, machines and appliances, iron ore reduction, and on-site vehicles.

The choice of energy carrier is based on levelized costs in manufacturing and EV uptake. For the energy mix of other end uses and for energy efficiency, our forecasts 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.

ENERGY CARRIERS

Among the 10 energy carriers that we model, seven are also primary energy sources; i.e., they can be used without any conversion or transformation process. The others are secondary forms of energy obtained from primary sources. Primary energy sources are coal (including peat and derived fuels), oil, natural gas (including ethane, propane, and butane), geothermal, biomass (including wood, charcoal, waste, biogases, and biofuels), solar thermal (thermal energy from solar water heaters), and off-grid PV (electricity from solar panels not connected to the grid). Secondary energy sources are electricity, direct heat (thermal energy produced by power stations), and hydrogen.

ENERGY TRANSFORMATIONS

We place special emphasis on electricity generation. We have calculated the regional equilibrium price, supply, and demand for 12 power-station types, four storage technologies, 12 load segments, and power-to-hydrogen conversion for hourly intervals over the whole year. Hourly profiles for load segments and variable renewable generation are deterministic but vary over years. Certain load segments, and all but variable renewable generation and storage technologies, respond to price. For power station and storage investments, we employ a profitability-based algorithm. Our estimate of the required additional generation 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 expected received price and the levelized cost of electricity. We explicitly estimate the effect of renewable support, carbon price, and the cost of CCS. The investment for storage is driven by expected received price and levelized cost of storage, both of which are informed from the hourly power-market module. The role of direct heat is a diminishing one. Consequently, we use a simple extrapolation to estimate regional mixes of direct heat supply.

BEYOND 2050

Our Outlook and model forecasts stop at 2050. Looking 30 years into the future involves large uncertainties that increase as horizons extend.

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, as yet, understand.

Consequently, this Outlook does not include any forecast or quantification of what may happen beyond 2050. The only exception to this is our assessment of climate implications, where we give an indication of the global temperature increase in 2100 on the assumption that the energy transition unfolds to 2050 as we have forecast.

Hydrogen is supplied either by electrolysis or from fossil fuels, through steam methane reforming (SMR). Annual operating hours and expected electricity price for electrolysis are calculated dynamically in the hourly power-market module. The profitability of electrolysis versus the cost of SMR determines the investments in electrolysis capacity. In our ETOM, we only model hydrogen that is tradeable as an energy carrier.

FOSSIL-FUEL EXTRACTION

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 use a cost-based approach to determine regional production dynamics. On the oil-supply side, we model production capacity as a cost-driven global competition between regions and in three field types: offshore, onshore conventional, 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 that of crude oil. First, we estimate the fraction of gas demand to be supplied from the region's own sources. This varies between regions due to economic, geographical, 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 and gas liquefaction / LNG regasification capacities are also part of the ETOM.

Coal production is modelled by differentiating 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 that most regions are self-sufficient.

TRADE

Trade, especially seaborne trade, of energy carriers, is a vital component of the ETOM. For crude oil, the gap between a region's production and refinery input determines the surplus for export or the 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. Coal from exporting regions is imported by those regions with domestic shortfalls. Our manufacturing sector provides a baseline for non-energy commodity trade of raw materials and manufactured goods.

DATA AVAILABILITY

All the forecast data behind each of the charts in this Outlook are available for downloading from DNV GL's industry platform, Veracity.com. For details on how to access this material, visit eto.dnvgl.com.

eto.dnvgl.com/forecast-data

ENERGY TRANSITION OUTLOOK MODEL

Figure A.6 below presents the framework of our model. The arrows in the diagram show information flows, starting with population and GDP per person, while physical flows are in the opposite direction. Policy influences all aspects of the energy system. Improvements in energy efficiency in extraction, conversion, and end use are cornerstones of the transition. A subset of the feedback loops in our model is shown opposite (Figure A.7) for the road transport and power sectors. Two of the cross-sector feedbacks are highlighted. Note that the figure is simplified. Similar feedback processes occur in other parts of our model.

FIGURE A.6

ETO model framework

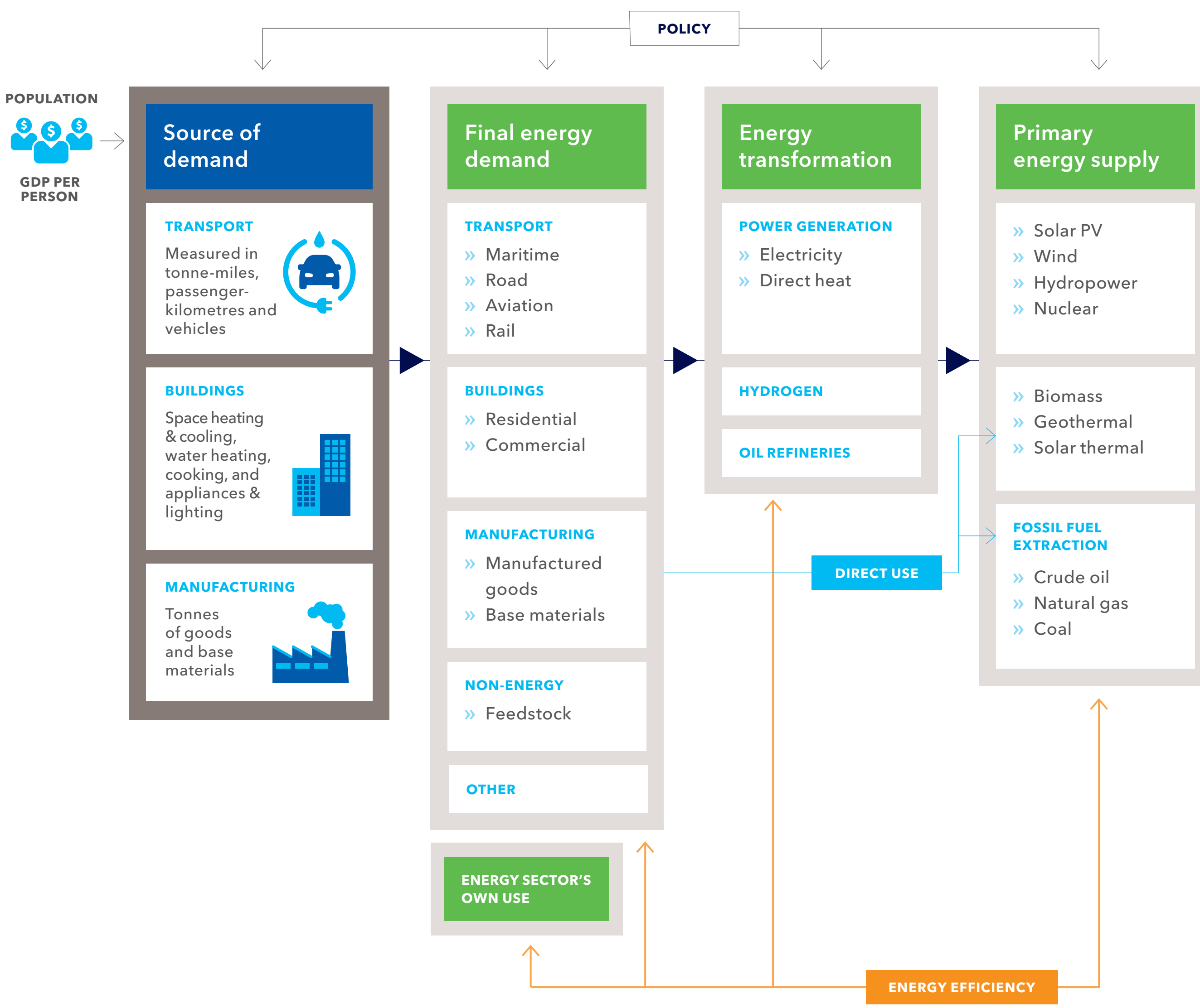
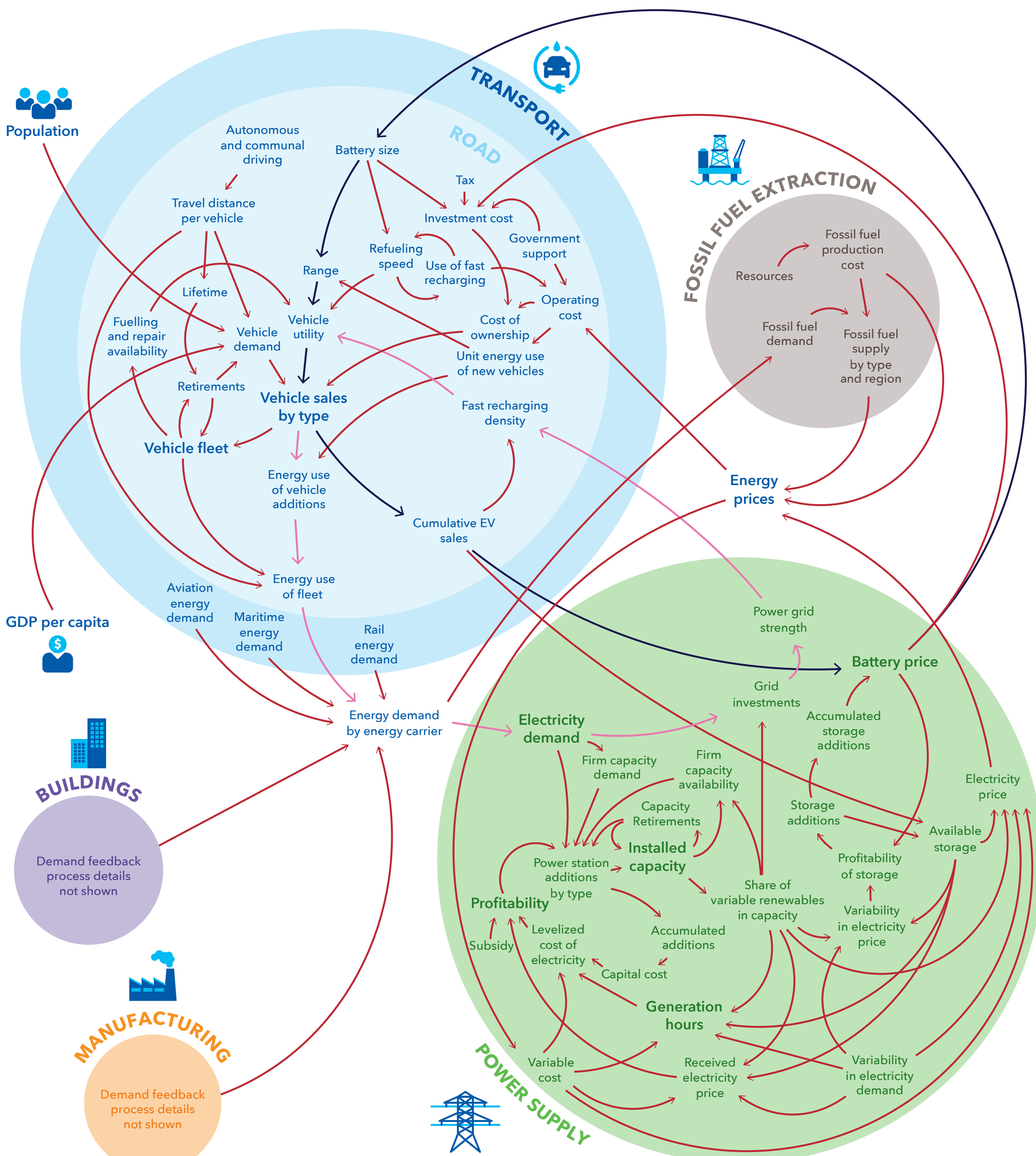


FIGURE A.7

Selected and simplified feedback loops in the power-supply and road-transport sectors



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HISTORICAL DATA

This work is partly based on the World Energy Balances database developed by the International Energy Agency © OECD/IEA 2019, but the resulting work has been prepared by DNV GL and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2017) numerical data is mainly based on IEA data from World Energy Balances © OECD/ IEA 2019, 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. The core model development and research have been conducted by a dedicated team in our Energy Transition research programme, part of the Group Technology and Research unit, based in Oslo, Norway. In addition, we have been greatly assisted by the external Energy Transition Outlook Collaboration Network, with some 30 experts listed in the opening pages of this report.

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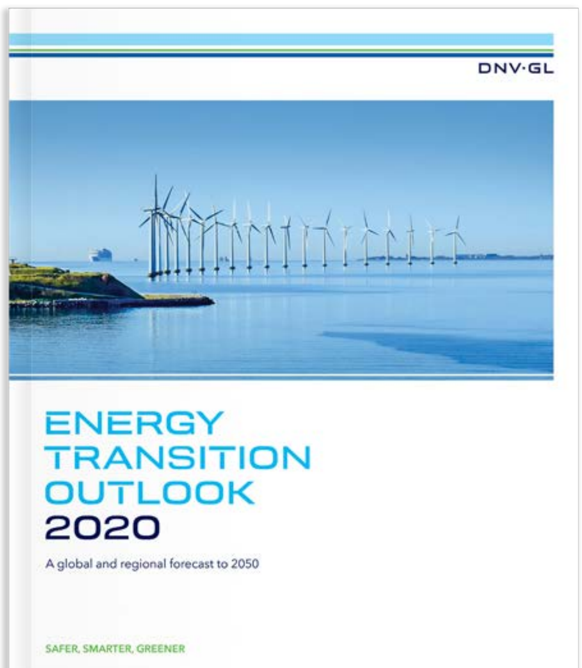
ENERGY TRANSITION OUTLOOK 2020 REPORTS OVERVIEW

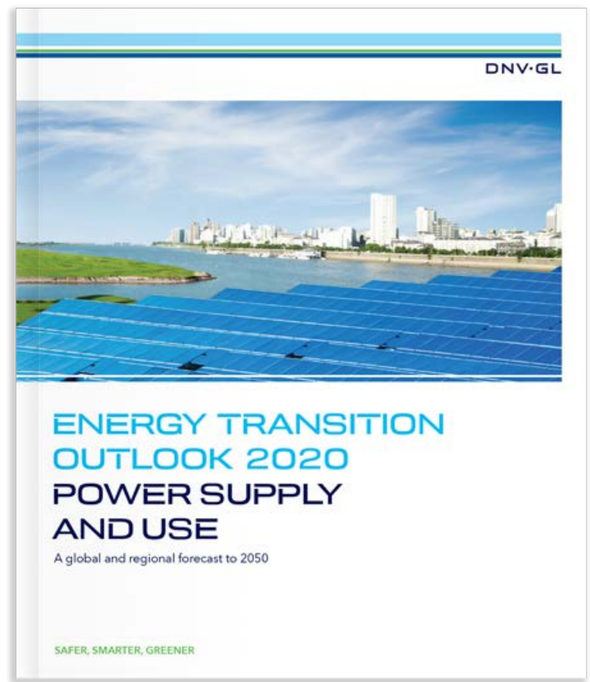


ENERGY TRANSITION OUTLOOK

Our main publication details our model-based forecast of the world's energy system through to 2050. It gives our independent view of what we consider to be the most likely trajectory of the coming energy transition, and covers:

- The global energy demand for transport, buildings, and manufacturing
- The changing energy supply mix, energy efficiency, and expenditures
- Detailed energy outlooks for 10 world regions
- The climate implications of our forecast, and solutions for closing the gap to well below 2°C.

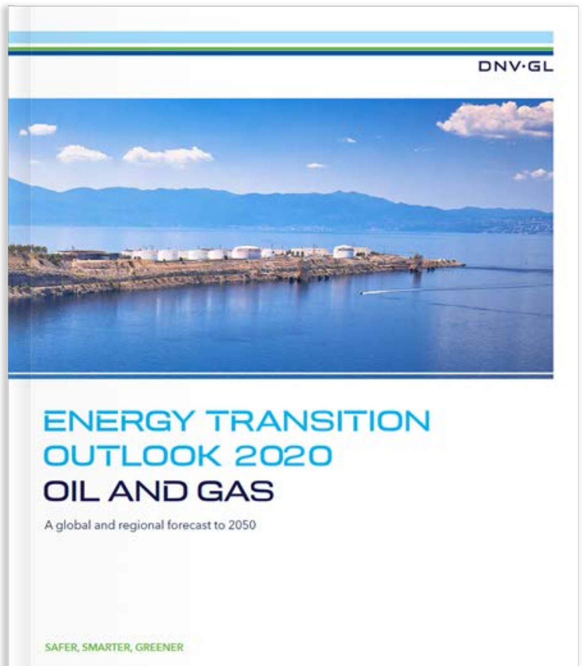
We also provide background details on the workings of our model and on our main assumptions (including population, GDP, technology costs and government policy). Our 2020 Outlook also details the impact of COVID-19 on the energy transition.

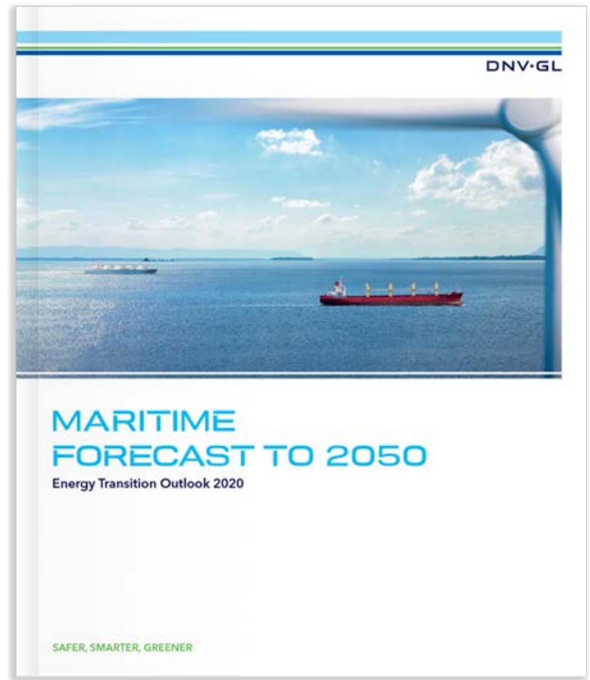


POWER SUPPLY AND USE

This report presents the implications of our energy forecast to 2050 for key stakeholders involved in electricity generation, electricity transmission and distribution, and energy use. Electricity use is increasing rapidly, and production becoming dominated by renewables; our report details the important industry implications of this evolution, including:

- Substantial opportunities for those parties involved in solar and wind generation
- Massive expansion, reinforcement and upgrading of transmission and distribution networks
- Further need for implementation of energy-efficiency measures
- Acceleration of the EV revolution
- Digitalization enabling process improvements and smarter operations
- The energy transition is fast, but not fast enough to meet the goals of the Paris Agreement.





OIL AND GAS

This report provides the demand, supply, and investment forecast for hydrocarbons to 2050, with a commentary on key trends:

- The world is moving from more oil to cheapest oil, as demand declines
- LNG is set to thrive in a strong gas market
- We forecast multiple energy transitions: from coal and oil to natural gas, and from fossil fuels to renewables and decarbonized gas. Further, we focus on decarbonizing the oil and gas industry:
- Pressure is mounting as emissions are set to remain stubbornly high until mid-2030s
- Decarbonization is on the agenda of industry and government, but not at the pace or depth to meet the Paris Agreement
- Hydrogen and CCS have the potential to transform the industry.

MARITIME

This year's Maritime Forecast aims to enhance the decision-making of shipowners as they navigate the technological, regulatory and market uncertainties surrounding decarbonization:

- A library of 30 scenarios has been developed that projects future fleet composition, energy use, fuel mix, and CO_2 emissions to 2050. Each of our scenarios belongs to one of three distinct decarbonization pathways.
- We model 16 different fuel types and 10 fuel technology systems. We analyse how particular fuel-technology alternatives perform commercially in a new Panamax bulk carrier as a case study.

Managing decarbonization risks is critical to protect the future value, profitability, and competitiveness of a vessel. Picking the wrong fuel solution today can lead to a significant competitive disadvantage.

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