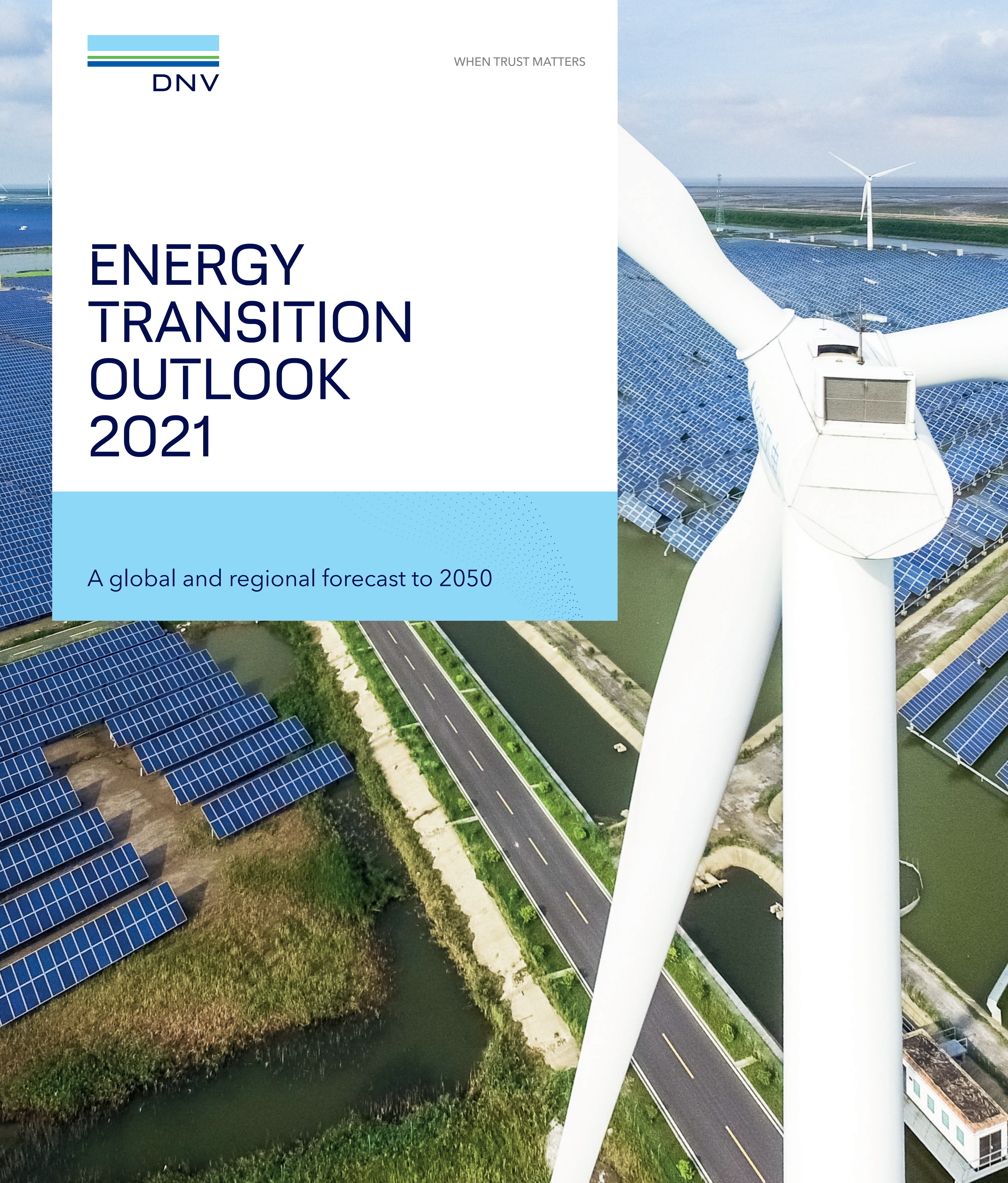
WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2021

A global and regional forecast to 2050



FOREWORD

This is the fifth annual Energy Transition Outlook issued by DNV. For half a decade, we have said, consistently, that the most likely future for the world's energy system is one that will result in global warming exceeding 2°C by 2100, and that is our conclusion once again this year.

The impact of global warming is becoming alarmingly apparent, and I believe there is a widening understanding of the long-term risks for humanity. However, while perceptions may have changed, reality has not.
Each year, in the foreword to this Outlook, I have stressed the need for governments and companies to take decisive action on climate change. COVID-19 has more than demonstrated that governments can act boldly. Yet, from an energy transition perspective, the pandemic has been a lost opportunity. Recovery packages have largely focused on protecting rather than transforming existing industries. There are exceptions to this, and our forecast incorporates slightly more clean energy in the mix over the next three decades than we did a year ago.

But large-scale action is still needed urgently, and our forecast provides clear guidelines on where such efforts should be directed. Wind and solar PV will expand 15- and 20-fold respectively in our forecast period. Twinned with the plunging costs and advancing technology of battery storage, variable renewables are already enabling a phase out of thermal power generation and the business case will become overwhelming by 2030.

Electricity demand will more than double by 2050 and by then over 80% of power will be provided by non-fossil sources. The accompanying efficiencies are staggering, both in the avoidance of heat losses in power generation and in end use – for example, with EVs and heat pumps. But the problem is this: even if all electricity was 'green' from this day forward, humanity would still fail to achieve net zero emissions by 2050.

Not everything can be electrified. That is what makes tackling the hard-to-abate sectors of high heat, aviation, shipping and trucking so very urgent. Yet our forecast shows that hydrogen enters the picture at scale only in the late 2030s. That is far too late: climate science points to the considerable risks of allowing emissions to accumulate before we act.

The verdict is clear: the world needs vastly more green electricity, both direct and indirect, more biofuel, and more carbon capture and storage on a dramatically accelerated timescale.

In October this year we will publish our first *Pathway to net zero emissions* report – a detailed look at how best to close the gap between this forecast and one that is aligned with the Paris Agreement. It is vital that we mobilize all the forces of the Fourth Industrial Revolution towards a green energy transformation, including innovative ways to finance this shift. This year we address that critical subject in our supplementary report – *Financing the Energy Transition*.

Remi Eriksen

Group president and CEO

DNV

Highlights

CORE INSIGHTS

1. **We are not meeting Paris ambitions; there is a very short window to close the gap**
   - Global energy-related emissions will fall only 9% by 2030, and the 1.5˚C carbon budget is emptied by then
   - We estimate the global average temperature increase to reach 2.3˚C by end of the century

2. **Electrification is surging ahead, and renewables will outcompete all other energy sources**
   - Electrification of final energy demand will grow from 19% to a 38% share by 2050, powered mainly by solar and wind
   - 50% of all passenger-vehicle sales will be EVs in 2032
   - Heat pump use will triple, providing 32% of heat in 2050 while consuming 9% of energy use for heating

3. **Efficiency gains lead to a flattening of energy demand from the 2030s**
   - Energy efficiency remains our greatest untapped resource against climate change
   - Energy intensity (unit of energy per dollar of GDP) improvements at 2.4%/yr outpace GDP growth during the coming three decades
   - Efficiency gains are driven mainly by electrification

4. **Fossil fuels are gradually losing position, but retain a 50% share in 2050**
   - Gas maintains its current position, oil demand halves, and coal falls to a third of current use by 2050
   - CCS deployment is too slow, and only 3.6% of fossil CO_2 emissions are abated in 2050

NEW INSIGHTS 2021

1. **COVID-19 economic recovery spending is a lost opportunity**
   - Apart from the EU, COVID-19 stimulus packages are largely locking in carbon-intensive systems

2. **Variability and low power prices are not roadblocks to a renewable-based power system**
   - Power-to-X, storage, connectivity, demand response, and carbon pricing will all help solar PV and wind maintain their competitiveness
   - Solar + storage is emerging as a new power plant category which will provide 12% of all grid-connected electricity by 2050

3. **Decarbonizing hard-to-abate sectors requires far greater scaling of hydrogen, e-fuels, and biofuels**
   - Combined, hydrogen and e-fuels will cover only 5% of global energy demand by 2050
   - Aviation, maritime, and heavy industry increase their relative share of emissions and remain heavy users of unabated fossil fuels

4. **Most hydrogen will be produced from dedicated renewables-based electrolysers by 2050**
   - Green hydrogen will dominate over time, with 18% of hydrogen supply produced via electrolysis from cheap grid electricity and 43% from electrolysis using dedicated off-grid renewables
   - Blue hydrogen will lose its cost advantage, providing only 19% of hydrogen supply for energy purposes by 2050

Highlights – Core insights

We are not meeting Paris ambitions; there is a short window of opportunity to close the gap
Global emissions likely peaked in 2019, followed by an unprecedented 6% drop in 2020 due to COVID-19. Emissions are now rising sharply again and will grow for the next three years before starting to decline.

While they are being added at great speed, renewables currently often supplement rather than fully replace thermal power generation. By 2030, global energy-related CO_2 emissions are likely to be only 9% lower than 2019 emissions, and by 2050 only 45% lower. This is in sharp contrast to ambitions to halve GHG emissions by 2030 and to achieve the net zero emissions by 2050 required to limit global warming to 1.5˚C. Our forecast is that we are most likely headed towards global warming of 2.3˚C by 2100.

As CO_2 emissions continue to accumulate, the window of opportunity to act narrows every year. Relying on large-scale net-negative emissions technologies and carbon removal in the latter half of the century is a dangerous, high-risk approach. With global warming, every fraction of a degree is important, and all options to reduce emissions need urgent realization.

Electrification is surging ahead, and renewables will outcompete all other power sources
Electrification is by far the most dynamic element of the energy transition. The share of electricity in final global energy demand is set to double from 19% to 38% within the next 30 years.

Solar PV and wind are already the cheapest form of new power almost everywhere, and within a decade will also be cheaper than operating existing thermal power in most places. By 2050, solar and wind will represent 69% of grid-connected power generation, and fossil power just 13%. Connectivity, storage and demand-response will be critical assets in the decarbonized power system.

On the demand side, passenger and commercial EV uptake is rising quickly in Europe, China and to some extent the US. Government incentives, cost reductions and technology improvements in both batteries and charging infrastructure will drive a rapid expansion. By 2032, half of all new passenger vehicles sold globally will be electric, with some regions lagging owing to infrastructure challenges. In buildings, heat pumps use will triple, providing 42% of space heat in 2050 while consuming only 15% of energy used for space heating.

FIGURE 1

World energy-related CO_2 emissions

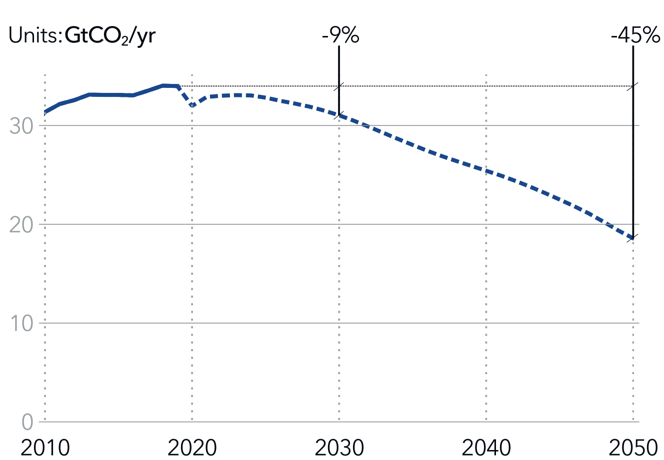
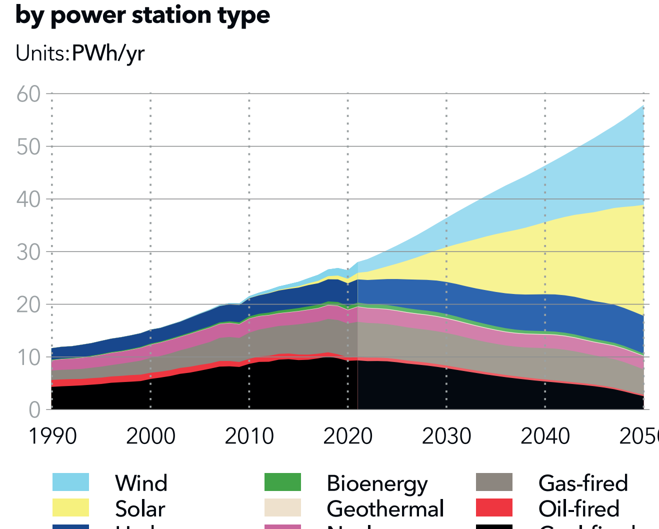


FIGURE 2

World grid-connected electricity generation by power station type



Historical data source: IEA WEB (2020), GlobalData (2021)

Efficiency gains lead to a flattening of energy demand from the 2030s

Energy efficiency is the unsung hero of the energy transition and should be the number one priority for companies and governments. Many efficiency measures have marginal or even negative costs, but due to split incentives and/or a lack of long-term thinking, industry standards and regulations are needed to ensure implementation.

Energy intensity (unit of energy per dollar of GDP) improvements will average 2.4%/yr during our forecast period – against the 1.7%/yr average over the last 20 years. Most of the accelerated efficiencies are linked to electrification, with the remainder coming largely from efficiency improvements in end uses, such as better insulation. The largest efficiency gains happen in the transport sector, but there are significant gains also in manufacturing and buildings.

Overall efficiency gains will result in a levelling off in global energy demand despite a population increase of 22% and the global economy growing 111% the next 30 years. Global energy demand will grow only 8% from 2019 to 2035, thereafter remain essentially flat the next 15 years.

Fossil fuels are gradually losing position, but retain a 50% share in 2050

Fossil fuels have held an 80% share of the global energy mix for decades. We forecast that, by mid-century, fossil fuels will decrease, but still hold a 50% share of the energy mix, testament to the inertia of fossil energy in an era of decarbonization.

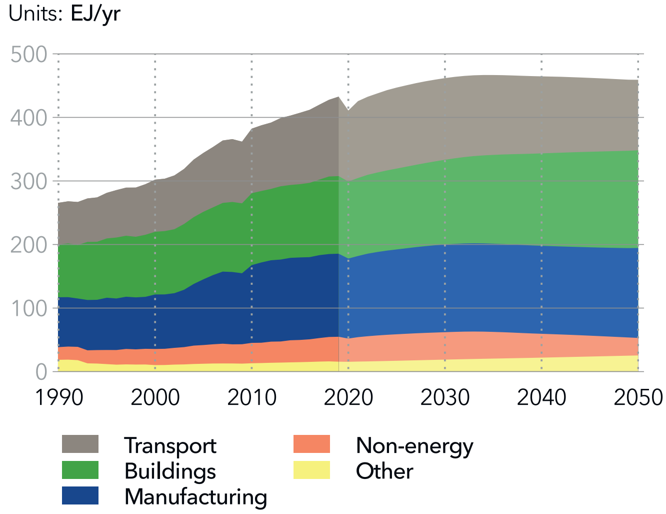
Coal use will fall fastest, down 62% by 2050. Oil use stays relatively flat until 2025 when it starts a steady decline, to just above half of current levels by mid-century. Gas use will grow over the coming decade, then levels off for a 15-year period before starting to reduce in the 2040s. Gas will surpass oil as the largest energy source and will represent 24% of global energy supply in 2050.

Decarbonized fossil energy is an important aspect of reaching the Paris Agreement, but the uptake of carbon capture and storage (CCS) is forecast to be woefully slow, mainly for reasons of cost, with just 3.6% of fossil CO_2 emissions abated in 2050.

FIGURE 3

World final energy demand by sector

Units: EJ/yr

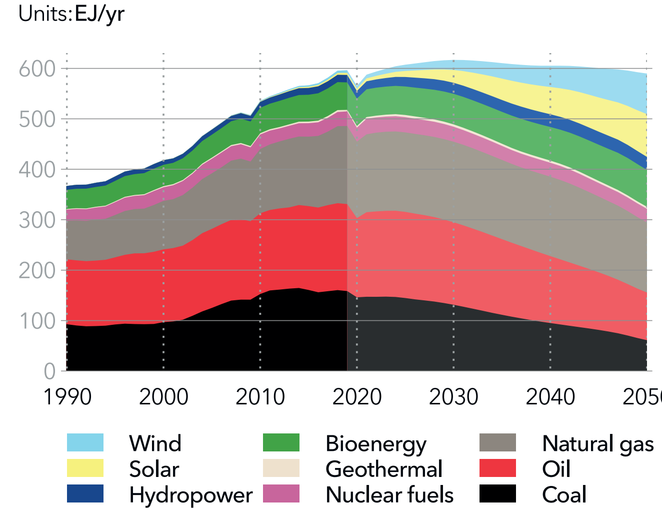


Historical data source: IEA WEB (2020)

FIGURE 4

World primary energy supply by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

Highlights – New insights

COVID-19 economic recovery spending is a lost opportunity

Government interventions, to stop the spread of the virus and then to restart activity, revealed how effective national and global actions can be. Similar action and funding have yet to be applied to the unfolding global climate crisis.

The trillion of dollars pushed into the global economy over the past 20 months have mainly been directed towards emergency measures like wage supplements and on building back the existing economic and industrial engine. Yet the opportunity for a green reset of production, transport and economic activity was unique, and as we wrote in ETO 2020, "The post-COVID-19 stimulus packages hold the potential to alter the speed of the transition." With some notable exceptions, particularly in the EU, governments have not steered recovery spending towards a decarbonized outcome.

Global CO_2 and GHG emissions fell 6% in 2020 but will rise again this year. While the emissions trajectory has shifted down slightly, that is due to lost economic activity, not energy-system renewal. The overall pace of the transition has not accelerated, and that is a lost opportunity.

Variability and low power prices are not roadblocks to a renewable-based power system

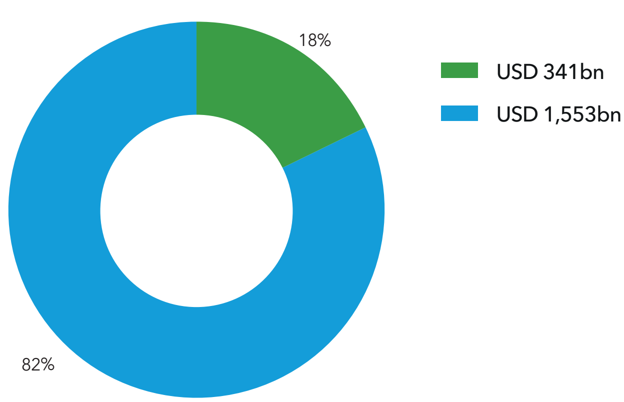
The present power system is not set up for variable renewables as the dominant source of production. Yet plunging costs, government support for renewable power buildout, and carbon pricing will ensure that renewables will eventually dominate power generation. Over the coming 30 years, USD 12 trillion will be invested in both building a larger grid and adapting it to the variability of solar and wind through technical solutions such as connectivity, storage, and demand response.

The cost of power from solar and wind will continue to reduce but price cannibalization threatens the investment case for renewable capacity if cheap power is unused at times of ample supply. However, indirect electrification through power-to-X will require massive renewable electricity production, and along with various storage solutions, will ensure that surplus power will be used, and capture prices maintained at a satisfactory level.

Solar PV + storage will make solar more directly competitive with thermal generation, nuclear and hydropower. We find that one third of all solar production will be built with direct storage, and by 2050, solar PV + storage will produce 12% of all grid-connected electricity.

FIGURE 5

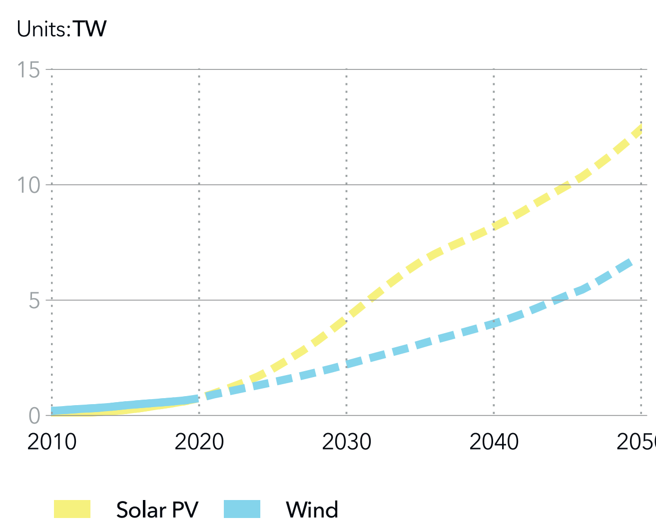
Pandemic recovery spending 2020



Source: UNEP report 'Are we building back better', Feb 2021
Note: In a separate report the IEA's Sustainable Recovery Tracker estimated that as of Q2 2021, clean energy measures totalled USD380bn or just 2% of total fiscal support related to COVID-19

FIGURE 6

Build-up of solar and wind - global installed capacity



Includes off-grid capacity for wind and solar. Historical data: GlobalData (2021)

Decarbonizing hard-to-abate sectors requires far greater scaling of hydrogen, e-fuels, and biofuels

Hard-to-abate sectors are those that cannot easily be decarbonized through electrification, and include aviation, maritime, long-haul trucking and large parts of heavy industry. These sectors are currently responsible for around 35% of global CO_2 emissions, and progress in reducing these emissions is stubbornly slow.

Hydrogen is seen as the main decarbonization alternative for these sectors, with biofuels in a supporting role, mainly in aviation. Direct hydrogen use is often not suitable, and ships and aircraft require hydrogen derivatives and e-fuels such as ammonia and synthetic jet fuel.

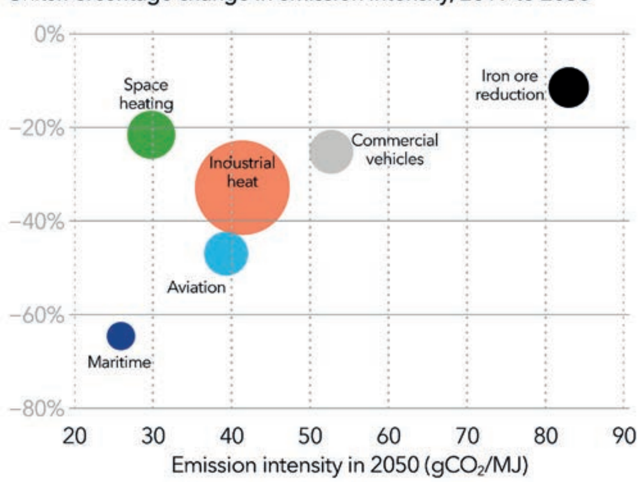
Global hydrogen production for energy purposes is currently negligible and will only start to scale from the late 2030s, meeting 5% of global energy demand by 2050. Government incentives, similar to those given to renewables, are needed to stimulate technology development and accelerate uptake of hydrogen and e-fuels.

Aviation, maritime and heavy industry thus retain high unabated fossil-fuel shares towards 2050, slowing the transition and significantly impeding the achievement of the Paris Agreement.

FIGURE 7

CO_2 emissions of hard-to-abate sectors by 2050

Units: Percentage change in emission intensity, 2019 to 2050



Bubble area is proportional to emissions in 2050.

Most hydrogen will be produced from dedicated renewables-based electrolysers by 2050

The current production of hydrogen as an energy carrier is negligible compared with the 75m tonnes of grey/brown hydrogen produced annually for fertilizer and chemicals production.

Blue hydrogen, produced by steam methane reforming (SMR) from gas with CCS, will replace some of the grey and brown hydrogen in the coming decades. In total, blue hydrogen will also comprise 18% of hydrogen supply for energy purposes by 2050.

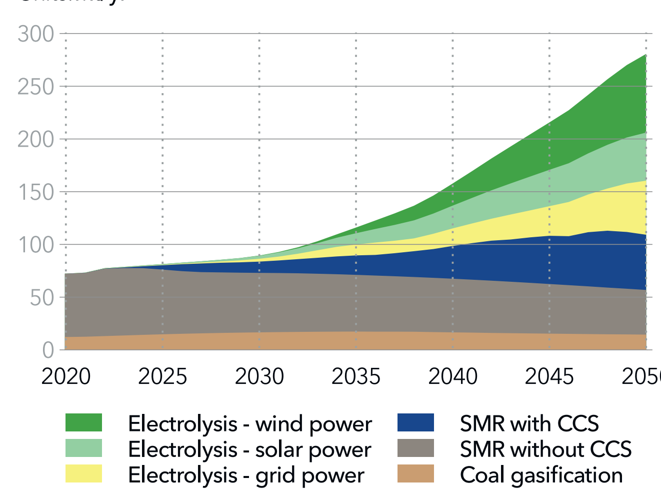
Green hydrogen from electrolysis will be the main long-term solution for decarbonizing hard-to-abate sectors, including hydrogen as a basis for other e-fuels.

Electrolysis powered by grid electricity is disadvantaged by the limited number of hours of low-priced electricity. Its CO_2 footprint will, however, improve as more renewables enter the power mix. The future production of hydrogen for energy purposes will be dominated by electrolysis using dedicated off-grid renewables, such as solar and wind farms. By 2050, 18% of hydrogen will be grid-based and 43% will come from dedicated capacity comprising solar PV (16%), onshore wind (16%) and fixed offshore wind (9%).

FIGURE 8

World hydrogen production by source

Units: Mt/yr



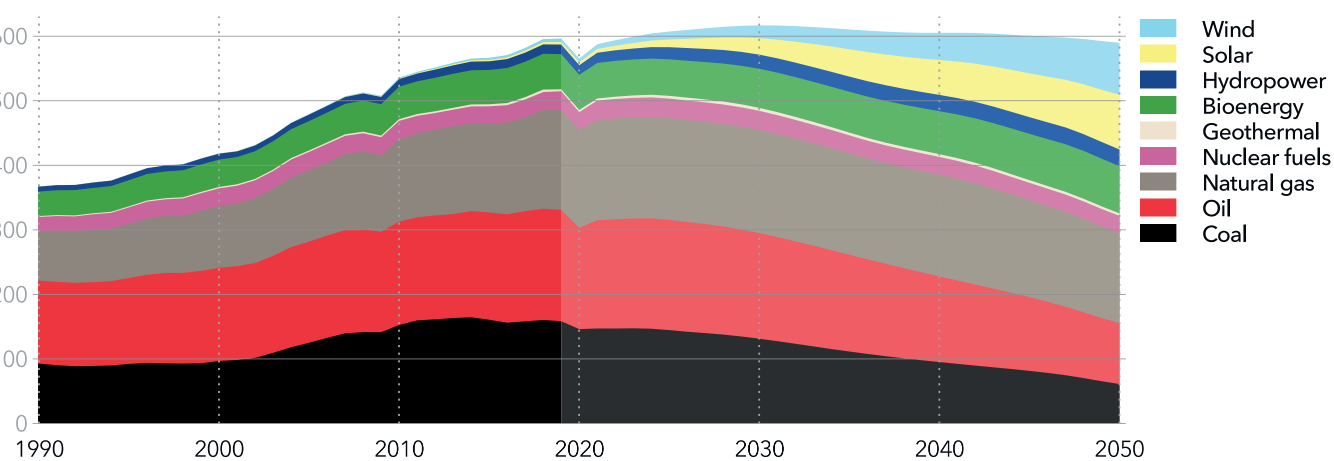
PRIMARY ENERGY 2019-2050

Shown here is our forecast for primary energy through to 2050. Primary-energy supply is the total amount of energy behind the provisioning of energy services. Considerable losses occur in the conversion and transport of energy (currently exceeding 100 EJ annually) and these are included in primary energy numbers, as is the energy industry's own use of energy, which is considerable – typically 7% of primary energy consumption. Primary energy, which was 594 EJ before the pandemic, will return to 2019 levels in 2022, but will then only increase by a further 4% percent and peak at 617 EJ in 2030 before slowly reducing by 4% to some 590 EJ in 2050.

FIGURE 9

World primary energy supply by source

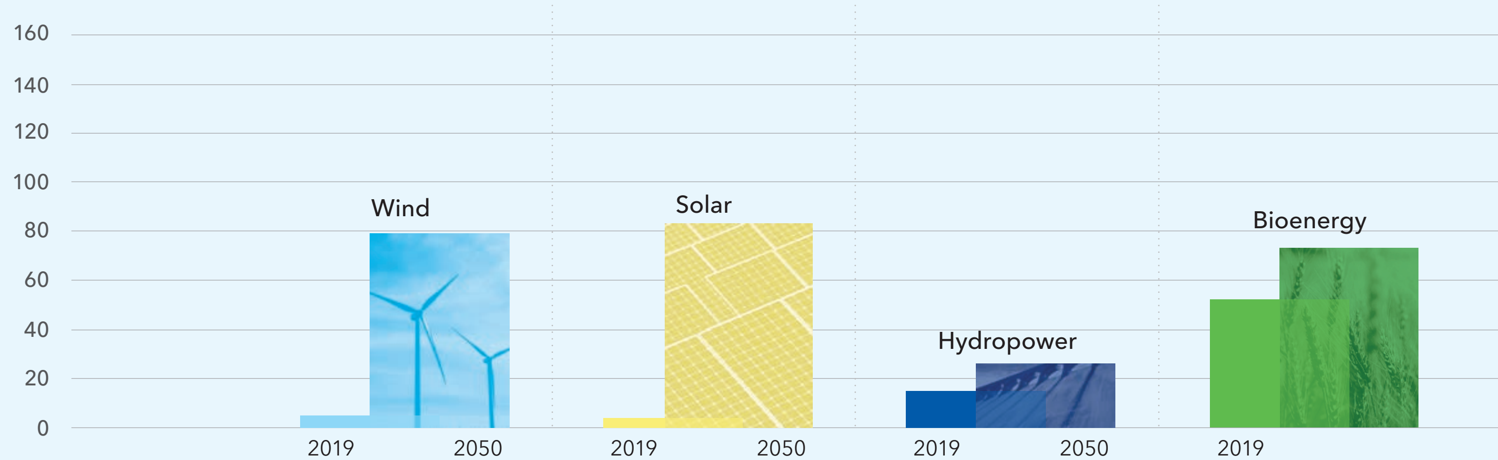
Units: EJ/yr



Historical data source: IEA WEB (2020)

World Energy Supply Transition 2020-2050

Units: Exajoules (EJ) per year

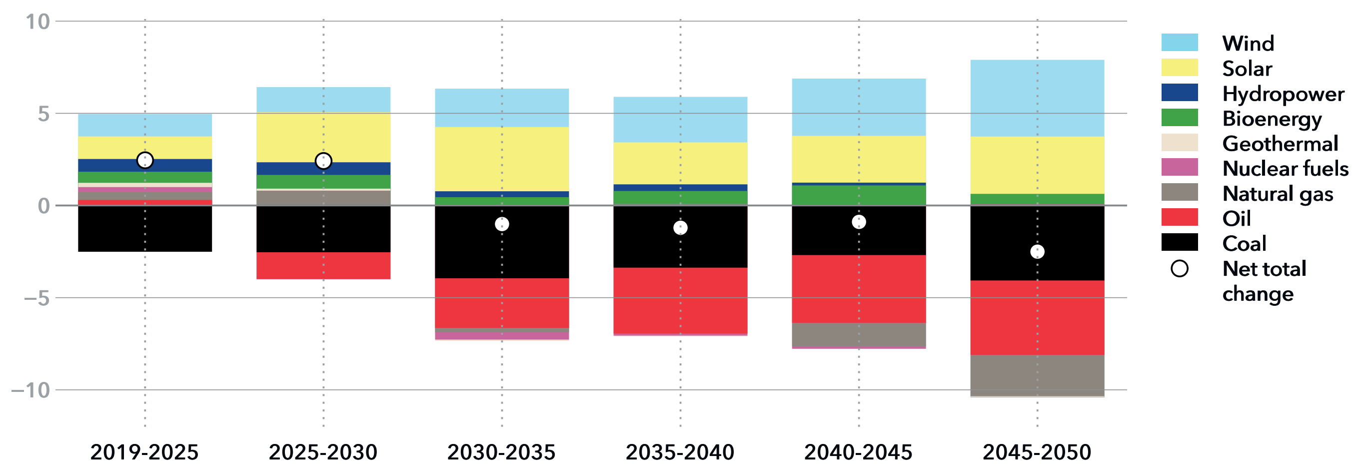


Contributions to changes in the primary-energy supply are shown in the figures below. In the forecast period, renewables will constantly be adding to the primary-energy supply, while fossil fuels will be reducing, except for natural gas, which only decreases in the 2040s. The fossil share of the energy mix will fall from 80% today to 50% by mid-century. Nuclear will be stable at 5% over the entire period, while renewables will triple from 15% today to 45% by the end of this forecast period.

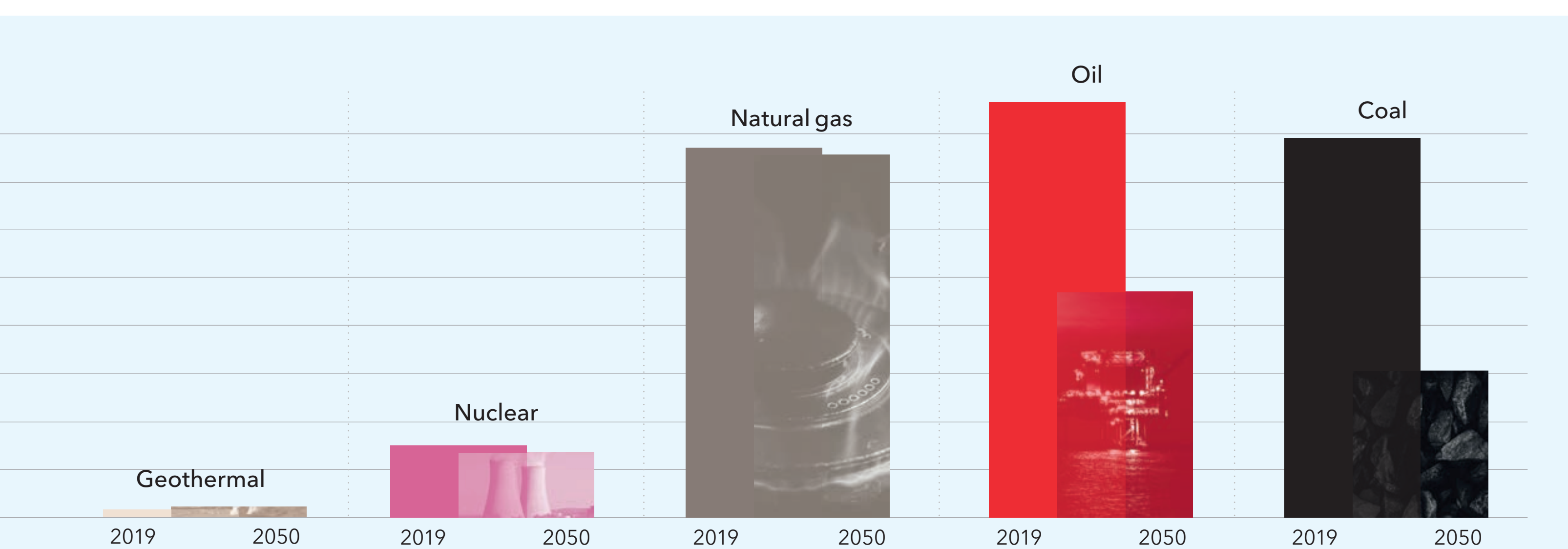
FIGURE 10

Net change in primary energy supply by source

Units: **EJ/yr**



Net change of primary energy between 5-year intervals. 2019 used to avoid effect of COVID-19. Historical data source: IEA WEB (2020)



CONTENTS

INTRODUCTION

About this Outlook

This annual Outlook 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. Our forecast data may be accessed at eto.dnv.com/data. More details on our methodology and model can be found on page 34. The changes we forecast hold significant risks and opportunities across many industries. Some of these are detailed in our supplements:

- Maritime forecast
- Financing the energy transition
- Technology progress report
- Pathway to net zero emissions

Our approach

In contrast to scenario-based outlooks, we present a single 'best estimate' forecast of the energy future, with sensitivities in relation to our main 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 ten world regions. The analysis covers the period 1980-2050, with changes unfolding on a multi-year scale that is some cases is fine-tuned to reflect hourly dynamics.

We continually update the structure of and input data to our model. The most signficant changes to the model since our 2020 Outlook are listed on page 265.

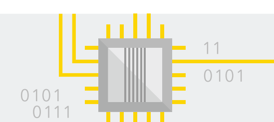
Independent view

DNV was founded 157 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. 70% of our business is related to the production, generation, transmission and transport of energy. Developing an independent understanding of, and forecasting, the energy transition is 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.

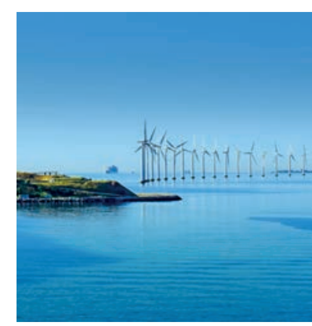
Behavioural changes: some assumptions made, e.g. linked to a changing environment

Our external collaboration network for our 2021 Outlook includes:
Harald Magnus Andreassen Sparebank 1 Markets, **Valentin Batteiger** Bauhaus Luftfahrt, **Kingsmill Bond** Carbon Tracker, **Sunil Gupta** Vena Energy, **Gørild Heggelund** Fridtjof Nansen Institute, **Robert Hornung** Canadian Renewable Energy Association, **Steffen Kallbekken** CICERO, **Francisco S. Laverón** Iberdrola, **Yang Lei** Institute of Energy, Peking University, **Wolfgang Lutz** Wittgenstein Centre for Demography and Global Human Capital, **Jinglong Ma** APEC Sustainability Center, **Tom Moultrie** University of Cape Town, **Susanne Nordbakke** Transportøkonomisk Institutt, TØI, **Glen Peters** CICERO, **Sergei P. Popov** Melentiev Energy Systems Institute, **Thina Margrethe Saltvedt** Nordea, **Jon Birger Skjærseth** Fridtjof Nansen Institute, **Marco Tagliabue** Oslo Met University, **Mena Testa** Enel Global Infrastructure and Networks, **Kevin Tu** Agora Energiewende China, **Jørgen Wettestad** Fridtjof Nansen Institute, **Yongping Zhai** Tencent / ADB

ENERGY TRANSITION OUTLOOK **2017**

ENERGY TRANSITION OUTLOOK **2018**

ENERGY TRANSITION OUTLOOK **2019**



ENERGY TRANSITION OUTLOOK **2020**

After five years of forecasting…

Our findings this year do not differ fundamentally to those of our first forecast issued four years ago. Over the years, we have extended and refined our model, for example by delving deeper into the dynamics of the key demand sectors of transport, manufacturing and buildings. We have also added additional energy carriers and sectors such as hydrogen, floating offshore wind and solar PV+storage, and introduced the modelling of power generation on an hourly basis. But one of our key findings – that the global energy mix will be split in roughly equal shares between fossil and non-fossil sources by 2050 – has not changed. Neither has our conclusion that the world will fail to achieve the climate goals of the Paris Agreement by an alarming margin.

The fact that these findings have remained consistent is a major cause for concern: In a half-decade where the costs of inaction on climate change have been mounting and the evidence of its effects are growing ever more visible, it is sobering to reflect on the fact that the pace of the energy transition has not accelerated beyond our first forecast.

Highlights

Historically, energy demand has grown in lockstep with GDP. But this is going to change dramatically in the next 30 years. **Global GDP will more than double by 2050, but energy demand will rise by only 8% from today to its peak around 2035, and then level off**. This is due to the dramatic effect of efficiency gains, largely enabled by accelerated electrification, that will outpace economic growth in the coming years.

Recovery from the COVID-19 pandemic is very uneven across the developed and developing world. Overall, the economic rebound is slightly stronger than anticipated last year, but there is still a 'permanent' loss of GDP growth of 3.2% through to 2050. Some effects of the pandemic – increased working from home and reduced air travel – will have a lasting impact on energy demand.

More importantly, **pandemic recovery spending by governments is a lost opportunity for the fight against climate change** – in aggregate only marginally shifting the needle towards a greener energy mix by mid-century.

Electrification strongly impacts end use in all three main demand sectors — transport, manufacturing and buildings. In transport, efficiency gains from the electrification of road transport more than offset demand growth in other subsectors (aviation and maritime). Manufacturing energy demand grows only marginally (by 6%) despite a doubling in output, measured in terms of Manufacturing Value Added. The buildings sector will overtake manufacturing as the largest source of demand, consuming 26% more energy in 2050 than in 2019.

1 ENERGY DEMAND

1.1 ENERGY DEMAND

Energy consumption is dependent on the supply and demand balance. In reality, however, it starts with demand, as the amount of energy in the world is sufficient to meet our requirements. This chapter describes the energy demands of the various sectors: transport, buildings, manufacturing, and feedstock.

Historically, energy demand has grown in lockstep with GDP – population growth and improvements in standards of living – moderated by efficiency improvements. Global population growth will slow down, reaching 9.4 billion people in 2050. Economic growth will also continue, and the size of the global economy in 2050 will be USD 293 trillion, with an average growth rate of 2.5% from 2019 to 2050. Further details on population and economic growth are included in the annex of this Outlook.

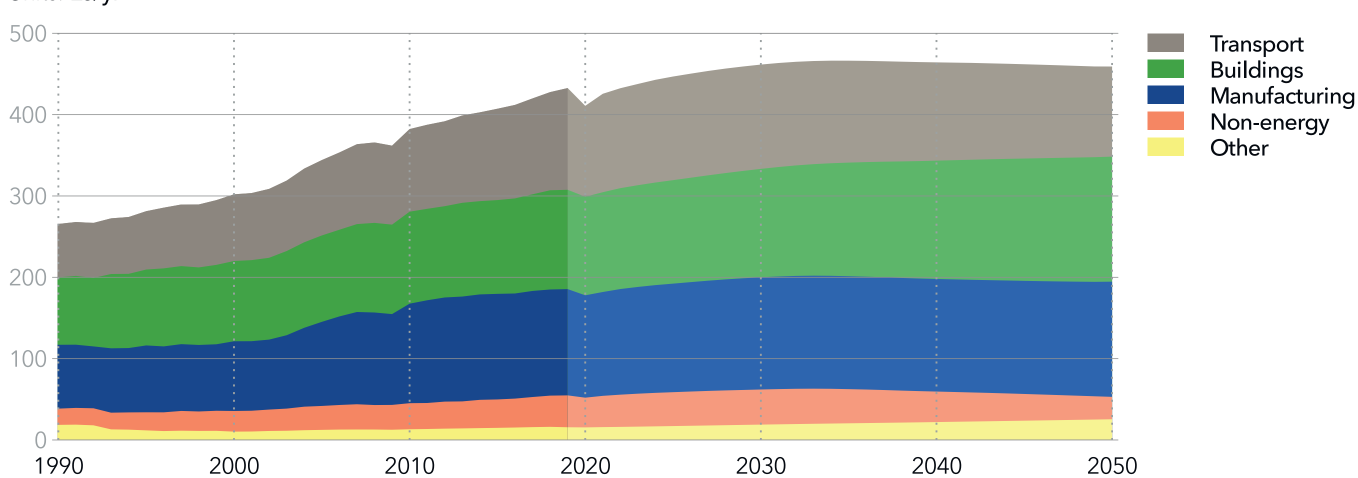
More and wealthier people request ever-more energy services – be it for transportation, for heating, or for consumer goods. This leads to increased energy demand, unless countered by strong efficiency gains.

In the coming three decades this counterforce will, indeed, be strong, with our forecast that efficiency gains, particularly those enabled by electrification, will offset 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, level off at some 466 EJ by around 2035. This level, which is only 8% higher than in 2019, will thereafter remain flat through to mid-century, as illustrated in Figure 1.1. However, it is not certain that the energy demand will remain flat after 2050; once most energy services are converted to electricity, which automatically improves energy efficiency in most sectors, energy demand might start to increase again.

FIGURE 1.1

World final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2020)

'Final' energy in this Outlook and as shown in Figure 1.1, 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.

Demand will not develop uniformly across sectors. The strongest growth will occur in the buildings sector, where significantly more residential and commercial floor area – with more cooling and heating per square metre – will be available to serve more prosperous populations. Consequently, buildings will collectively consume 26% more energy in 2050 than in 2019, and the sector's share of global final energy demand grows from 28% to 33% in 2050.

In manufacturing, substantial energy-efficiency gains, including increased recycling, will balance the growth in demand for goods, such that manufacturing energy use will grow by 6% to 2033 and thereafter remain flat to 2050. The feedstock sector will see energy demand grow initially by 11% to peak in 2032, but then reduce by 37% to 2050 due to increased recycling and efficiency gains.

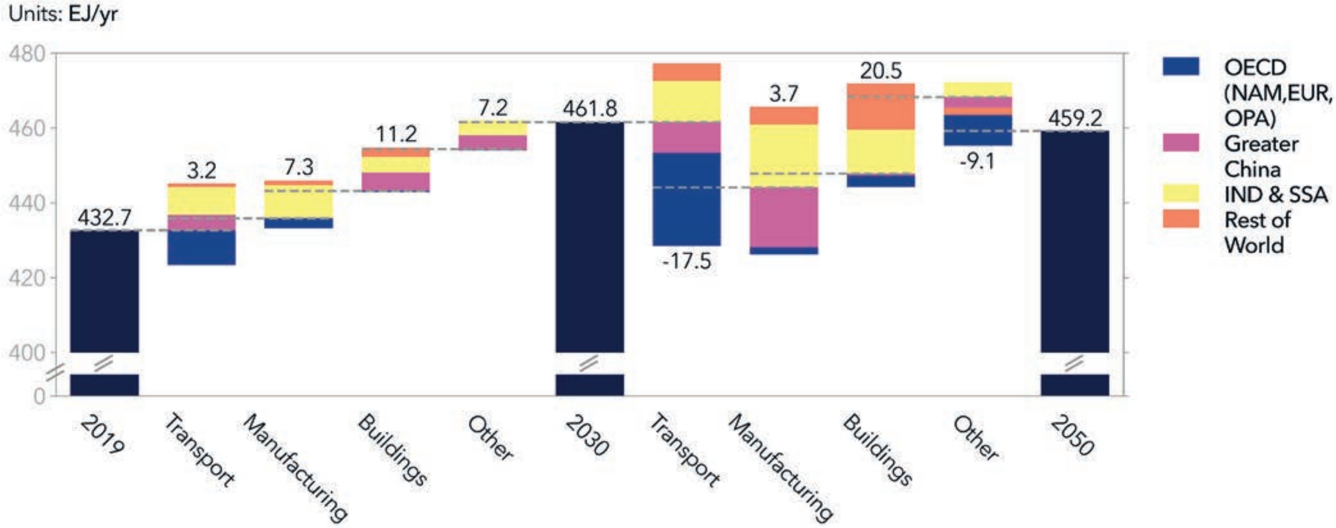
Although transport services will grow significantly over the forecast period, overall energy demand in the transport sector will reduce. The most important reason for this counterintuitive trend is the significant efficiency improvement associated with the switch from internal combustion engines to battery electric ones, with half of the world's fleet of passenger vehicles being electric by 2042. Efficiency gains in the road-transport subsector will more than counterbalance growth in energy demand in aviation and rail. This trend will also be helped by the maritime sector experiencing significant efficiency gains that will reduce energy use, despite growth in the size of the world fleet.

Although global final energy demand is flat, growth will vary significantly between the different regions. Figure 1.2 illustrates the regional changes within each of the demand sectors. Energy demand by carriers is summarized in Section 1.6.

FIGURE 1.2

Changes in final energy demand by sector and region

Units: EJ/yr



Measuring energy; joules, watts and toes

EJ, TWh, or Mtoe? The oil and gas industry normally presents its energy figures in tonnes of oil equivalents (toe) based on m³ of gas and barrels of oil, whereas 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.

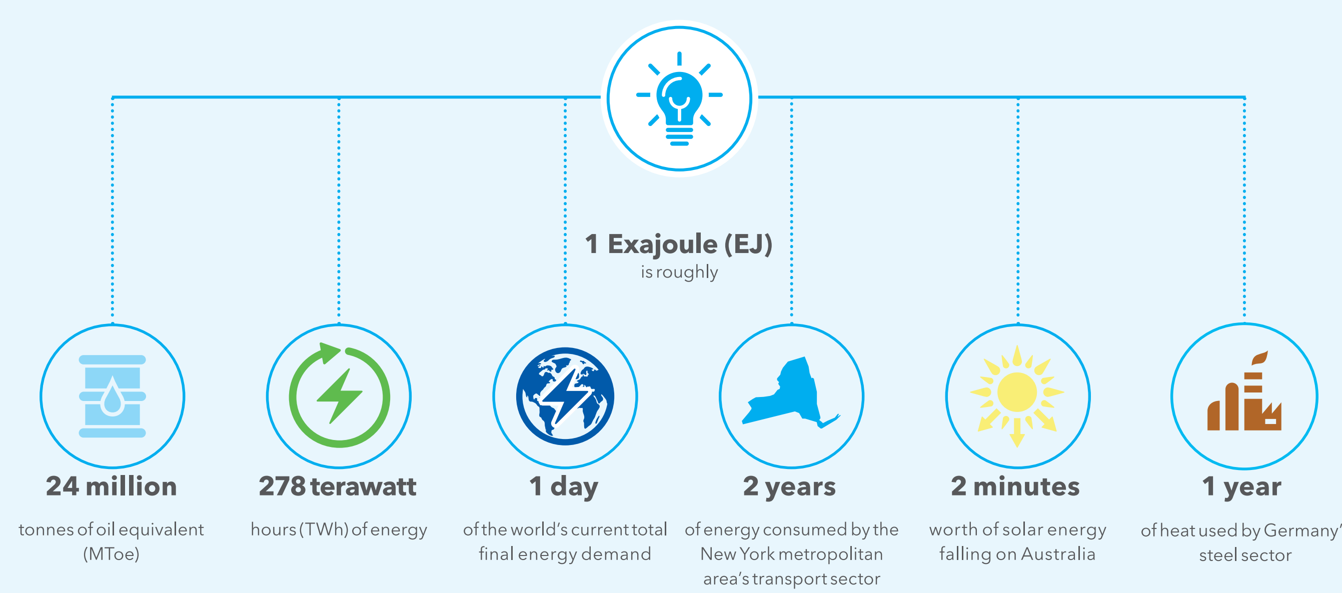
So, what is a joule? Practically, a joule can be thought of as the energy needed to lift a 100 g smartphone 1 metre up; or the amount of electricity needed to power a 1-watt LED bulb for 1 second (1 Ws). In other words, a joule is a very small unit of energy, and, when talking about global energy, we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

While 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 2021, the effect of the COVID-19 pandemic on the world's economy and energy use is still severe but is showing signs of receding, at least in the developed world. Developed countries are slated to complete vaccination of more than half of their populations before the end of Q3, 2021, whereas emerging, and especially developing nations, are lagging in vaccination rollouts; some have barely begun. Powerful stimulus packages in North America and Europe are giving rise to concerns about inflation and component shortages are already apparent.

As with our ETO 2020, we have used the IMF World Economic Outlook scenarios to chart the effect of the pandemic on the global economy. Whereas in 2020 we used the IMF's 'longer outbreak' scenario variant – which played out well for the last six months of 2020 and the first half of 2021 – we have now returned to the IMF base outlook. In one sign of reduced uncertainty, the IMF has now dropped its "named" scenarios, but both "optimistic" and "pessimistic" outlooks are described.

Eighteen months into the pandemic, myriad effects have been seen, but some of them are already disappearing again. The most relevant question for the energy transition concerns which of the effects will last beyond the pandemic itself. Here we focus on possible effects of pandemic-linked changes on workplace patterns, leisure travel, supply chains, job creation, and (possibly) greener public policies.

Working from home

The extent to which people work from home impacts both daily commutes and business trips, and also influences requirements for both office and residential space. Depending on the region, up to half the workforce might work from home (Dingel and Neiman, 2020), with more developed regions having the higher share. The COVID-19 pandemic caused a jump in home-office use, creating widespread familiarity with remote-working platforms, as well as improving the quality of digital tools and work processes. Similarly, travel restrictions have boosted acceptance of and skills in using virtual communication with colleagues and clients across the world. In addition, new ways of engagement and digital technologies have accelerated use of electronic service solutions, such as legal counselling, medical consultation, and even cultural experiences. Closer to DNV, the use of remote technical surveys has increased markedly.

The consolidation of using remote communication and digital tools has permanently affected our ways of working and service provision, reducing transport needs in all sectors. In our estimate, this will decrease the demand for workspace (i.e., commercial buildings) by 5% compared with our pre-pandemic estimates in developed regions (including China), and by half of that (2.5%) in developing and emerging economy regions. The energy intensity of these buildings will also decline permanently – by 1% in developed regions and 0.5 % in developing regions. We are also likely to see a small increase in private car use in preference to public transport. In addition, the currently increasing demand for suburban and rural residences will counterbalance the effect of lower frequency of office working, leaving overall car use unchanged. Homeworking will lead to the size of the average residence increasing by 2% in developed regions and China, and by 1% in other regions. As people spend more time in their homes working, buildings energy intensity will rise by 2% in developed regions (which have a workforce best suited for home offices) and 1% elsewhere. Residential energy demand in developed regions will thus increase by 4%, half of which arises from bigger dwelling sizes and half from increased requirements for heating and cooling.

Although road transport will not be permanently impacted by the pandemic, for air travel longer-term effects are expected. Work-related flights are driven by GDP. We expect that such travel will reach a new stable level for a given GDP in a region by 2025. This level is estimated to be 20% lower than our pre-pandemic projections. However, we see little reason why the present (summer 2021) severe impact of the pandemic on international leisure travel will become permanent. It could be argued that vacationers who, in 2021, 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, unlike working from home, leisure activities have not developed new ways of operating. As leisure travel – representing two thirds of all air travel – is expected to rebound fully from the pandemic effects, the permanent decrease in air travel will be 7% after 2024 compared with pre-pandemic forecasts. Until then, air travel will gradually rebound from current (summer 2021) levels of just over half that of pre-pandemic levels.

> The consolidation of the use of remote communication and digital tools has permanently affected our ways of working and service provision, reducing transport needs in all sectors.

Re-design of supply chains

Travel restrictions and social-distancing regulations have strained international supply chains and exposed vulnerabilities in security of supplies, magnified by a 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 as possible 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, has strengthened. The former trend should 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 a growth in importance of "national arguments", we see the net result of these two competing narratives as leading to a marginally slower growth in cross-border collaboration and supply chains.

International maritime transport is in a process of full rebound, with severe bottlenecks still felt, for example in container markets in the summer of 2021.

The economic impact

The pandemic stimulus packages afforded a unique opportunity for governments to hasten the energy transition. However, with minor exceptions, this has become a missed opportunity. Recovery spending has focused predominantly on a return to the pre-pandemic state of affairs which includes large spending on the conventional (fossil fuel) industry. This return to the status quo has done very little to advance the pace of the energy transition.

In order to address the economic crisis following the pandemic, governments have established financial stimulus packages with the main intention of regaining and maintaining activity and jobs. The specific content of these packages affects how COVID-19 accelerates or delays the energy transition. Some regions are using this opportunity to push a faster energy transition, supporting, for example, the production and purchase of EVs. Others, however, have injected tax relief into vulnerable oil and gas industries. At the time of writing (summer 2021), we see North American and European recovery packages clearly pushing the green agenda. Other regions have more timid economy-boosting programmes, and the effects of those give both faster and slower transition speeds.

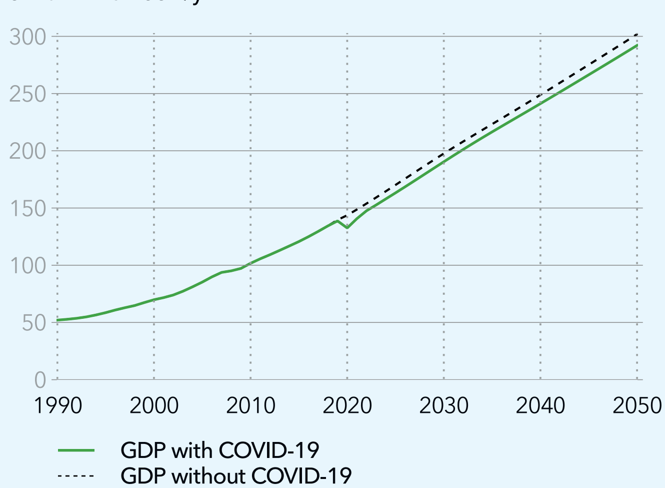
COVID-19 responses also facilitate discussions on behavioural changes, which have previously received less attention than technological changes in the energy-transition debate. Behaviours can and do change with the perception of crisis. Decisive government intervention has been critical during the pandemic, and some argue that this experience may result in the public becoming more open to decisive government action on the climate crisis. This remains to be seen.

Negative COVID-19 impacts will still be significant in Q3 and Q4 of 2021 in most regions, but other regions will see a healthy rebound by then, returning to normality within another 2 years. Currently, the COVID-19 appears to have a dual effect. On the side of accelerating the transition, public money and policy are being used in the OECD – within a Keynesian framework – to boost aggregate demand for products and services and thus enhance employment. This favours future green investments. On the other hand, activity-enhancing time delays are shorter in fossil-related activities, so these are likely to be favoured. In sum, the pandemic job-boosting activities fall slightly more on the green side, and thus COVID-19 will have a marginally positive net long-term accelerating effect on the transition speed. This nudges the present ETO 2021 towards a somewhat greener 2050 energy mix than described in last years' report, The chance to use COVID-19 economic recovery spending to speed up the transition, however, has not been utilized, and this is a lost opportunity.

FIGURE 1.3

World GDP - with and without COVID-19

Units: Trillion USD/yr



Historical data source: IMF (2021), World Bank (2018), Gapminder (2018)

Using the IMF (2021a) base scenario, and also in line with a consensus view (OECD, 2021), we expect the relative global GDP reduction to differ across regions. The short-term downturns 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. Instead of our originally projected annual growth of 3.5% in both 2021 and 2022, IMF sees a stronger global rebound (after a decline of 4.4% in 2020) of 6.1% in 2021 and 4.9% in 2022. COVID-19 results in a 2023 global economy that has lost 4.1% of GDP compared to the pre-pandemic projections. This loss is almost permanent, but the post COVID-19 boost in 2023 will result in some regional economies growing slightly faster than they otherwise would have, and in 2050 the loss declines to 3.2%.

The delta variant was spreading through the summer of 2021, leading IMF (2021b) to update its 2021 and 2022 projections. This update had a neutral global impact for 2021, which included stronger growth in developed countries than projected in the spring, but weaker growth in developing parts of the world where the delta variant projected to provide an added toll both in health and economic terms: OECD countries not only have better access to vaccines, but also stronger tools enabling them to better counter negative economic developments. The summer IMF update also upwardly revised global outlook for 2022, again with developed nations benefitting.

In Figure 1.3, we show how GDP projections differ from the no-COVID-19 situation.

1.2 TRANSPORT

Efficiency gains and fuel switches – mainly to electricity and hydrogen – will result in transport-energy demand falling from 125 EJ in 2019 to 111 EJ in 2050.

Current developments

The transport sector has seen pandemic-associated reductions in energy demand in all subsectors – road, rail, air and at sea – albeit with significant differences. Transport-sector energy demand declined by 11% in 2020. The aviation sector experienced the highest reduction percentagewise, almost halving from 2019 to 2020. By contrast, energy demand for maritime transportation fell by 4%, similar to rail (5%) and road (7%).

In 2019, transport was responsible for 29% of global final energy demand, almost entirely in the form of fossil fuels. Figure 1.4 shows that 92% of road transport energy use is oil, with biofuels and natural gas taking 3% and 4% shares respectively and electricity 1%. The energy mix in aviation, maritime, and road transport sectors differs little, whereas rail energy is supplied mainly by electricity.

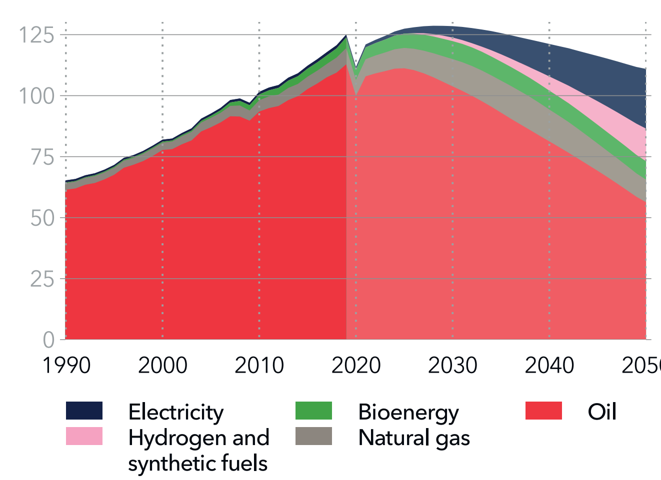
To reduce local air pollution and global emissions, natural gas, biofuels and electrification have been introduced. Greater China has a leading natural gas share (7%) in road transport. All regions, with the exception of Middle East and North Africa, have biofuel-blend mandates or give biofuels preferential treatment. In Norway, 90% of new sales of passenger vehicles are plug-ins, mostly battery-powered electric vehicles. Biofuel mandates and push-and-pull strategies to support the uptake of EVs are prime examples of the role of public policy in transport fuels. Decarbonization and fuel efficiency are interlinked, and some regions, notably Greater China and OECD countries, use a mixture of push-and-pull policy measures to achieve their decarbonization ambitions. We envisage public policy targeting and banning emissions, with significant industrial and consumer support, continuing for at least another decade.

However, over time, technology cost-learning dynamics will render such policies superfluous – at least in the road-transport subsector, which accounts for almost 75% of transport-energy use. Vehicle manufacturers are increasingly overhauling their strategies to cope with the looming market dominance of EVs[1] . For most uses, EVs will soon become more cost effective than internal combustion engine vehicles (ICEVs); they typically have less than a third of the energy consumption, and lower maintenance costs. However, removing EV support too soon will reverse EV-uptake dynamics (Testa and Bakken, 2018). Recently, Europe overtook Greater China as the largest market for EVs, reaching a record-high sales share of new vehicles of almost 5%. Within this decade, EVs will reach cost parity with ICEVs, and sales will accelerate as an ever-larger range of models come onto the market.

FIGURE 1.4

World transport sector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

[1] EVs in this analysis include BEVs and FCEVs, but not PHEVs – as the latter category typically uses more fossil fuels than electricity

Road

Vehicle fleet size and dynamics

Standard of living, defined as GDP/person, is the driver for vehicle density (vehicles per person). The exact relationship differs between regions and is influenced by a mixture of geographical, cultural, technological, infrastructure and environmental factors, as well as the availability of alternatives to road-transport. To predict future developments in vehicle density, for both commercial and passenger vehicles, in each of the 10 regions related to GDP/person, historical vehicle-density data have been fitted to a Gompertz curve (type of S-shape curve), as illustrated in Figure 1.5. In some regions this is supplemented by expert opinion, enabling a synthesis of e.g., effects of policy support for alternatives to road transportation.

The category "passenger vehicles" encompasses all vehicles with three to eight passenger seats. Thus, it includes most taxis, but excludes buses. Other non-passenger vehicles with at least four wheels are considered "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-vehicle share of the fleet increases. However, we expect this trend to bottom out within the next few years.

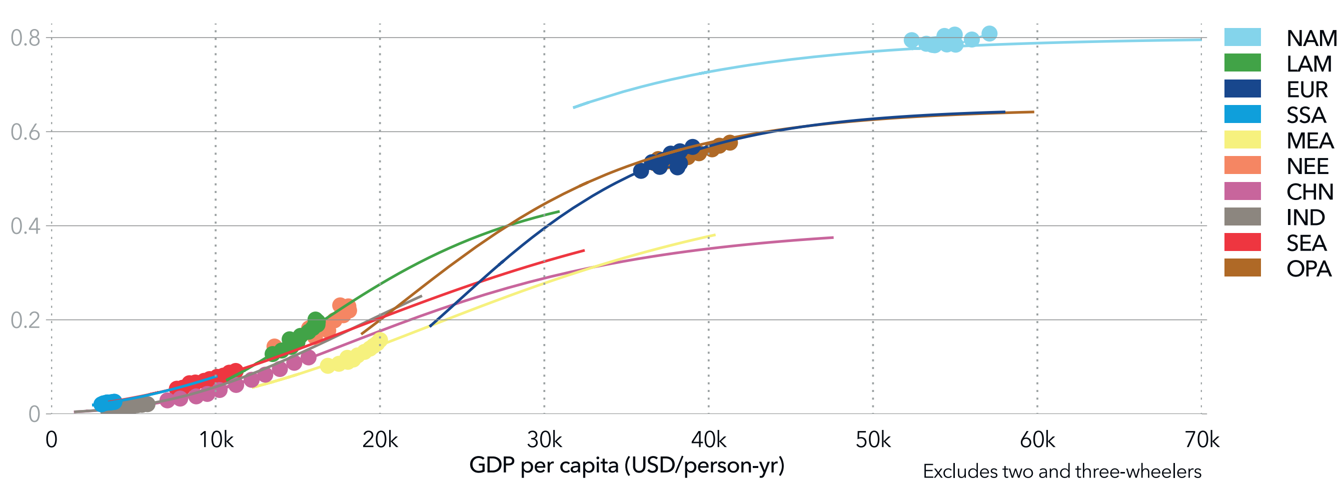
At present, taxis represent a significant fraction of the global passenger-vehicle fleet. Communal use of passenger vehicles is typically more prevalent in less-developed regions than in developed ones. However, several recent developments, such as platform-based ride services, support increasing communal passenger transport in OECD countries too, starting with urban road-passenger transport. Because platform-based ridesharing services can offer improved services at higher efficiency and lower costs, this segment will continue to grow. Similarly, car-sharing platforms have higher asset utilization than traditional car use, a reduction in private ownership will ensue, especially in developed regions.

Self-driving taxis and automated driving of privately-owned passenger vehicles will additionally contribute to increased asset utilization, leading to shorter asset lifetimes and thus faster renewal of the fleet. As BEV use rises, their much-lower energy consumption will reduce average fuel consumption. We assume 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 privately-owned

FIGURE 1.5

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

passenger vehicles. Consequently, an automated, communal vehicle will be driven 7.5 times as much as a non-automated 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.

EV uptake

This does not detract from our main finding: the uptake of EVs – passenger EVs first – will occur rapidly. Supported by contemporary findings (Keith et al., 2018), we assume that people choosing to acquire an EV will base their decision on weighing costs against benefits. Within our approach, simulated buyers have the choice between EVs (becoming increasingly cheaper and providing a longer range over time) and ICEVs in the categories: passenger vehicle, commercial vehicle and two- and three-wheelers. Potential buyers of passenger vehicles will consider purchase price to be the main factor and put less emphasis on operating costs, whereas owners of commercial vehicles will take the advantages of EVs operational costs into greater consideration.

Currently, too few charging stations within range is a major barrier to EV uptake in most regions, 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.3, it is assumed that the current battery cost-learning rate (CLR) of 19% (per doubling of accumulated capacity) will continue throughout the forecast period. Consequently, vehicle prices will also fall.

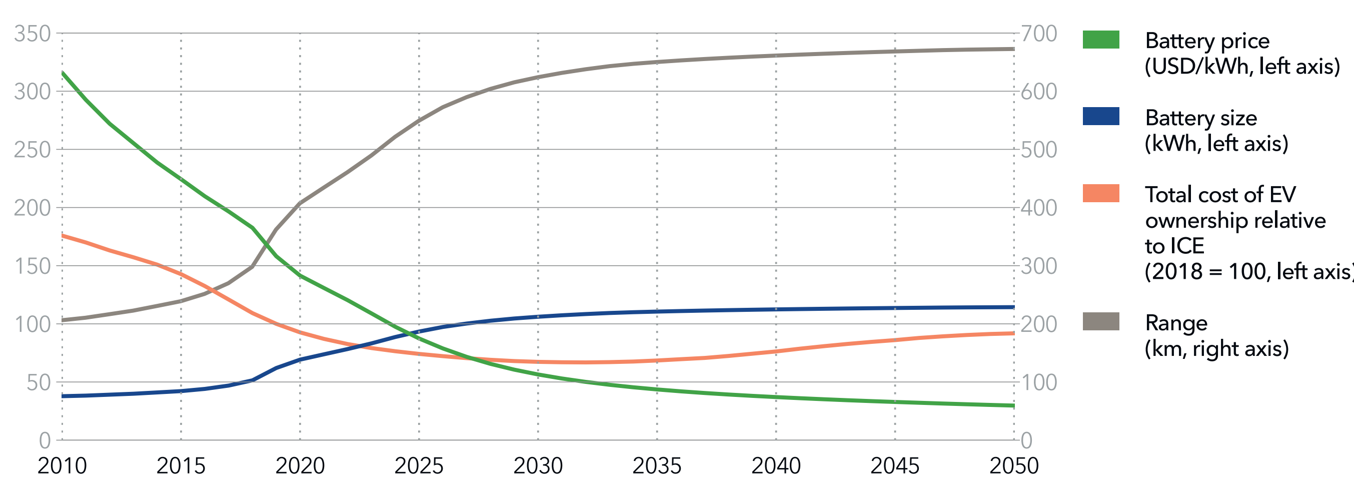
Figure 1.6 shows that as battery prices fall, average battery sizes will benefit. In Europe, the average battery size will more than double from today's 49 kWh/vehicle to slightly above 100 kWh/vehicle in 10 years, resulting in an expanded vehicle range and EVs seeming more attractive.

Total cost of ownership

In addition, Figure 1.6 shows that EV total cost of ownership (TCO) will decrease only slightly between 2020 and 2025, as increasing battery sizes almost offset lower battery costs. Passenger-vehicle TCO increases from the 2030s onwards. This is mainly due to an increase in vehicle operating costs, based on an assumption that low operating costs will inch EV driving distance upwards. Passenger EV costs are similar to those of commercial vehicles.

FIGURE 1.6

Development of key parameters of electric vehicles in Europe



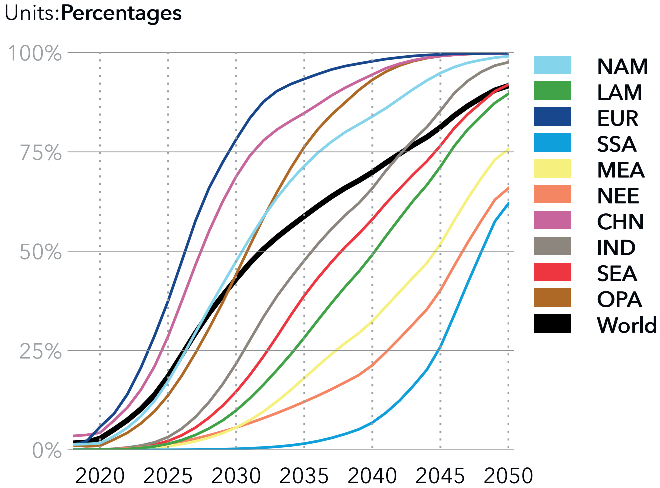
TCO is a purchase decision construct, reflecting public policy support. The two countries with highest EV uptake rates, China (commercial vehicles) and Norway (passenger vehicles), use a mixture of preferential treatment of EVs and de facto subsidies on the buyers' side, as shown by Testa and Bakken (2018). In Europe current policies favouring EVs are implemented as vehicle emission limits, giving carmakers bonuses for zero-emissions vehicles, and surtaxing fleets that exceed the target (EC, 2019). Current policies introduce buyer incentives for passenger EVs varying from none in poor countries, to a few hundred USD in others, to over a thousand USD per vehicle in OECD regions. Both passenger and commercial vehicles are supported by subsidies. When calculating the value of subsidies, we have included significant support provided to vehicle and battery manufacturers.

Commercial vehicles require much larger batteries, and we expect significantly higher and more-prolonged subsidy levels per vehicle. We assume that in OECD regions and Greater China there will be willingness to continue such support, which boosts EV uptake through TCO and also works in the same direction by making ICEs less attractive through higher carbon prices.

FIGURE 1.7

Market share of electric passenger vehicle new sales

Units: **Percentages**



Electric vehicles include BEVs and FCEVs.
Historical data source: Marklines (2021), IEA EV Outlook (2021)

In addition to direct purchase and manufacturing subsidies, a host of preferential operating treatments for EVs are used, 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; thus far, EVs have not been taxed at the same levels. With the exception of a few oil-rich countries in Middle East and North Africa (Mundaca, 2017), direct fossil-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, 2019). We foresee increasing tax and carbon-price levels to reflect local air-pollution prevention, efforts to limit congestion and emissions.

Relative utility: EVs and ICEVs

In terms of the 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

The EV footprint advantage reflects the weight at which low-emission electricity as fuel and associated sustainability gains are valued (or not). However, even EVs that use electricity with high shares of fossil fuel-based power have better lifetime carbon efficiency than size-equivalent ICEVs (ICCT, 2018). Comparing the utility of EVs and ICEVs by the aforementioned four factors, EV-uptake rates are significantly slower for commercial vehicles than for passenger vehicles – despite prolonged subsidies being forecast.

As shown in Figure 1.7, in Greater China and Europe, EVs will reach 50% passenger market share in the late 2020s, while in OECD Pacific and North America this will happen by 2031. For the world as a whole, the milestone of 50% global sales share for EVs will be passed in 2032. In less-developed regions, uptake will come later as a combination of low charging-infrastructure density, and lower or no subsidies hinder early uptake. However, even in the slowest uptake region, the 50% sales figures will be reached before 2047. By 2050, hardly any ICEVs will be sold in Greater China and Europe, while in other regions sales of ICEVs (up to 30% in North East Eurasia) will continue. For commercial vehicles, electrification will be more prolonged. The world is split into frontrunner regions and laggards regarding uptake of commercial BEVs. Greater China will see a 50% sales share for commercial BEVs in about 5 years, Europe only 2 after that. North East Eurasia and Middle East and North Africa will not see a 50% split in sales within our forecast period (Figure 1.8).

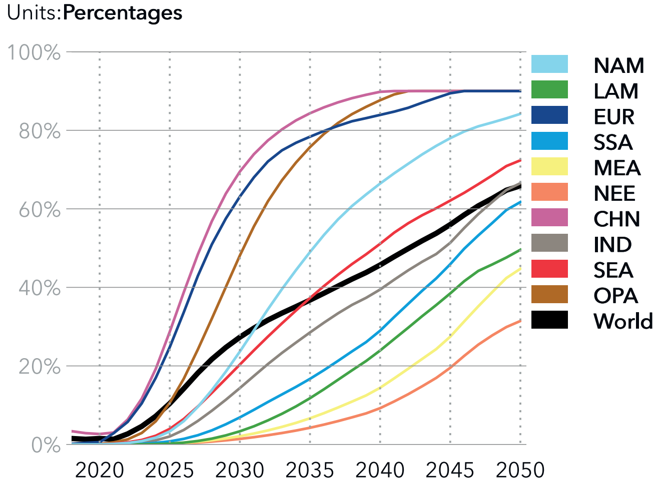
As there are further barriers to completely replacing current commercial ICEVs with battery electric ones, we foresee that fuel-cell electric vehicles (FCEVs) will play a significant role after 2030. These will account for up to 16% of the commercial EV fleet in OECD regions and China by 2050, and to a smaller amount in the other regions. The cost and energy-efficiency disadvantage of fuels cells compared with BEVs will prevent their uptake in all but one market segment – heavy and long-haul commercial-vehicle transport. We have limited the sales rate of commercial EVs to 90%. The remaining 10% are assumed to be unsuitable for EV use. This segment will continue to use combustion technologies, although it should be noted that this also allows for biofuel use.

Some countries, such as Japan and South Korea, strongly

FIGURE 1.8

Market share of electric commercial vehicle sales by region

Units: **Percentages**



Electric vehicles include BEVs and FCEVs.
Historical data source: Marklines (2021), IEA EV Outlook (2021)

support the uptake of FCEVs as part of their automotive emission-reduction plans (see Chapter 7 for more details). However, there is a significant energy loss (approximately by a factor of two) when converting power to hydrogen. Additional well-to-wheel efficiency reduction happens when hydrogen is converted to electricity in the vehicle. Consequently, FCEVs can only reach an overall well-to-wheel efficiency of between 25% – 35%, significantly lower than the 70% - 90% for BEVs. Furthermore, FCEV propulsion is more complicated, and thus more costly, than that of BEVs. For these reasons, most major vehicle manufacturers appear to be introducing solely BEV models.

As there are further barriers to completely replacing current commercial ICEVs with battery electric ones, we foresee that fuel-cell electric vehicles (FCEVs) will play a significant role after 2030.

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 vehicle demand and electrification of two- and three-wheelers in those three regions only, limited to those vehicles requiring registration (electric bikes are categorized as household appliances rather than road vehicles). We forecast rapid electrification in this sector – already over one third of all Chinese two- and three-wheeler sales are BEVs.

The combined forecast, including two- and three-wheelers, for 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 1.9. 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), which we consider as a bridge in our forecast. However, its existence will not be sustained once EVs have sufficient range and charging infrastructure has been widely implemented. This is because, with both an electric and a petrol engine, PHEVs have a high initial purchase price and also high operating costs.

Conclusions

Despite the dampening effect on demand due to 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 EVs have energy efficiencies that are 3-4 times higher than those of combustion engines. Consequently, road-sector energy demand will be lower in 2050 than it is today.

Figure 1.10 shows that, in 2050, while the vast majority of vehicles globally will be EVs, they will constitute just 30% of the road subsector's energy demand. The demand from FCEVs will be 3% of road transport (using only hydrogen). Mostly through mandated blend rates, 3% of sectoral energy will come from biofuel. The smaller part of the vehicle fleet still reliant on fossil fuel combustion will be responsible for the lion's share of energy consumption. Fossil fuel oil constitutes 60% of the global road-subsector's energy demand in 2050, while natural gas will be for niche uses only in a global context – at around 4%.

Sensitivities

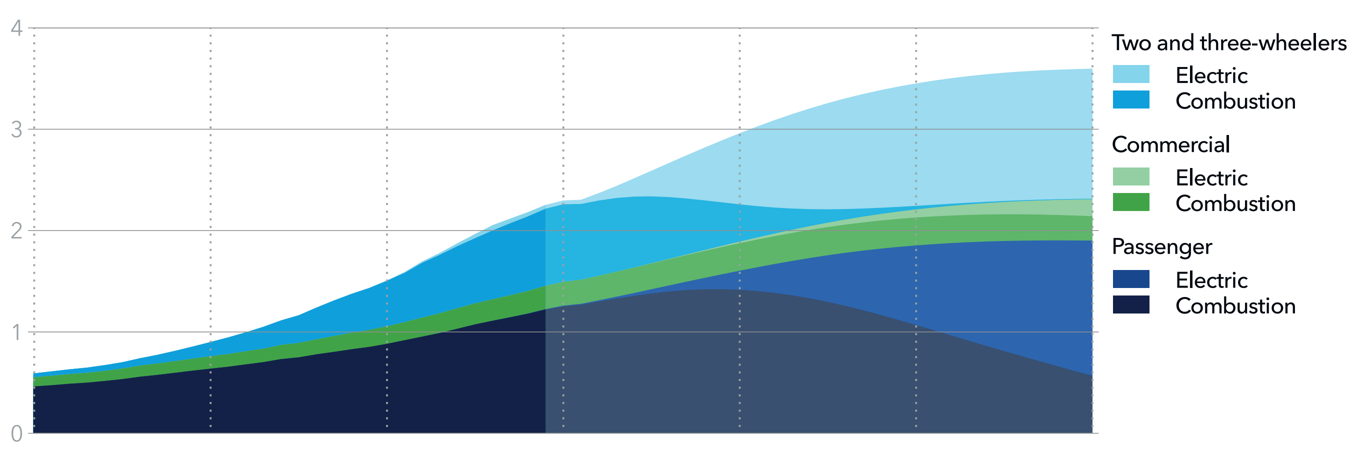
We have examined how sensitive our results are to changing various factors. The effect of battery CLRs is substantial. Regarding battery cost-learning, we see labs filled with alternative options, and while their cost dynamics are highly uncertain, they might reduce aggregate global battery CLRs, at least for a transition period. As a consequence, we may observe even stronger CLRs later. A 50% higher battery CLR (27% instead of 18%) results in 150 million more passenger vehicles (+11%) and 85 million more commercial vehicles (+50%) by 2050.

Subsidy levels for passenger and commercial EVs, which are assumed to be substantial, have considerable effect. Cutting them by 90% from the base case, will result in six million fewer passenger EVs in 2050. Subsidies are even

FIGURE 1.9

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: Marklines (2021), IEA EV Outlook (2021), OICA (2016)

more important for commercial vehicles, and, doubling them from our base case, will result in a much faster uptake – some 35 million more commercial EVs. Note, however, that the main conclusion is that EV uptake over time is not insensitive to subsidies, with support given during early market uptake being most important.

Our sensitivity analysis indicates that if manufacturers were to install larger batteries in their EVs, this would be detrimental to short-term sales, if battery costs per kWh remained the same. For example, a 25% increase in battery sizes would lead to a 11% reduction in global EV stock and 22% fewer EV sales in 2025. The long-term impact, however, would be negligible.

Aviation

Prior to the pandemic, almost 9% of the world's oil was consumed by civilian aircraft, and that share was growing. Driven by rising standards of living, global aviation tripled over the last twenty years. There is a clear relationship between GDP growth and the number of people that fly – and the number of flights they make. By 2050, we will see annual global passenger flights growing 130% from 4.4 billion flights in 2019 to 10.2 billion flights in 2050 (Figure 1.11). The strongest growth will occur in China, followed by South East Asia.

From the onset of the pandemic, air travel more than halved and the rebound has been slow compared with other sectors. As described in the COVID-19 fact-box at the start of this chapter, aviation will experience dramatic negative long-term effects from the pandemic-induced downturn. We expect a permanently-lowered aviation demand as a result of the pandemic, stemming from a behavioural shift in work-related travel patterns, with business travel going down 20% compared with our pre-pandemic forecast. On the other hand, no permanent effect on leisure travel is expected.

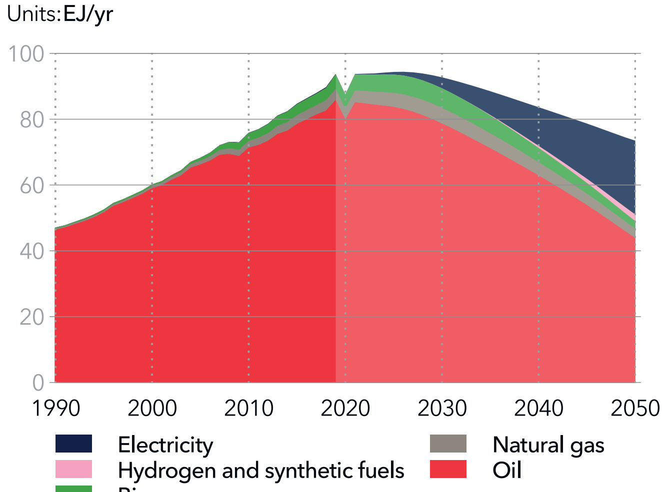
Efficiency, as measured in energy use per passenger km, will continue to improve. This is due to efficiency gains in aircraft and engine technology, better routes and operational patterns, and some gains in higher load factors and larger planes. Annual efficiency improvements will, however, slow from 1.9%/yr today to 1.2%/yr in 2050. This leads to aviation fuel use increasing by only 40% despite a 140% rise in the number of flights, as shown in Figure 1.12.

Cargo flights also contribute to aviation numbers and energy use. The number of cargo flights will also increase, but aviation is and will continue to be dominated by passenger flights. Cargo trips represent 15% of global

FIGURE 1.10

World road subsector energy demand by carrier

Units: EJ/yr

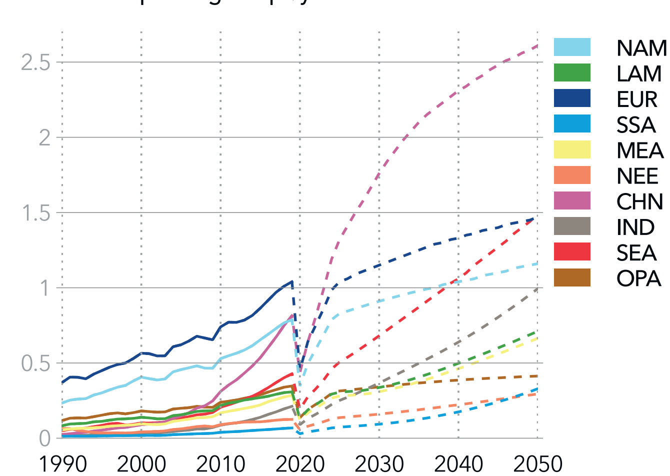


Natural gas includes LPG. Historical data source: IEA WEB (2020)

FIGURE 1.11

Air passenger demand by region of origin

Units: Billion passenger-trips/yr



Historical data source: ICAO (2020), Airbus GMF (2018) aviation energy use (WEF, 2020a), and we keep this fraction constant for all regions and throughout the forecast period. Cargo is included in the aviation energy use numbers below.

Fuel mix

From a technology standpoint, aviation has relatively few options to replace oil-based fuel and is frequently termed a hard-to-abate sector. Yet, with a limited set of stake-holders, and an international governance structure enabling decision-making, it should be relatively easy to implement and monitor the uptake of less-emitting technologies and fuels. However, even if alternatives to fossil fuels progress in the future, they are still prohibi-tively expensive and less readily available in terms of supply and infrastructure. Batteries will not work for long-haul flights as battery weight makes electrification a realistic option for propulsion only in the short-haul flight segment.

The three main routes investigated and expected to change aviation fuel mix are electricity, hydrogen and sustainable aviation fuels (SAFs). Common for all three is that costs, both short term and towards 2050, will be higher than existing technical solutions. All fuel- and technological changes are therefore expected to come as the result of regulatory and consumer-supported forces, such as the ReFuelEU Aviation initiative in the 'Fit for 55' legislative package, higher carbon pricing from removal of free allowances to aviation in the future EU emission-trading scheme (EU ETS) (EC, 2021) and individual willingness to pay for sustainable aviation.

Deployment of electric aeroplanes is likely to start before 2030 on the very small planes with less than 20 passen-gers, and in the 2030s for slightly larger short-haul planes in leading regions. Batteries have very low energy density, and only hybrid-electric solutions are relevant for medium and long haul. Since only a minor part of aviation fuel is consumed on short-haul flights, electricity will represent only 2% of aviation fuel mix in 2050.

Hydrogen is a possible future fuel, and the aviation industry is now starting extensive research into this option, which is likely most promising for medium-haul aircraft. There are technology, cost and regulatory challenges aplenty, and realistically, we will see hydrogen-powered airplanes in use only after 2040 in the first few regions, with limited wider uptake before mid-century.

SAF is already implemented at small scale as a result of mandatory biofuel blend rates in certain countries and is expected to scale relatively fast given regulatory push and consumer pull. In leading regions, we expect half of the kerosene to be replaced with SAF by 2050.

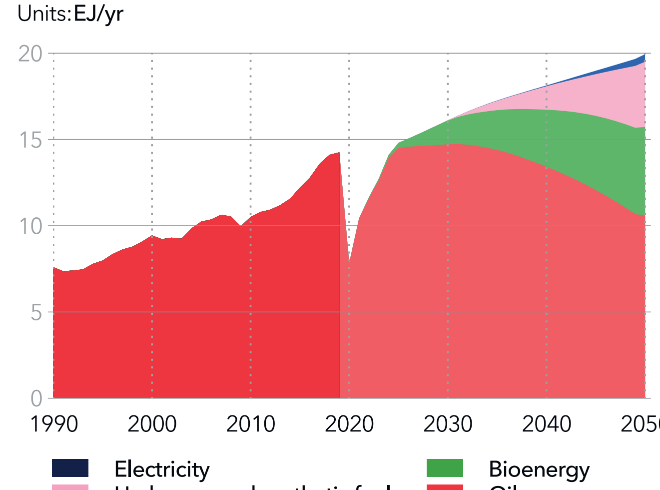
In the short and medium term, SAF is likely to consist mainly of biofuels. As described in the bioenergy section in Chapter 3, providing large amounts of sustainably produced biofuel is a challenge, but aviation has both fewer decarbonization options and a higher ability to pay. In the longer term other SAF solutions will be developed, and liquid synthetic fuel originating from hydrogen is likely to represent a decent share of SAF. As for most synthetic fuels, the efficiencies in the entire production process are low.

Figure 1.12 shows how the aviation fuel mix will change significantly towards 2050, with biofuels having a 26% share and with hydrogen and e-fuels accounting for 19% – here denoting both pure hydrogen aircrafts and (more

FIGURE 1.12

World aviation subsector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

predominantly) hydrogen-based SAF. Oil remains the main fuel source, responsible for 53% of aviation fuel in 2050, but in absolute terms oil use will be 26% lower than today. The efficiency gains and the gradual change in fuel mix means that in our forecast, aviation longer term will fare better than the (current-under revision) CORSIA goals of carbon-neutral aviation growth to 2050.

Maritime transport

Maritime transport is by far the most energy efficient mode of transportation in terms of energy/tonne-kilometre. Nearly 3% of the world's final energy demand, including 7% of the world's oil, is presently consumed by ships, mainly by international cargo shipping.

In 2020, the IMO regulation on a global sulphur cap came into force, resulting in a dramatic change in the type of fuels the fleet is using. The main shift has been to a much larger share of lighter distillates, or other variants of fuels with less sulphur. However, a decent share of marine heavy fuel oil is still being used on ships with scrubbers installed.

In the longer run, the the International Maritime Organization – supported by both shipowners and governments – targets a 50% absolute reduction in CO_2 emissions from 2008 to 2050. Our forecast is that a mixture of improved utilization and energy efficiencies, combined with a massive fuel switch including conversion from oil to gas and ammonia and other low- and zero-carbon fuel alternatives, will enable this goal to be met. In the short-term, the IMO's 2020 target for reducing sulphur emissions will result in an increase – rather than a decrease – in carbon emissions as especially scrubbers are cleaning processes that require additional use of energy, otherwise used for propulsion.

World cargo shipping is an integral part of our analysis. Fossil-fuel demand and supply are regionally determined, and so any mismatch between regions is shipped from the regions in surplus to those with a deficit. Also, within the regions there is considerable seaborne transport of fossil fuel. 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 transportation needs that considerably outweigh efficiency improvements and therefore cargo tonne-miles will increase in almost all ship categories (Figure 1.13), with a total growth of 28% between 2019 and 2035. In the later part of the forecast period, the growth will be minor – or non-existent – in most segments, as efficiency improvements equal demand growth. Ongoing decarbonization will also be reflected in global trade patterns. Consequently, coal transport in 2050 is only 50% of its current size in tonnes, crude oil and oil products is reduced by 20%.

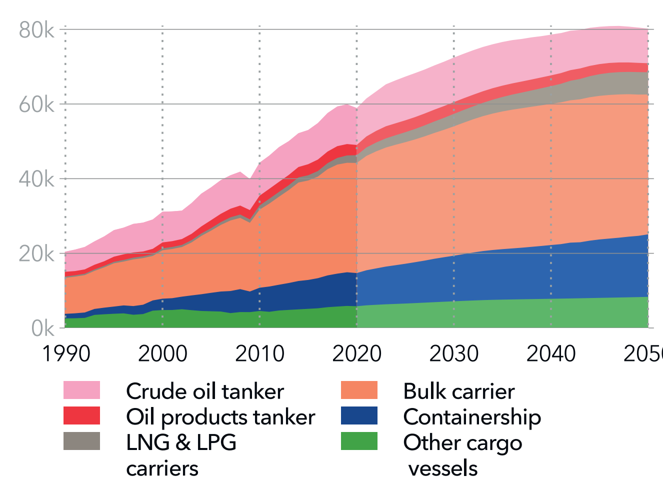
Fuel mix

Driven by the decarbonization push, the fuel mix in the maritime sector will change significantly over the coming decades. Unlike road transport, the potential for electrification in the maritime sector is limited to the short-sea shipping segment, as the energy density of batteries both today and in the future are likely to remain too low to play a larger role in deep-sea shipping, and even unlikely as main propulsion for medium distance trips. Port manoeuvring and shore power will increasingly be electrified for more and more ship types. Efficiency improvements, in the maritime-trans-

FIGURE 1.13

World seaborne trade in tonne-miles by vessel type

Units: Gt-nm/yr



Historical data source: Clarksons Research (2021) portation subsector, are achieved through a mixture of logistics and further hull and engine efficiency measures, as opposed to widespread electrification.

The fuel-mix switch, from being almost entirely oil dominated today to a mix dominated by the use of low- and/or zero-carbon fuels (42%) and natural gas (39%, mostly liquefied natural gas) in 2050, is shown in Figure 1.14 and is supported by a host of successful, regionally imposed, decarbonization efforts. The low-carbon fuels here denote a mixture of ammonia, hydrogen and other electro-based fuels such as e-methanol. We refer to our special Maritime Outlook companion report (DNV, 2021c) 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 covered in the maritime report. The report's fuel mix information is included here, converted into the main energy-carrier categories used in this Outlook.

Rail

The rail subsector consists of all rail-using transportation, including urban rail systems. In 2019, a little less than 2% of global transport energy demand came from the rail sector, which equals about 0.5% of global energy demand. The rise in passenger numbers will be substantial – with a global passenger increase of about 140% by 2050 to 9.9 tn passenger-km. On a global scale, rail freight transport is growing by 90% towards the end of the forecast period with significant regional differences. Strongest growth is expected in Greater China doubling its rail freight demand in the next three decades whereas Europe`s rail freight demand is stable in this period.

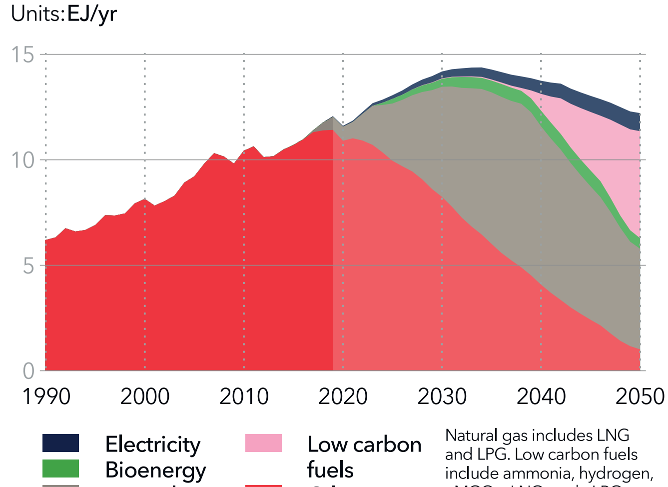
For passenger transport, especially in urban areas, the space efficiency of rail transport is superior to other options, and the ease of electrification also makes it a favourable option for transport decarbonization. Another related explanation of growth is the increasing speed and competitiveness of high-speed trains vis-à-vis aviation, again with decarbonization as a main driver. The greatest passenger growth will happen in the Indian Subcontinent and Greater China, driven by a combination of a significant rise in standards of living and a strong public policy push for rail transport development. As shown in Figure 1.15, almost the entire global passenger rail growth will happen in these two regions, which will see, respectively, about 57% (the Indian Subcontinent) and 27% (Greater China) of global rail passenger transport in 2050.

In all regions, apart from Europe, where rail freight has

FIGURE 1.14

World maritime subsector energy demand by carrier

Units: EJ/yr

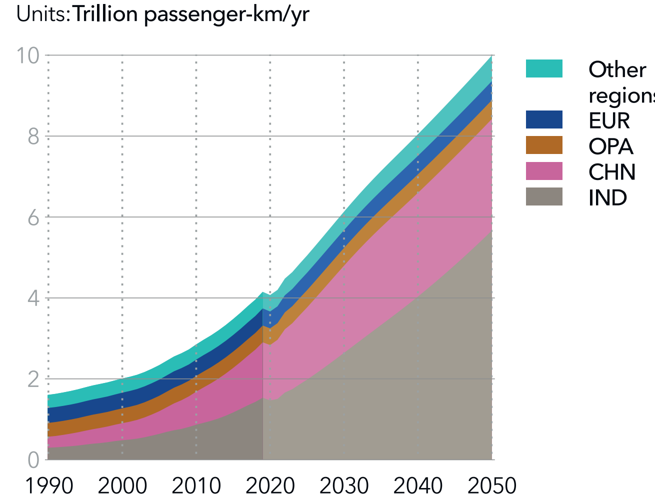


Historical data source: IEA WEB (2020)

FIGURE 1.15

Rail passengers by region

Units: Trillion passenger-km/yr



Historical data source: IEA UIC (2019)

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.

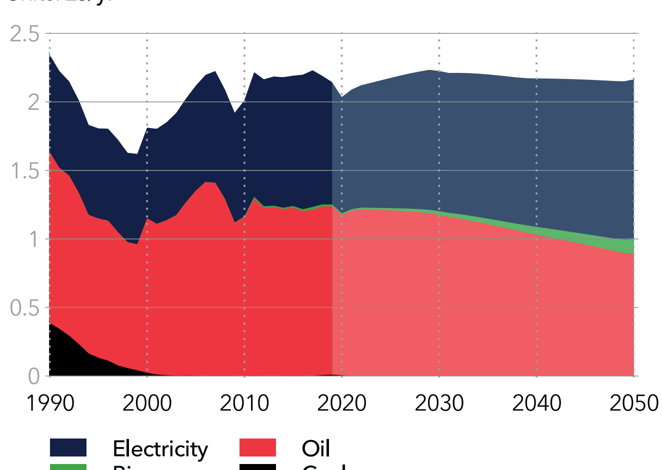
Energy-efficiency improvements will be strong and relates mainly to electrification, but, diesel-powered units will also experience significant efficiency gains. As shown in Figure 1.16, we forecast current growth trends in electrification to be sustained, with a 54% electricity share (up from 41% today), 41% diesel share, and 5% biofuel share by 2050 to meet rail demand. Although hydrogen has potential to replace diesel on non-electrified rail, no significant use of gaseous energy carriers (e.g. hydrogen) is foreseen.

On a global scale, rail freight transport grows by 90% towards the end of the forecast period with significant regional differences.

FIGURE 1.16

World rail subsector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

1.3 BUILDINGS

A growing, more prosperous population will see a rapid growth in residential and commercial floor area, with more heating and cooling per square metre due to the effects of global warming. Owing to significant energy efficiency gains, energy demand will not growth nearly as fast. Nevertheless, buildings will collectively consume 26% more energy in 2050 than in 2019, and the sector's share of global final energy demand grows from 28% to 33% in 2050.

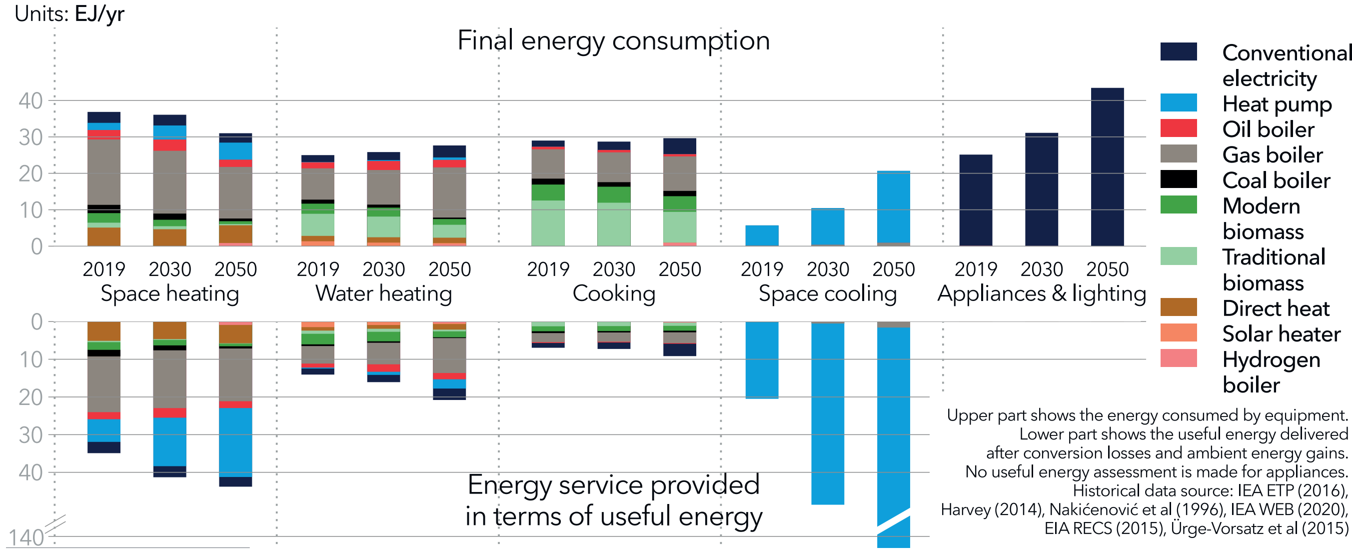
In 2019, 28% of the world's total final energy and 48% of the global electricity was consumed in buildings. About three-quarters of this consumption (88 EJ) was in residential buildings, and the rest (34 EJ) was in commercial buildings, including private and public workspaces, hotels, hospitals, schools, and other non-residential buildings. Direct CO_2 emissions from this sector amounted to 3.1 Gt in 2019, or 9% of all energy-related CO_2 emissions. Including the indirect emissions associated with the electricity and direct heat production, this amount increases to 8.5 $GtCO_2$, or 25% of the total CO_2 emissions.

As the world population continues to increase and the standard of living rises across the world, we will see a continuation of the historical growth in the energy services provided in the buildings sector. However, the associated energy consumption will not increase at the same speed thanks to energy efficiency improvements, driven by higher energy efficiency standards, continued decline in the costs of the energy-efficient technologies and improvements in the building stock. Figure 1.17 highlights this. For example, heat pump technology enables heat provision (useful energy) over three times higher than the electricity provided (final energy). In the case of space cooling, useful energy refers to the amount of heat removed.

FIGURE 1.17

Energy consumption and energy services provided in the buildings sector

Units: EJ/yr



Upper part shows the energy consumed by equipment. Lower part shows the useful energy delivered after conversion losses and ambient energy gains. No useful energy assessment is made for appliances. Historical data source: IEA ETP (2016), Harvey (2014), Nakićenović et al (1996), IEA WEB (2020), EIA RECS (2015), Ürge-Vorsatz et al (2015)

Appliances and lighting

In 2019, appliances and lighting made up 20% of global buildings energy demand and 28% of all electricity consumed globally. Although significant improvements in the energy efficiency of appliances and lighting was made in the last decades, electricity use for appliances and lighting has been steadily rising as the standard of living increase, offsetting any efficiency gains. First postulated by Jevons (1865) in the context of the impact of blast-furnace efficiency on the coal consumption, Jevons Paradox asserts that efficiency gains will lead to a demand increase, not decrease, as savings from efficiency increase will be used to consume more. This rebound effect has many examples, from cars to refrigerators, across various times and cultures.

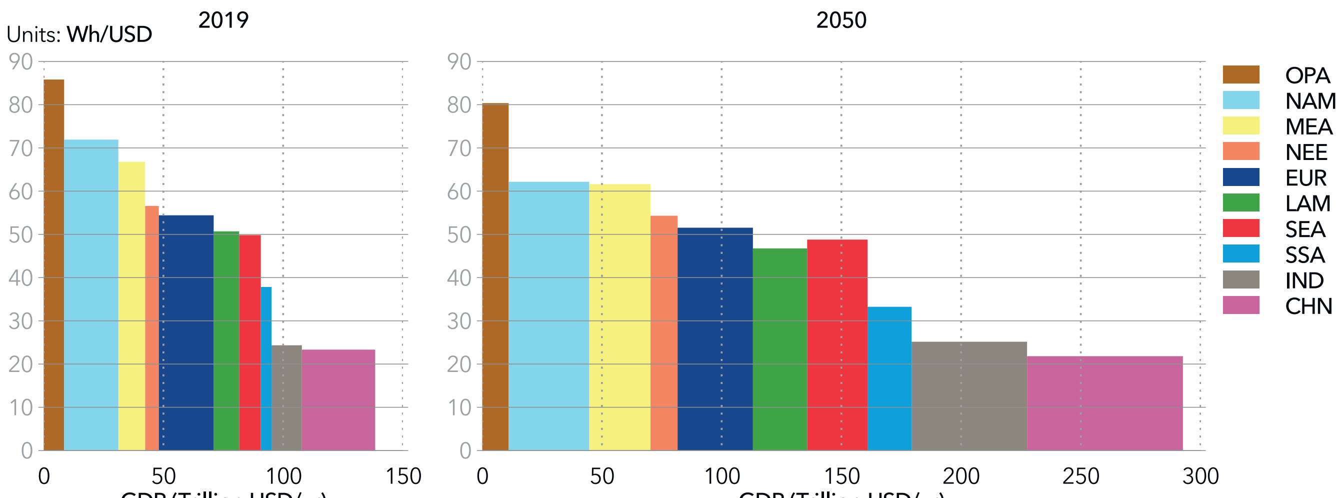
Going in the future, we expect the relationship between GDP and appliances' energy consumption to be maintained with only a modest 0.6%/yr reduction in the unit energy intensity. We forecast that the combined energy demand for appliances and lighting for both residential and commercial buildings will almost double between 2018 and 2050 (Figure 1.18). Three regions – Greater China, the Indian Subcontinent, and North America – will account for half the growth.

Global internet traffic has been steadily growing as more people become connected and the popularity and availability of high-bandwidth activities, like video streaming and videoconferencing, rise. This has increased the load on data centres and on the infrastructure supporting the network traffic. The International Energy Agency (IEA) (2020b) estimates that despite the rise in the demand, the energy consumption of data centres has remained at about 250 TWh, due to efficiency improvements in hardware and infrastructure. We expect the electricity consumption of data centres, which together constitute about 4% electricity demand from commercial buildings (IEA, 2017a), to increase by 2.5% annually (Sverdlik, 2016), reaching 450 TWh/yr, or 5% of the electricity demand of commercial buildings in 2050.

The energy consumption of digital currencies like bitcoin continues to draw significant attention. Concerns escalated when the price of bitcoin surged to 50,000 USD in early 2021, making bitcoin mining more attractive. Electricity consumption from bitcoin mining is estimated to be in the range of 20-80 TWh per year (IEA, 2019), or 0.1-0.3% of global electricity consumption. Future demand for mining of bitcoin and other cryptocurrencies depends on the demand for them, which is linked to

FIGURE 1.18

Appliances and lighting specific energy demand vs GDP by region



Areas show annual energy use. Historical data source: WorldBank (2018), IMF (2021), Harvey (2014), IEA ETP (2016), IEA WEB (2020) government actions that help or hinder their use, and the difficulty of mining, which is a design feature of crypto-currencies. To restrict the volume of bitcoins in circulation, its mining becomes more difficult by design, and hence more energy intensive. Although this feature, by itself, raises concerns for the future energy consumption from bitcoin mining, miners can easily switch to alternative cryptocurrencies like ethereum, which is many times more efficient than bitcoin, when such alternatives become more profitable. Furthermore, bitcoin miners are located where electricity is cheap. Thus, creating demand in the form of bitcoin mining at locations and times with zero or negative electricity prices can potentially support maintaining a balanced market when variable renewable penetration is high.

In Sub-Saharan Africa and the Indian Subcontinent, where the electricity load is low, due to large distances, the cost of grid connection is high, and 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, although it represents only 0.4% of global electricity at 260 TWh in 2050, off-grid solar PV supply will meet 33% of Sub-Saharan Africa's energy demand for appliances and lighting, and 5% of that of the Indian Subcontinent.

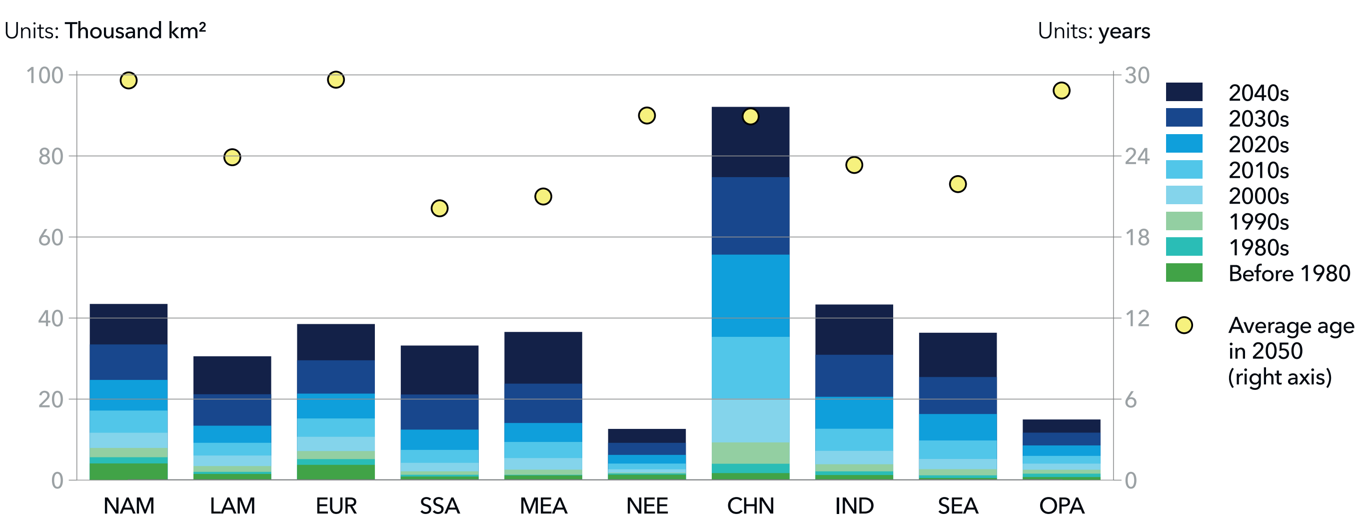
Building stock

The floor area of building stock is one of the most important drivers of energy demand in buildings, as a result of energy consumption in key end uses, such as space heating and cooling, scale with floor area. In 2019, the total floor area of residential and commercial buildings covered 235,000 km², about the same size as Romania or Ghana. The floor area of residential buildings will grow globally by 51% through to 2050, while commercial floor area will more than double in line with the increase in the economic activity, resulting in in combined residential/commercial floor area expansion of 62%. Two-thirds of this floor area in 2050 is yet to be built. The share of new buildings in the building stock will be above 70% with higher population growth, such as in Sub-Saharan Africa and South East Asia (Figure 1.19).

For regions where existing build quality is higher and population growth is slower, renewal will be slower, resulting in a higher age average. The age distribution of buildings has implications regarding the ease and cost of adaptation of new and more-efficient technologies and insulation. Therefore, in the developed parts of the world, where the building stock is older, governments will likely provide stronger incentives for energy efficiency as part of their emissions-reduction policies.

FIGURE 1.19

Floor area of buildings in 2050 by building decade



Space cooling

We estimate that space cooling accounted for only 4.8% of the energy demand of the buildings sector in 2019 but predict that its share will increase to 14% by 2050, 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 air conditioners, as rises in both income levels and standards of living mean that they can be afforded by more people;
- Greater air-conditioner usage as a result of global warming;
- 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 quadrupling to 21 EJ, or 5,800 TWh per year, from 2019 to 2050.

This is despite an average doubling of efficiency, and an insulation-driven reduction in energy losses of 8% over the 2019-2050 period.

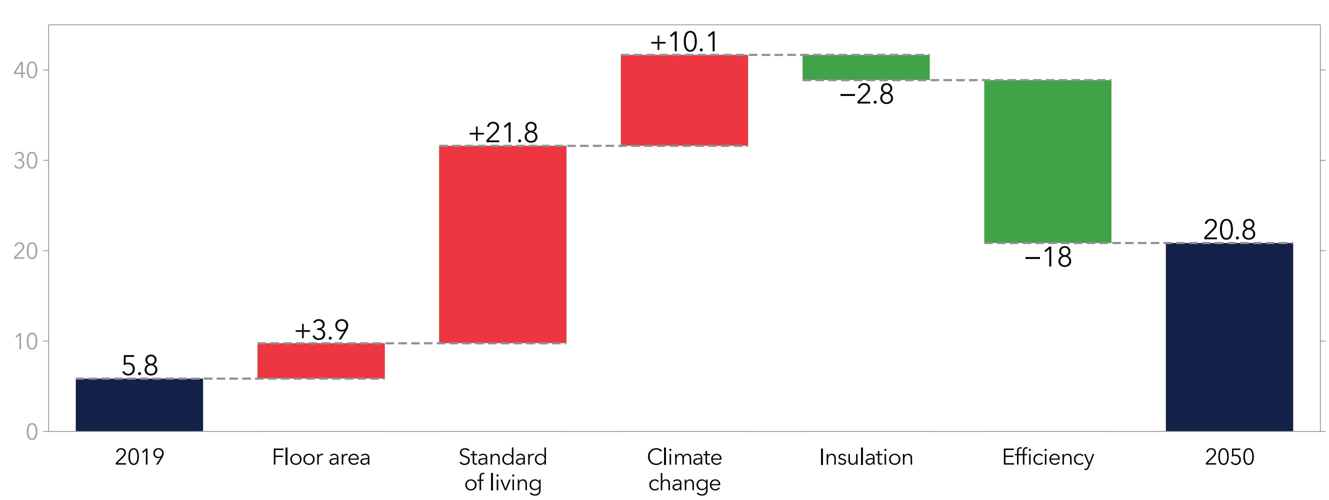
North America presently accounts for about 52% of global electricity demand for cooling. However, in 2050, about 35% of cooling demand will be from Greater China, and only 12% from North America. Europe's electricity consumption for cooling will double from 2019 to 2050.

Those regions with the greatest economic growth also happen to be 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). Currently, four regions have CDD above 1000°C-days/yr: the Indian Subcontinent, Middle East and North Africa, South-East Asia and Sub-Saharan Africa. All of these regions will see their economies more than double by 2050. The result would be a 7 times increase in electricity consumption associated with space cooling for these four regions. Global warming increases the number of CDD and further amplifies this effect. Latin America will join the regions with CDD above 1000°C-days/yr by 2050. By mid-century 44% of all energy consumed for cooling will be in these regions with high cooling degree-days.

FIGURE 1.20

Sources of change in world energy demand for space cooling between 2019 and 2050

Units: EJ/yr



Space and water heating

Space and water heating constituted 31% and 21% respectively of the buildings sector's total energy consumption in 2019. With an increasing population and greater floor area, demand for space heating will continue to grow, rising by 21%, in terms of useful heat provided for space heating, by 2050. Improvements in insulation and fewer heating degree days due to climate change will help reduce the speed of this growth by about 20%. For residential buildings, GDP per capita is the biggest driver of hot-water demand per person. The water-heating demand of commercial buildings – about 27% of global final energy used for water heating – is driven primarily by floor area. Globally, the demand for hot water will increase from 12 EJ of useful heat in 2019 to 20 EJ in 2050.

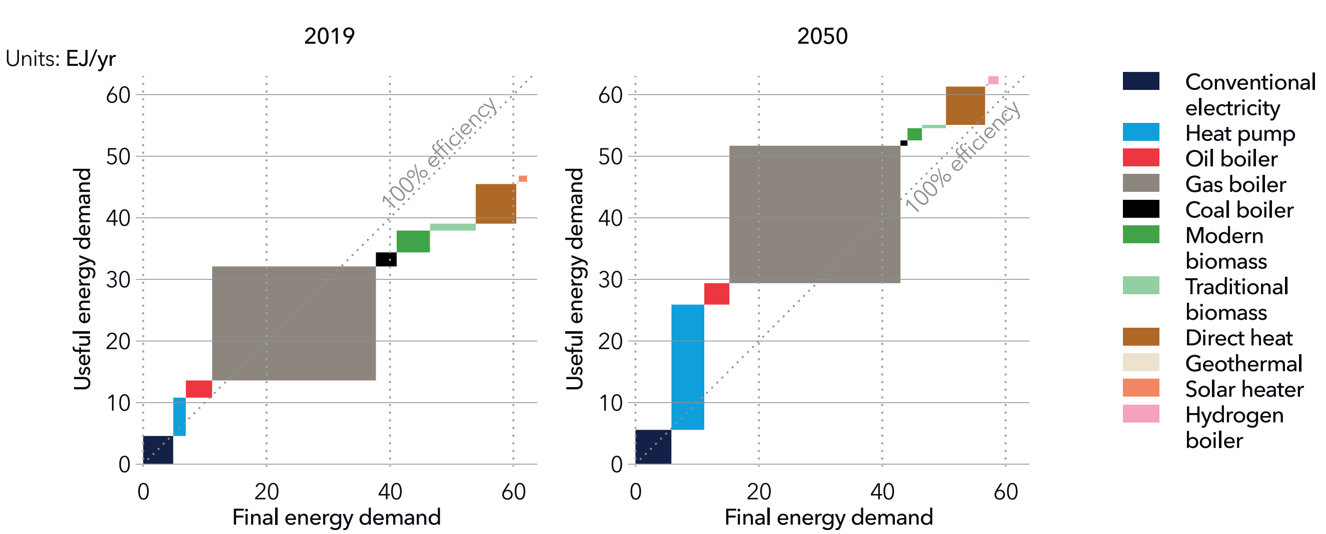
Regions with colder climates (North East Eurasia, North America, Europe, and Greater China) create most of the demand for space heating. For water heating, the regional differences are mostly driven by standard of living. In developed regions, increasingly efficient hot-water tanks are used continuously to serve multiple needs, from daily showers to washing dishes. In some less-developed countries, water is heated as required for basic needs using inefficient methods.

Figure 1.21 shows the relationship between final energy consumed for providing space and water heating versus the useful heat provided. 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, as heat pumps extract more heat energy from the air or the soil than the energy they consume in the form of electricity. The average efficiency will increase from 77% in 2019 to 108% in 2050, due to gradual efficiency improvements as well as large shifts due to transition to heat pumps and away from traditional biomass for water heating.

Although energy-efficiency improvements in buildings are typically profitable, developers and retrofitters frequently fail to implement them. One factor in under-investment is the high upfront costs, with liquidity constraints discouraging homeowners from investing in energy-efficiency measures like insulation, even if they will benefit in the longer term. Smarter policy inter-ventions will continue to target this short-sightedness and the split incentives that frequently result in under-investment in efficiency measures; the potential gains to society are too positive to ignore. We expect a 10%

FIGURE 1.21

Final vs useful energy demand for space and water heating



Although energy-efficiency improvements in buildings are typically profitable, developers and retrofitters frequently fail to implement them.

reduction in space-heating demand by 2050 due to better insulation, representing a modest improvement trajectory.

The uptake of heat pumps is helped by cost-learning rates. Current costs of heat pump systems vary between USD 850 and 1,400 per kW thermal, depending on the regional conditions. With a global learning rate of 20%, decreasing gradually to 15% in 2050, the cost of heat pumps falls to a USD 550-950/kW range in 2050. Figure 1.22 presents the average levelized cost of various heating technologies per MWh of heat. This contains the fuel cost and part of the investment cost when it is allocated to the total heat that it provides over the lifetime. For heat pumps, the electricity price constitutes about 40% of levelized cost in regions where heating demand is high; the exception is Europe where the share is about 65% due to high end-use electricity prices. European households carry a tax burden averaging over 30%, whereas the rates are less than half of this is other regions. Thus, although heat pumps reach a levelized cost parity with gas boilers in Greater China during the 2020s, they remain relatively expensive in Europe. Nonetheless, in some local markets like Norway, where cheaper electricity prices lower operating costs and long winters ensure a higher investment profitability, heat pumps constitute the majority of the market, although cold temperatures mean a lower coefficient of performance. Thus, even in Europe, heat pumps manage to maintain 10-20% market share. Globally, heat pumps will provide about 40% of the useful heat for space heating in 2050 while consuming only 15% of the total final energy supply.

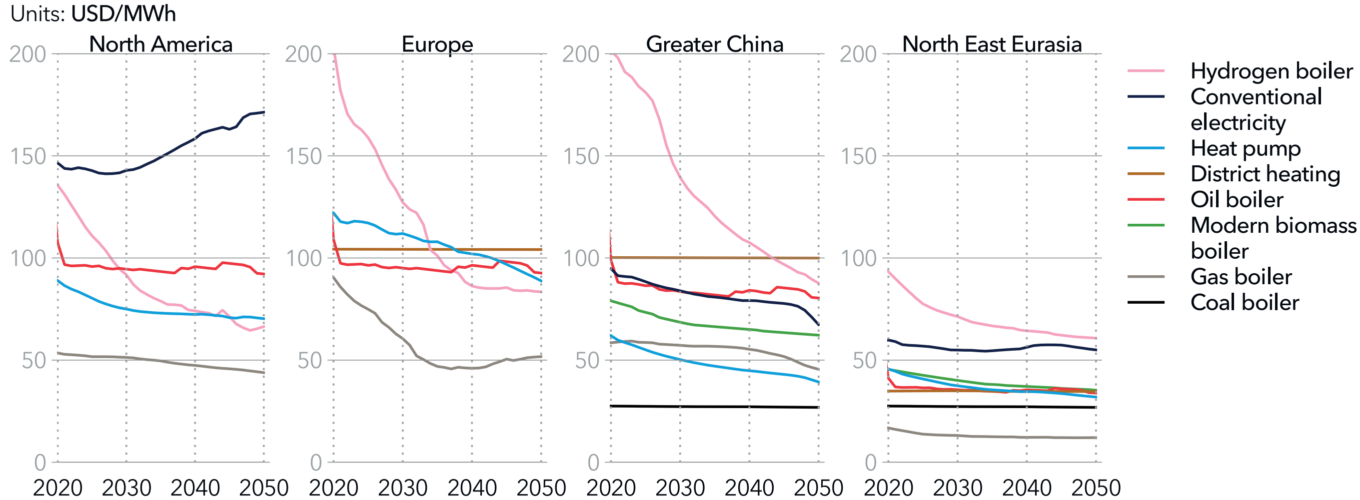
Another big driver of improvements in efficiency is the move away from traditional biomass stoves for water heating. Although consuming 24% of the final energy used globally for water heating in 2019, traditional biomass only provided 6% of the useful energy. Increased energy access will bring the final energy represented by traditional biomass to 13% by 2050, resulting in savings of 2.5 EJ per year.

As a result of these developments, final-energy demand for water heating will only increase from 25 EJ in 2019 to 28 EJ in 2050, with a slight shift from residential to commercial buildings. Final-energy demand for space heating will fall from 37 EJ/yr to 31 EJ/yr in the same period as the usage of heat-pumps spreads.

FIGURE 1.22

Levelized cost of various heating technologies in selected regions

Units: USD/MWh



Cooking

Cooking is responsible for one fifth of the energy consumed in buildings, and nearly 7% of all energy consumption. We estimate that a typical household needs 4.3 GJ of useful heat for cooking annually, based on 2014 estimates of final-energy use for cooking (IEA, 2017b). Due to heat losses in the cooking process, this amount of cooking requires 18 GJ of final energy, in the form of fossil fuel, biomass, or electricity.

Regions with more people per household and less economic means to eat out or buy ready meals tend to cook more often (Figure 1.23). 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 1.8 GJ of final energy for cooking annually.

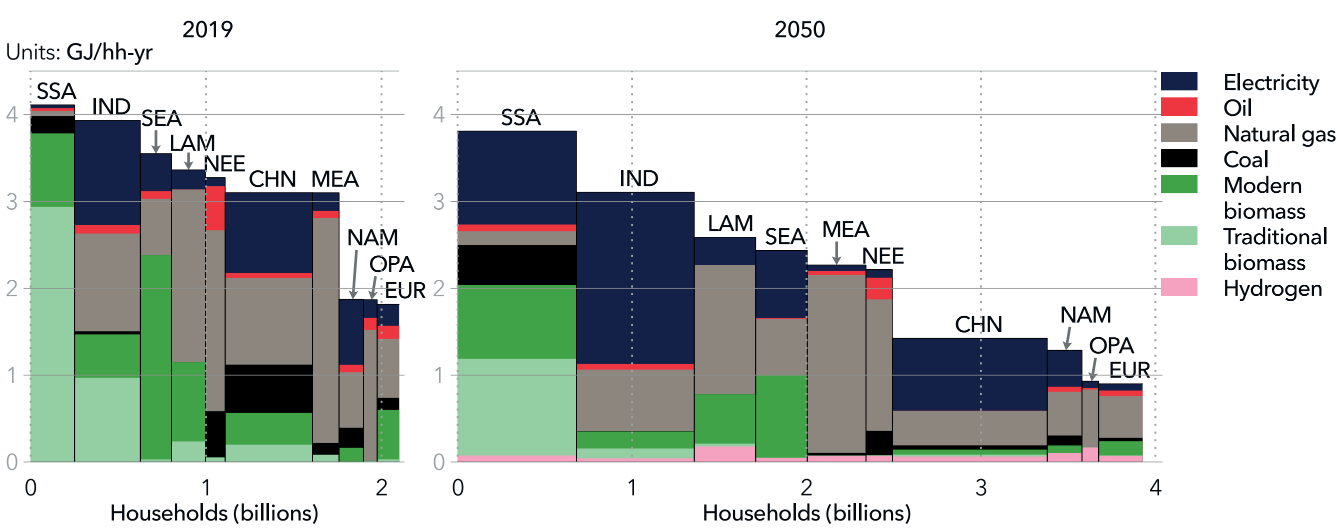
By 2050, the global average household size is expected to decline to 2.4 (Ürge-Vorsatz et al., 2015), which will reduce useful-energy demand for cooking per household to 2.4 GJ/year. Accounting for the increase in the number of households, we expect global total useful-energy demand for cooking to rise from 7 EJ/yr in 2019 to 9.3 EJ/yr in 2050.

Globally, 19% of the population uses traditional cooking methods, burning biomass (animal waste, charcoal, wood) with efficiencies of around 10%. This involves about 1.5 billion people, the majority of whom live in Sub-Saharan Africa and the Indian Subcontinent. Developing countries will seek to reduce both burning of solid biomass for cooking and the local use of kerosene, a major health hazard that is responsible for many deaths. By 2050, the population without access to modern cooking fuels will decline by 43%, 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.

FIGURE 1.23

Cooking specific useful energy demand vs number of households by region



Historical data source: IEA ETP (2016), Harvey (2014), Nakićenović et al (1996), IEA WEB (2020), Ürge-Vorsatz et al (2015)

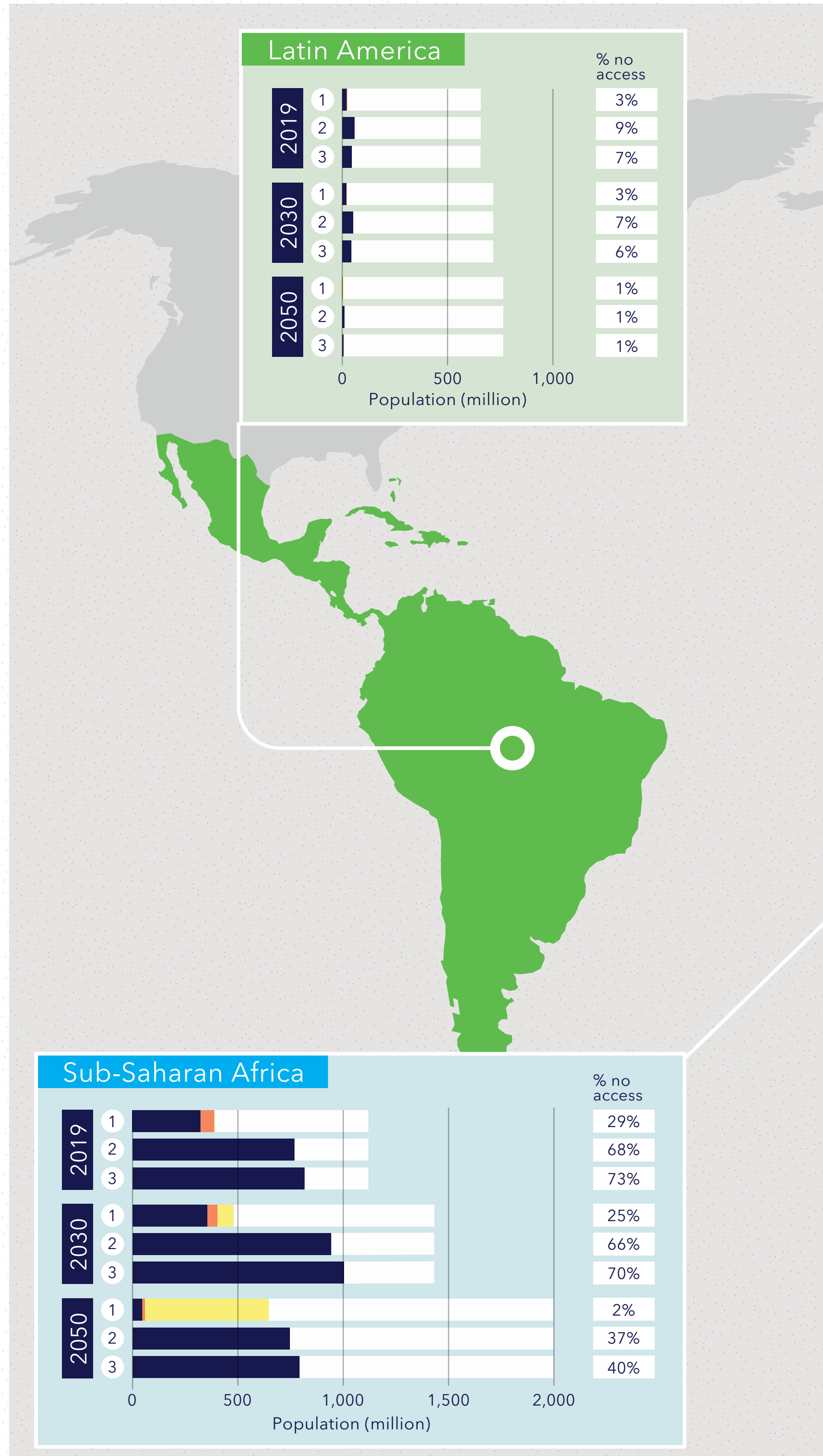
ENERGY ACCESS: PROGRESS ACROSS FIVE REGIONS

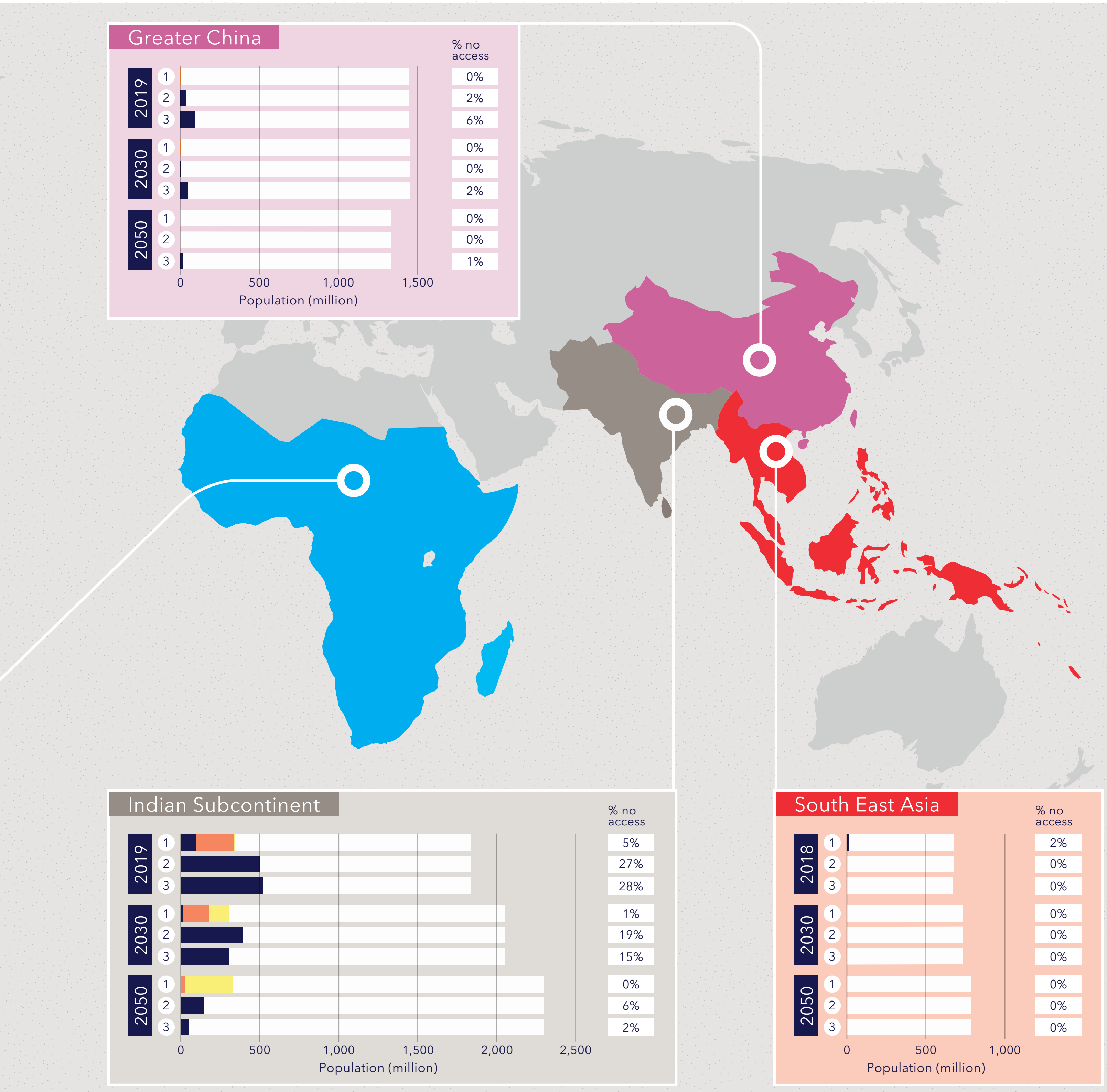
Energy access
This infographic shows improvements during the forecast period in energy access across five regions. Energy access has multiple facets: affordability, reliability, sustainability and modernity of fuels. Moreover, each of these facets lie on a continuum, for example in terms of hours per 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, liquefied petroleum gas, electricity, coal and biogas, or improved biomass cook stoves.

Two regions (Sub-Saharan Africa and the 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, 850–800 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
2019
1
2
3
0%
2%
6%
2030
1
2
3
0%
0%
2%
2050
1
2
3
0%
0%
1%
0
500
1,000
1,500
Population (million)
Indian Subcontinent
% no access
2019
1
2
3
5%
27%
28%
2030
1
2
3
1%
19%
15%
2050
1
2
3
0%
6%
2%
0
500
1,000
1,500
2,000
2,500
Population (million)
South East Asia
% no access
2018
1
2
3
2%
0%
0%
2030
1
2
3
0%
0%
0%
2050
1
2
3
0%
0%
0%
0
500
1,000
Population (million)

1.4 MANUFACTURING

Manufacturing energy demand, at 131 EJ in 2019, is forecast to grow by 8%, reaching 142 EJ in 2050. The economic output from production of base materials, construction, manufactured goods and mining will grow by 75%, indicating an efficiency improvement of 1.6%/yr.

The manufacturing sector in our analysis consists of the extraction of raw materials and their conversion into finished goods. However, fuel extraction – coal, oil, natural gas, and biomass – and their conversion, are accounted for under "Energy sector own use" (see below). Manufacturing in our Outlook covers four separate subsectors:

Construction & mining – includes mining and construction (e.g. roads, buildings, and infrastructure).

Base materials – includes production of non-metallic minerals (including conversion into cement), chemicals, and petrochemicals; non-ferrous materials, including aluminium; wood and its products, incl. paper, pulp, and print.

Iron & steel – includes the production of iron and steel.

Manufactured goods – includes production of general consumer goods; food and tobacco; electronics, appliances, and machinery; textiles and leather; and vehicles and other transport equipment.

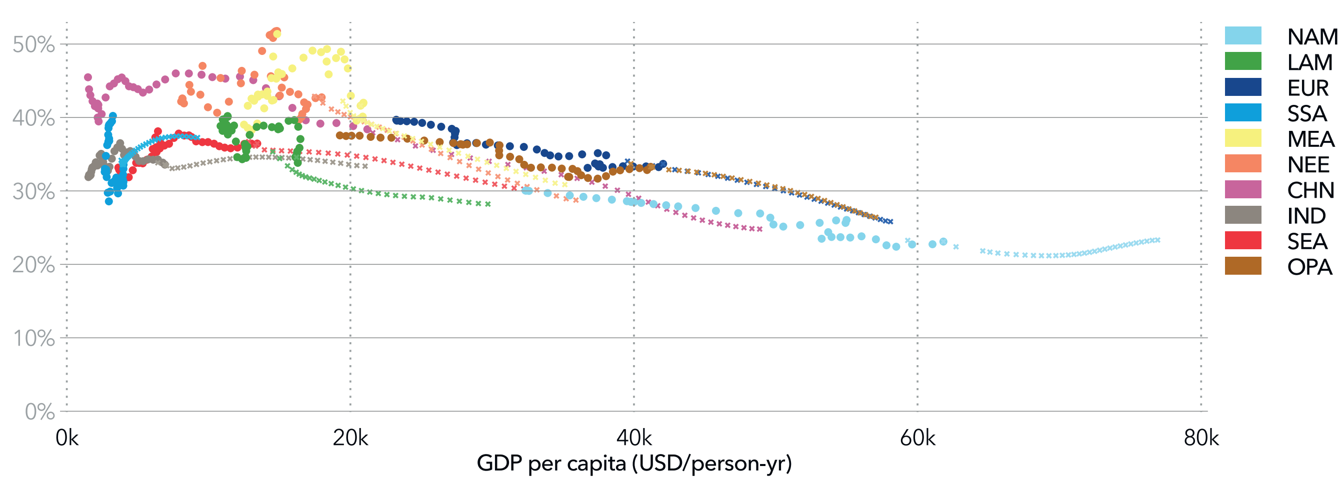
Manufacturing demand

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

FIGURE 1.24

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

Units: Percentages



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

transitions from being an agrarian (primary) economy through to being an industrial (secondary) one, and finally, to a service-based (tertiary) economy, whereupon the industrial sector declines. In our analysis, we have mapped the different sectors of the economy from historical records and then extrapolated those trends into the future (Figure 1.24).

The least-developed regions like the Indian Subcontinent together with Sub-Saharan Africa, currently have growing secondary-sector shares. However, whereas Sub-Saharan Africa shows growth in this sector over the whole forecast period, the secondary sector peaks in the Indian Subcontinent in the mid-2030s and then declines as the tertiary sector grows with increased affluence. For the rest of the regions, most notably in Greater China, national economies are transitioning to become increasingly dominated by the tertiary (services) sector of the economy. North America is the most affluent (per capita) of all regions and therefore has the highest tertiary sector share (75%), which will grow slightly towards 2030 and then recede back to today's levels. It nevertheless remains the region with highest share of GDP in the tertiary sector.

Modelling manufacturing energy demand

There is a strong historical correlation between the individual output of a manufacturing subsector as measured by Manufacturing Value Added (MVA) and the fraction it contributes to the overall secondary sector GDP. Figure 1.25 shows the global MVA and how much each part of the manufacturing sector contributes to its MVA. Using the historical values and extrapolating the same split into the future, we find the output MVA from each subsector which can be used as a basis for converting MVA into energy demand.

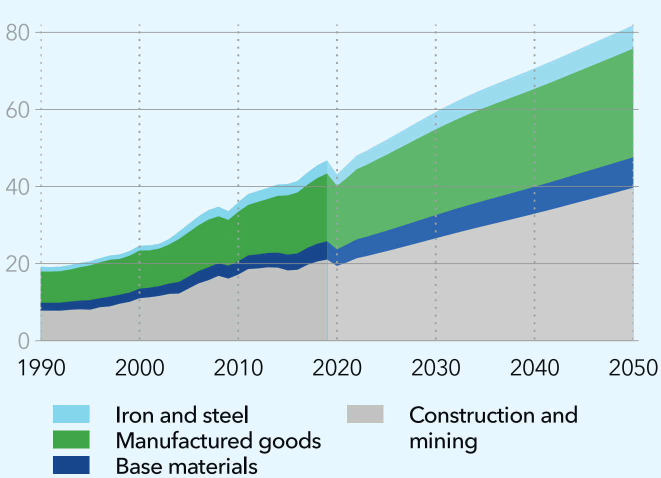
We first estimate the total energy demand for each of our four manufacturing subsectors. This is done by further splitting each subsector into three different end-uses: (1) heating processes (and spaces); (2) powering machines, motors, and appliances (MM&A); and (3) on-site industrial vehicles. The construction and mining subsector uses energy mostly for powering machinery and motors such as cranes and drills, while the base materials subsector uses energy mostly for heating and conversion such as for cement and aluminium. Within the manufactured goods sector, the fraction of energy used for MM&A differs per industry (EIA, 2013), and we keep each region's historical industry mix in estimating their share of different energy end-uses. Finally, the fraction of MM&A in each subsector's energy use depends on the region's technological maturity and associated level of automation in manufacturing. Regions with higher levels of automation will have had a higher historical share of MM&A in their total energy use.

Each region's and each subsector's energy consumption is used to calculate the historical energy intensity (MJ/USD) for each end-use, e.g. the industrial heat intensity and the MM&A intensity. It uses each sector's MVA in the denominator. We filtered out the effect of different contributing factors to historical energy intensity, so that we can more accurately forecast the future by distinguishing between different and sometimes opposing effects on intensity.

FIGURE 1.25

World manufacturing value added by subsector

Units: Trillion USD/yr

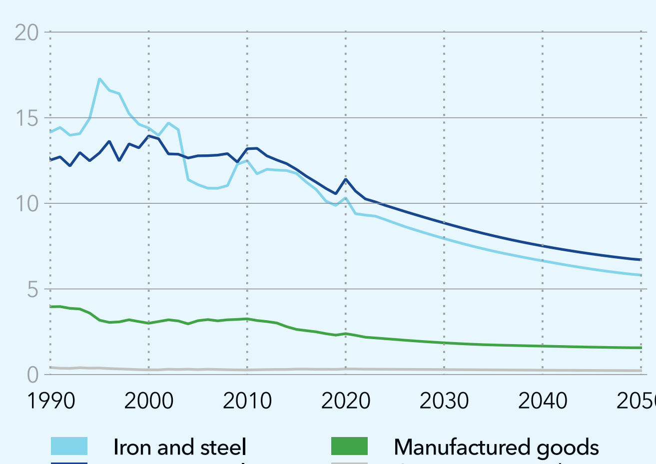


Historical data source: World Bank (2020), UNIDO (2019)

FIGURE 1.26

Energy intensity of manufacturing by subsector

Units: MJ/USD



Historical data source: World Bank (2020), IEA WEB (2020)

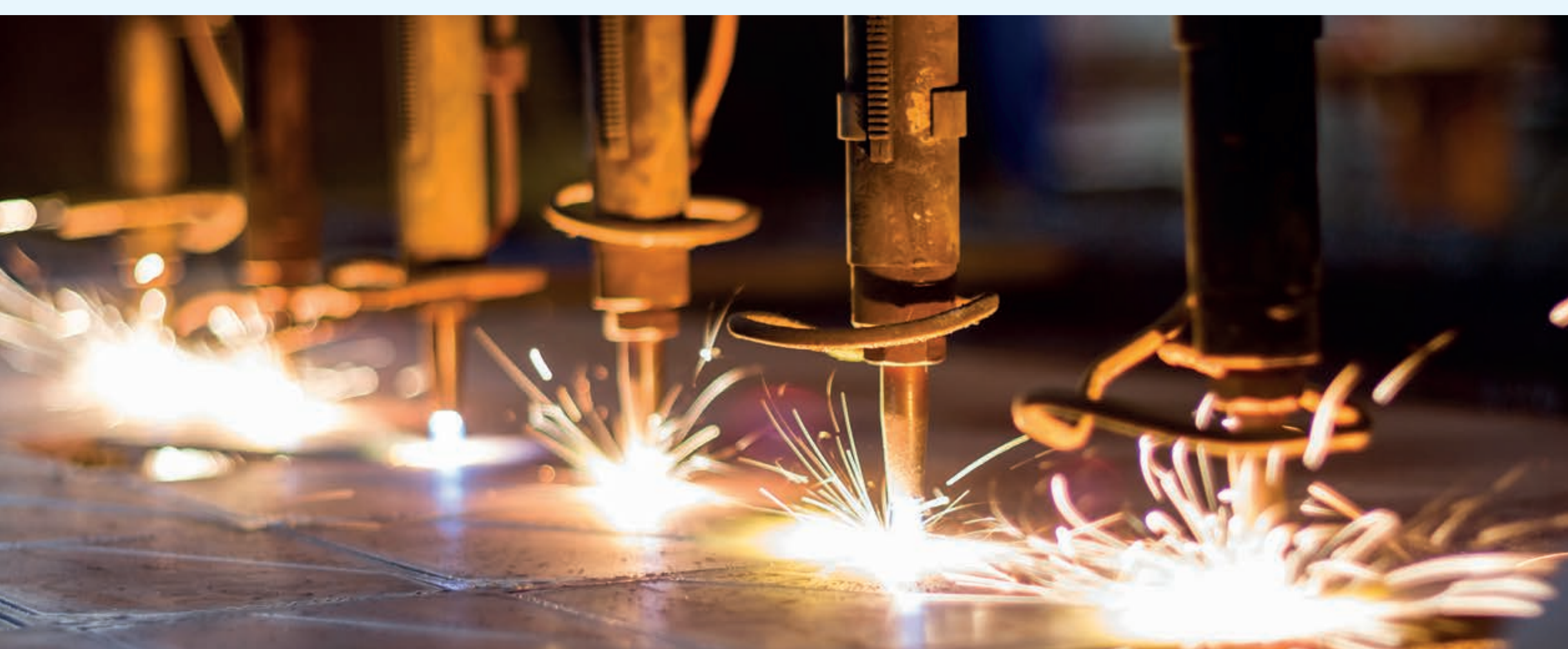
For MM&A, we have accounted separately for the effects of efficiency gains from improved technology (reduces energy intensity), from the use of more efficient energy carriers (reduces energy intensity) and from continued automation (increases energy intensity). We follow the EIA (2013) forecast of annual efficiency gains from technology of some 0.50-0.60% per annum, with the manufactured goods subsector seeing the largest gains.

The effect of more-efficient energy carriers applies most notably to the construction and mining subsector, as it will experience a shift from MM&A powered by oil to more efficient energy carriers such as electricity and hydrogen. The effect of continued automation will be extrapolated towards the future and this will offset some of the intensity gains from more-efficient technology and fuels.

For heating processes, we have accounted separately for the effect of the fuel mix on the heating intensity. In all regions, the fuel mix efficiency has increased significantly over our forecast period. In our forecast we use a levelized cost of heating to determine the fuel mix towards the future. Other contributing factors to heating intensity are, the efficiency of heating technology and equipment, re-use and recycling, and changes in the industry-mix of each region. These effects have been consolidated in a separate trend forecast which is based on historical data. For on-site industrial vehicles, the effects on energy intensity include those from automation and changes in the fuel mix.

Figure 1.26 shows the historical trend and our forecast for the future energy intensity of each manufacturing subsector. This forecast includes the aggregated effects of the various model inputs discussed above. We thus forecast a significant reduction in energy intensity, with both the iron and steel and base materials sector seeing the largest decline, 41% and 36% respectively.

The energy demand for each region and subsector is calculated by multiplying the energy intensity for each end-use with the respective region's and subsector's MVA.



Energy demand

The manufacturing sector is currently the largest consumer of energy, with 131 EJ or 30% of final-energy demand in 2019. The base-materials subsector is the largest manufacturing subsector in terms of energy use, responsible for 38% of the total in 2019. Manufactured goods are responsible for 31% of energy use, followed by iron and steel at 26%, and by construction and mining at 5%.

Substantial energy-efficiency gains, including increased recycling, will balance the growth in demand for goods, such that goods manufacturing energy use will grow by 6% to 2033 and remain flat to 2050. The base materials or 'feedstock' sector will see 11% growth to 2032, but with a 37% reduction in demand thereafter to 2050, due to increased recycling and efficiency gains.

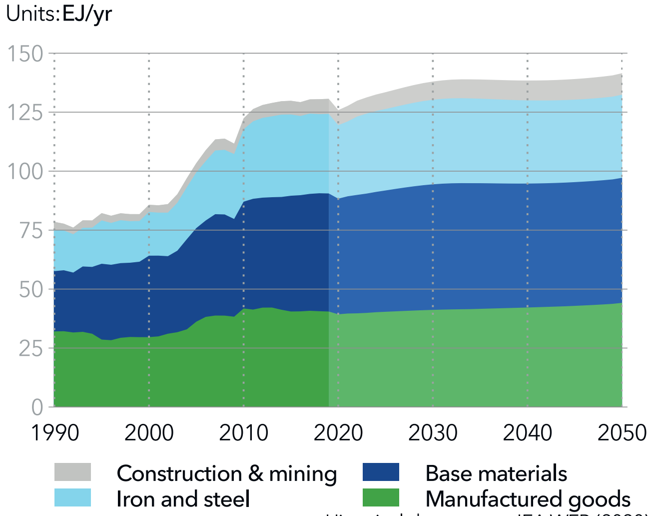
Overall, we forecast global manufacturing energy demand to increase (Figure 1.27), growing by 6% to 138 EJ in 2030, following which it levels off to the end of our forecast period.

The split in total energy use among the four manufacturing subsectors will remain fairly consistent (Figure 1.27), despite evolving differences in the energy mixes of the subsectors. With the exception of construction and mining, energy used for heating purposes makes up the largest share in all subsectors (Figure 1.28). In construction and mining, most energy is used for powering MM&A. In iron and steel there is a significant fraction of energy that is used for the reduction of iron ore to iron, a transformation process required for virgin steel. The reduction of iron ore is accounted for separately because coal consumed in blast furnaces is used both for heat and as a reduction agent.

FIGURE 1.27

World manufacturing energy demand by subsector

Units: EJ/yr



Historical data source: IEA WEB (2020)

In 2019, manufactured-goods energy demand was 40 EJ. As economies grow, the demand for finished goods experiences a similar rise, as is shown by the 60% forecast growth in MVA (Figure 1.25) between 2019 and 2050. Despite this growth, efficiency improvements result in the energy demand from this subsector growing by only 9% to 2050. In particular, heating energy will continue to decline, from 27 EJ in 2019 to 23 EJ by 2050. Energy use by MM&A will increase from 13 EJ in 2019 to 20 EJ in 2050, driven by automation and digitalization. Thereby, MM&A raises its share from 32% in 2019 to 44% by 2050.

Base-materials production is energy intensive (50 EJ in 2019) in its conversion of raw materials into feedstock. Most of the energy use is for industrial high-heat processes (75%) and the rest is mostly for MM&A operation (Figure 1.28). We forecast energy demand in this subsector to grow by 6% to 2030, remaining at that level.

Iron and steel used some 34 EJ of energy in 2019. In a similar way to base materials, the subsector will see a slight increase to 36 EJ in 2030 at which point it levels off. Most of the energy demand in iron and steel is used for heating processes (53% in 2019) and for the reduction of iron ore (35% in 2019). Increasing use of recycled steel will decrease the need for virgin iron ore, triggering growth in electric arc furnaces at the expense of (usually coal-based) blast furnaces. As a result, energy demand for iron ore reduction will reduce from 12 EJ in 2019 to 8 EJ by 2050. In some regions with mature hydrogen infrastructure, there will also be a transition towards direct reduced iron using hydrogen.

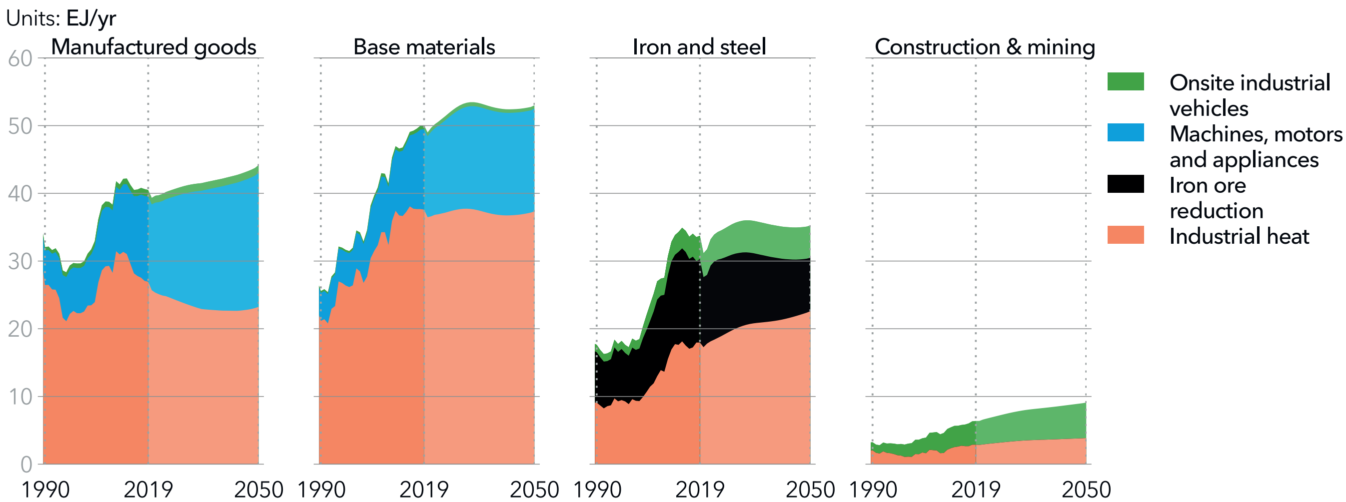
Construction and mining use most of its energy for MM&A, and, with regional differences, energy is also used for space heating. This subsector will see the largest relative increase in energy use, from 6 EJ in 2019 to 9 EJ in 2050. The growth is especially pronounced in regions that will see rapid economic growth including Sub-Saharan Africa, the Indian Subcontinent and South East Asia. The split will remain relatively constant between MM&A, heating, and on-site vehicles.

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 assume manufacturers will act to maximize their profits, subject to regulations, and will therefore use the cheapest fuel. Public policy not only regulates use of

FIGURE 1.28

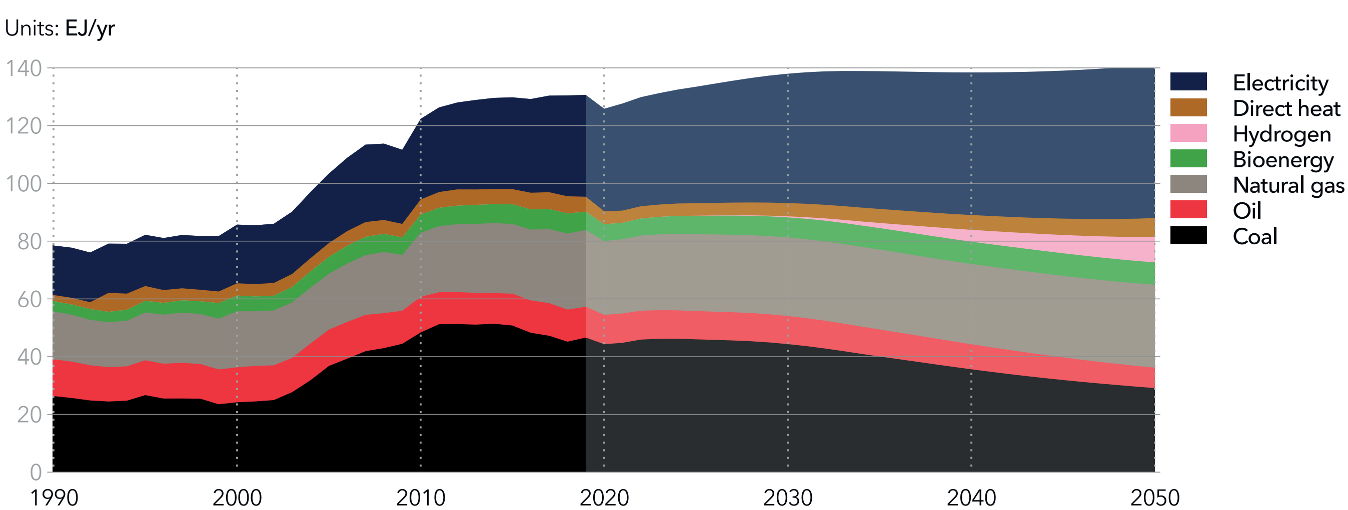
World manufacturing subsector energy demand by end use



Historical data source: IEA WEB (2020)

FIGURE 1.29

World manufacturing energy demand by carrier



Historical data source: IEA WEB (2020)

fuels, but also incentivizes the development of new processes and uptake of new fuels to tackle global warming and local air pollution.

In 2019, about 65% of the global energy used in manufacturing was for heating purposes, which includes both process and non-process heating. Another 24% is used for MM&A 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 fuels and technology developments encouraging the more widespread use of heat pumps, as well as structural changes in the manufacturing sector towards more efficient use of materials. We distinguish between useful and final heat demand, due to energy losses in the heating process that can be as high as 25%. As efficiencies improve, the share of heat in total energy use will decrease to 61% by 2050. Due to continuing automation and digitalization, MMA will see its share increase to 32%, most evident in the manufactured goods subsector. While emerging hydrogen and electricity will see their share increasing (Figure 1.29), coal will see its role amongst energy carriers declining the most.

Heat energy mix

Costs determine the fuel mix and explicitly include: technology cost, fuel price, and policy measures such as carbon pricing, local air pollution policy interventions, and other preferential treatments for cleaner technologies. Figure 1.30 shows the changes in the heat energy mix. Coal will see its share reduced, from 40% in 2019 to 26% by 2050. Natural gas will keep its 31%, while electric heating will increase from 7% to 11%. Hydrogen will see rapid growth from almost zero to 10%.

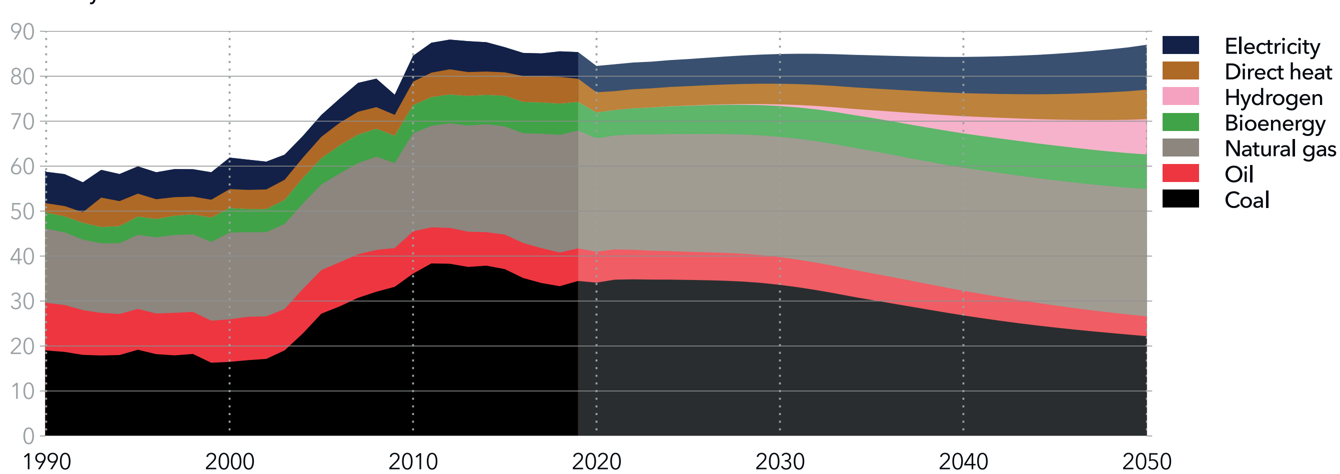
The changes in the heat mix will differ significantly between the different subsectors. In manufactured goods, heating temperature requirements are moderate and will afford uptake of industrial heat pumps. Industrial heat pumps will increasingly be commercially competitive as their high coefficient of performance will increase, up to factor 6. As a result, electricity will see its share in the heat mix in manufactured goods increase from 8% in 2019 to 16% in 2050.

In the base-materials and iron and steel subsectors, where energy is used for high-heat processes, fossil fuels remain the most competitive energy carrier. Electrification of heat processes in these high-heat subsectors 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

FIGURE 1.30

World energy demand for industrial heat by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

near-term electricity is still mainly produced from fossil-fuel sources, there are significant 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 for this reason, the subsector's associated emissions are considered hard to abate. Hydrogen will start to become a viable heat medium in those – high carbon price – regions where it will partly out-compete natural gas.

The base-materials subsector will see a rapid decline in the use of coal for heating, reducing its share from 40% in 2019 to 21% by 2050. Natural gas will be a transition fuel, increasing its share from 30% in 2019 to 36% by 2050. Non-existing in 2019, hydrogen as an energy carrier will represent 11% of this subsector heat generation in 2050, while bioenergy will decrease from 9% to 7%.

Coal will remain the largest energy carrier for heating in iron and steel, although it will see its share decrease from 75% in 2019 to 49% by 2050. Natural gas will become more important in this subsector, growing from 14% in 2019 to 25% by 2050. Hydrogen will increasingly be used for heating as well as reducing agent and will hold a share of 8% by the end of our forecast period.

Construction and mining, where heating is a less important end-use category, will see growth in both natural gas (from 31% in 2019 to 38% in 2050) and hydrogen (from zero to 17%).

Iron ore reduction

The energy used in the process of iron ore reduction has been dominated by coal and still represents 35% of the total energy demand in iron and steel production. Coal use will prevail, as steel production increasingly will occur in regions where coal is competitive. However, a gradual transition to direct reduced steel production will be seen, which is less coal intensive and relies on electricity (converted to hydrogen) and/or natural gas. Increasing use of recycled steel that does not require reduction processing will also contribute to less coal and higher electricity demand. Growth in regional natural gas use (for heating), for example in the Middle East and North Africa, Latin America, and North America will ensue.

Hydrogen is an alternative for use in iron ore reduction but will only enter the mix in Europe and OECD Pacific, where a lower hydrogen price will ensue as a spinoff of hydrogen uptake in other demand sectors. This will ensure high utilization rate of electrolysers, reducing the fixed cost element.

Machines, motors, and appliances (mm&a)

MM&A relies predominantly on electricity as an energy carrier. The manufactured-goods subsector will experience the largest jump in energy demand from MM&A, growing by more than 50% towards 2050, due mainly to increasing output and automation. The other subsectors will see a slower growth in MM&A energy demand. In the construction and mining sector, most energy is used for heavy machinery, such as cranes and drilling equipment. Here, mirroring changes in the heavy-vehicles segment, we forecast a transition away from oil, which provided 44% of MM&A energy use in 2019, to 30% in 2050. Electricity will increase from 50% to 56%, with hydrogen growing from nothing to 10% by 2050.

Onsite industrial vehicles

Most onsite vehicles in use today are fuelled by gasoline or diesel, and represented 1.4% of overall manufacturing-energy demand in 2019. 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 segment in road transport where cost reduction in batteries improves the commercial viability of electric transport. By 2050, oil use will have reduced to 60% of the energy mix, electricity will represent 23%, and we expect some of the heavy vehicles to rely on hydrogen (9%).

1.5 NON-ENERGY USE

Non-energy use reflects consumption of coal, oil and natural gas as industrial feedstock and typically results in something tangible, like plastics. In 2019, about 8% of global primary fossil-fuel supply was used for non-energy purposes. Petrochemicals is the subsector's largest consumer of feedstock, where 45% is used to produce plastics. The rest of fossil-fuel consumption goes to manufacture of cosmetics, fertilizers, paints, and other chemicals. By 2050, the plastic proportion will have grown to about 61% of petrochemical feedstock demand.

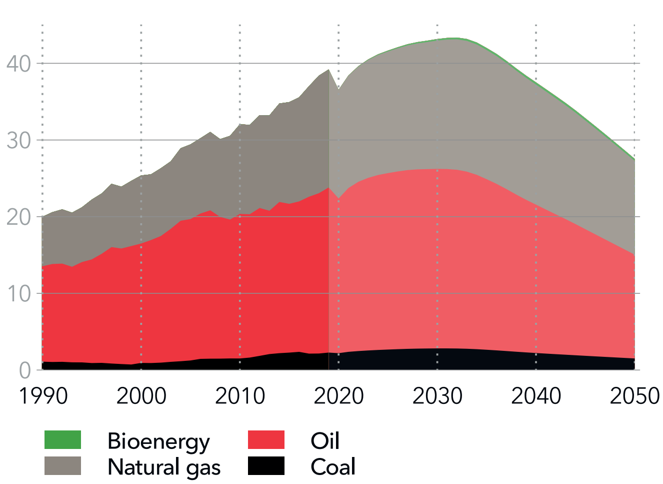
GDP per capita drives plastics demand, reflecting that consumption of plastics increases with wealth (Lebreton, 2019). Rising demand is counterbalanced by re-designs, thinner films and recycling rates. So, while plastic demand continues to grow towards 2050, demand for virgin feedstock from fossil fuels is countered by increasing recycling rates. We estimate the global rate of plastic recycling will improve from around 13% in 2019 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 1.31 shows the resulting non-energy use of virgin coal, oil, natural gas as its feed-stock energy demand will peak in 2032, then, due to improved efficiency and recycling rates, will decline to 64% 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 50% of global feed-stock-energy demand by mid-century. The share of natural gas as feedstock is forecast to grow, rising from 39% in 2019 to 44% in 2050. Coal will remain an important feedstock in Greater China and Sub-Saharan Africa. Bio-based feedstocks as well as electro-based feedstock produced from hydrogen mixing in organic material have the potential to reduce fossil-fuel demand in the long term but will need strong policy support for deployment. We do not expect such support to become available; as non-energy use does not produce the carbon emissions that are accounted for in national inventories, so governments are likely to focus their efforts elsewhere.

FIGURE 1.31

World non-energy demand for energy carriers

Units: EJ/yr



Historical data source: IEA WEB (2020)

Bio-based feedstocks as well as electro-based feedstock produced from hydrogen mixing in organic material have the potential to reduce fossil-fuel demand in the long term but will need strong policy support for deployment.

1.6 FINAL ENERGY DEMAND BY CARRIER

The final energy demand by energy carrier is included in Figure 1.32. The ongoing transition is extraordinary in relation to the growing dominance of electricity in the final-energy demand mix. In 2019, electricity represented just 19% of the world's final-energy use, but in 2050 will represent 38%, growing from 82 EJ/yr to 176 EJ/yr, or 2.5% per year. As electricity has a higher efficiency in its end use, one could argue that more than half of all energy services in mid-century are provided by electricity.

The reason for a steady increase in electrification share is the combination of cost, technology, and policy. As costs of solar and wind will continue to decline rapidly and their share of the electricity mix also increase, electricity will become cheaper relative to other fuels. Technological progress makes electricity available and viable for use in ever-more subsectors and new applications, often in sectors where electric alternatives was either non-existent or very expensive. 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's low-carbon footprint, an advantage that further strengthens as the electricity mix becomes greener.

As electricity has a higher efficiency in its end use, one could argue that more than half of all energy services in mid-century are provided by electricity.

The share of hydrogen as an energy carrier also increases significantly, from a negligible share today to 5% in 2050.

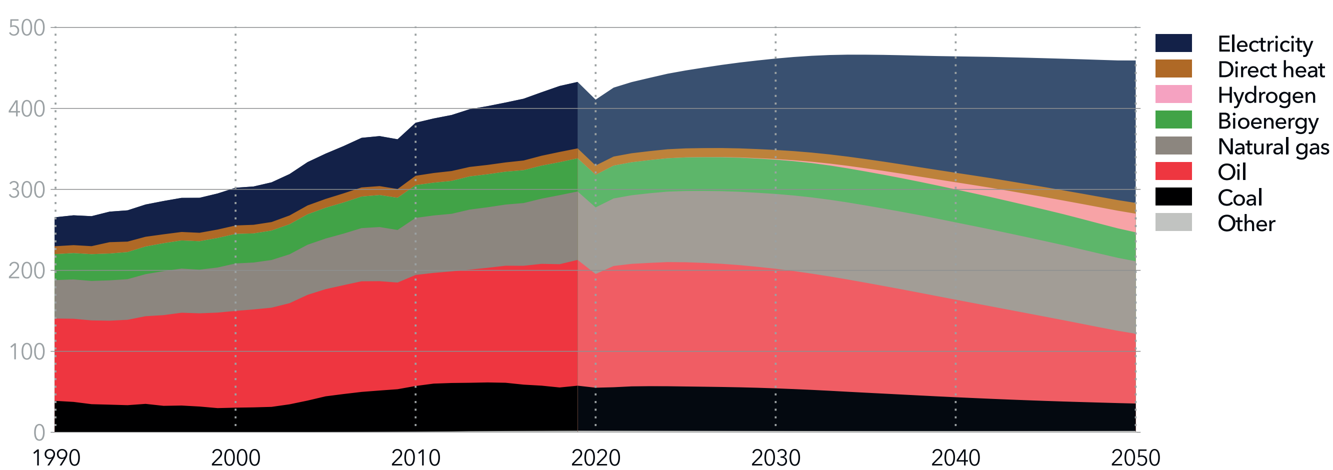
Direct use of oil and coal half over the forecast period, while direct use of gas, bioenergy and heat have stable shares.

The next chapter in this Outlook deals with the electricity and hydrogen production.

FIGURE 1.32

World final energy demand by carrier

Units: EJ/yr



Hydrogen includes synthetic fuels. Historical data source: IEA WEB (2020)

Highlights

Electrification is pivotal to the ongoing energy transition. Electricity demand will more than double between now and 2050, with the share of variable renewable energy sources (VRES) in the power mix growing from 8% to 69% of power generation in 2050.

Rising electricity demand will outpace economic growth in spite of continuous efficiency improvements. This is due to vast new categories of demand: the electrification of road transport (2.8 billion EVs by 2050); space cooling; manufacturing; and the production of green hydrogen.

We detail the changing dynamics in the power market. In the 2050 power system, the maximum price arises when wind and solar supply are at their lowest, unlike the current power system where peak price would typically be at the time of maximum load.

Large investments in a buildout of the grid include doubling the circuit kilometres of transmission lines and a more-than-doubling of distribution line circuit-kilometres by 2050. Ever-larger investments will be made in flexibility, storage and in digitalization.

This year's Outlook provides more detail on the prospects for indirect electrification through hydrogen, with total installed electrolysis capacity reaching 3 TW by 2050. Although that is a large number, in the absence of substantial policy changes, green hydrogen arrives too late and at insufficient scale for a net-zero energy system by 2050.

2 ELECTRICITY AND HYDROGEN

2.1 ELECTRICITY

Although electricity and hydrogen currently rely heavily on fossil fuels, their potential makes them key for the energy transition. Once energy end uses shift to being powered by electricity and hydrogen, they will benefit from fast decarbonization of these energy carriers.

Electricity Demand

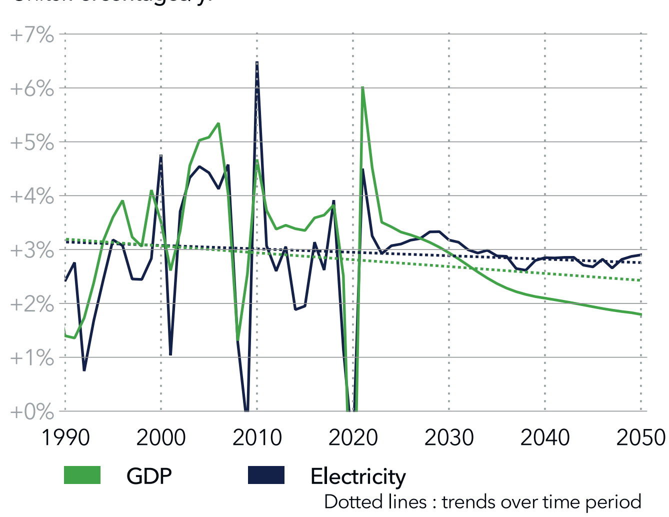
World electricity demand has been growing by about 3% per year since the 1980s, in line with economic growth (Figure 2.1). Not only are the two growth rates similar, but the pattern for growth in electricity demand closely follows the annual pattern of change in GDP. Looking at where electricity is consumed, explains why these two indicators go hand in hand (Figure 2.2).

In industry, most of the electricity is used for running machines, motors, and other appliances that produce everything from food and textiles to vehicles and electronics. The demand for these products fluctuates with economic activity, affecting the associated electricity demand. Another considerable component of electricity demand is the buildings sector, where electricity is used for lighting, cooling, washing, cleaning, and entertainment. Unlike in the manufacturing sector, GDP has a relatively minor impact on the utilization rate of the equipment providing these services, but strongly influences their purchase rate. Efficiency is equally important in the relationship between economic activity and electricity demand; strong efficiency improvements in some end uses, such as lighting, are offset by new consumption categories. Other equipment, like resistive heating, does not have any possibility for efficiency improvement, as practically 100% of electricity is already converted to heat. One notable exception is heat pumps that transfer more heat energy from the ambient environment than the electrical energy they consume; the efficiency of heat pumps already exceeds 300%, with potential for further growth.

FIGURE 2.1

Annual growth in global electricity demand vs GDP

Units: Percentages/yr



Future growth in electricity demand will be slightly under 3%/yr, reaching about 60 petawatt-hours (or 60,000 terawatt-hours) in 2050, including the energy sector's own use and off-grid electricity demand. Electricity will constitute 38% of the world's final energy demand in 2050. Rising electricity demand will outpace economic growth, despite the expansion in heat-pump use and their continued improvements in efficiency. The main reason is the emergence of new electricity-consumption categories.

Of the 35,400 TWh/yr increase in global electricity demand between 2019 and 2050, 6,600 TWh will be come from the transport sector. The vast majority of this energy will be used to charge 2.8 billion EVs. In 2050, grid-connected and off-grid electrolysers will consume 8,100 TWh of electricity to produce 171 Mt of hydrogen – about two thirds of the world's hydrogen demand. Other notable contributors to electricity demand growth are space cooling and the category of industrial vehicles, machines, motors, and appliances. Each of these two categories is responsible for 11% of the 35,400 TWh/yr increase to mid-century.

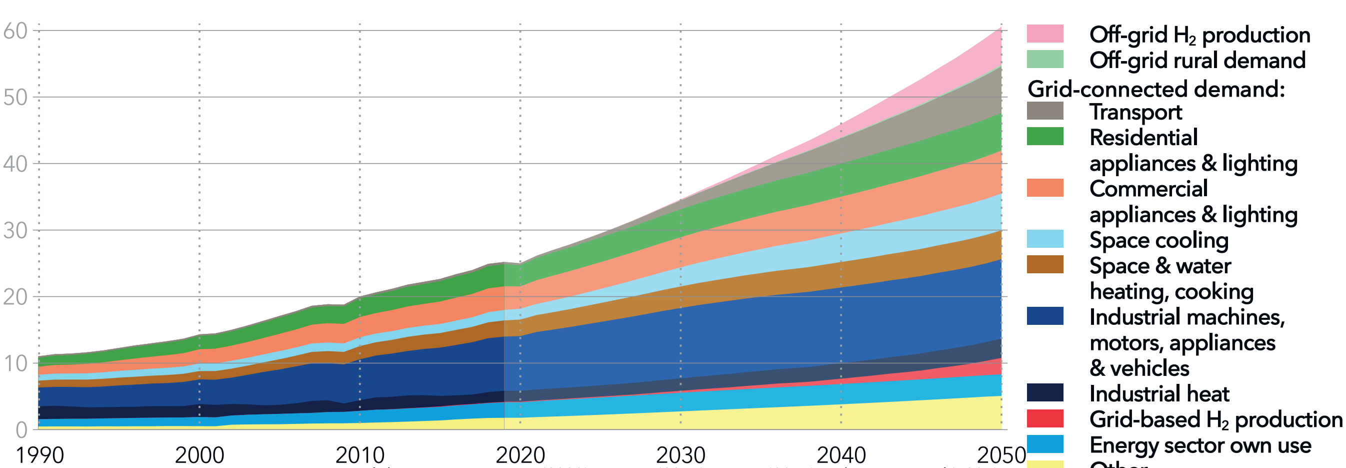
Our electricity-demand forecast is most sensitive to parameters that affect the competitiveness of electricity against hydrogen, and the competitiveness of green hydrogen against blue. Grid charges, taxes and levies such as renewable charges, support for energy-related government programs and VAT vary significantly between countries and may constitute a large portion of electricity bills in many countries; for example, these charges constitute more than half of the total amount paid by residential consumers in many parts of Europe. A blanket 50% reduction in electricity prices across the world would increase electricity's share in 2050 global final-energy demand from 38% to 45%, most of the difference coming from the fuel switch for space heating, changing from gas boilers to heat pumps. The removal of taxes for electrolysers, which use grid electricity to produce hydrogen, would increase global electricity demand by 9 PWh/yr in 2050, or 15%. Increased use of power-to-hydrogen will not only increase electricity demand but will also support variable-renewable technologies by purchasing their cheap electricity and helping them to maintain their revenues. The result would be a further 2% reduction in fossil-based power in 2050.

Rising electricity demand will outpace economic growth, mainly due to new electricity consumption categories.

FIGURE 2.2

World electricity demand by sector

Units: **PWh/yr**



Historical data source: IEA WEB (2020); IEA ETP (2016); Harvey (2014); Nakićenović et al (1996); EIA RECS (2015); Ürge-Vorsatz et al (2015)

Electricity supply

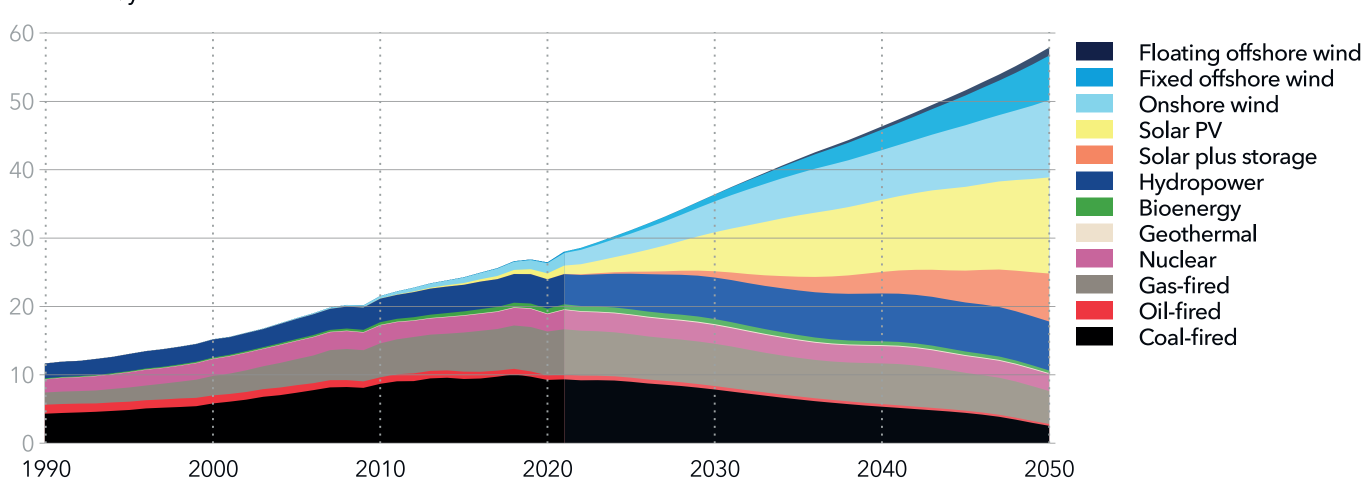
In 2019, only 26% of electricity was supplied from renewable sources, and two thirds of this was from hydropower. With continued declines in the costs of solar, wind, and related technologies, such as batteries, variable renewable-energy sources (VRES) will gradually – but steadily – transition from being marginal, to becoming the major electricity sources in 2050. By then, 82% of the world's grid-connected electricity will be generated from renewable sources, and 69% alone from variable renewables. Enjoying the lowest levelized costs, solar PV's share in the 2050 power supply will be 36%. A third of this will be utility-scale solar farms with on-site storage (solar+storage), as storage will help solar's business case, enabling energy to be utilized not only during daytime, but also at night. Despite having somewhat higher costs than solar, wind will also have growing shares in all regions, as, unlike solar energy, it does not have a cyclical daily intermittency problem. This ensures a higher income for wind plants on the yearly average and results in continued investments. In 2050, 33% of grid-connected electricity supply will be wind-based: 20% onshore wind, 11% bottom-fixed offshore wind, and 2% floating offshore wind. With higher and more-reliable wind speeds, and less constraints on hub heights and site locations, offshore wind will show a 14% average annual growth from 2019 to mid-century.

The role of fossil fuels in the power supply will still be central in some regions, such as Middle East and North Africa and North East Eurasia, 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 the electricity supply. Their role will be reduced to providing flexibility and backup in power systems when VRES are unavailable, especially through low-Capital expenditures (CAPEX) gas-fired power stations. In 2050, fossil fuels will generate 13% of power needs and nuclear 4%. Nonetheless, dispatchable power will still be price-setting and hence will 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 the electricity supply.

FIGURE 2.3

World grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021)

With higher and more-reliable wind speeds, and less constraints on hub heights and site locations, offshore wind will show a 14% average annual growth from 2019 to mid-century. (Image courtesy Øyvind Gravås / Woldcam / Equinor.)

The future electricity system

Historically, the electricity system has been shaped by the variability of demand following daily, weekly, and annual cycles, and by conventional power generators responding to this variability by adjusting their supply. Prices have been set by the variable cost of the most-expensive generation technology, providing revenue for all generators. In recent decades, there has been a constant influx of new technologies, including solar, wind, storage, and power-to-X, but until now, none of these technologies made a large enough impact to create any fundamental change to the rules of the game. However, as these new players mature and grow, they will dictate the new rules, pushing the old-timers to supporting roles.

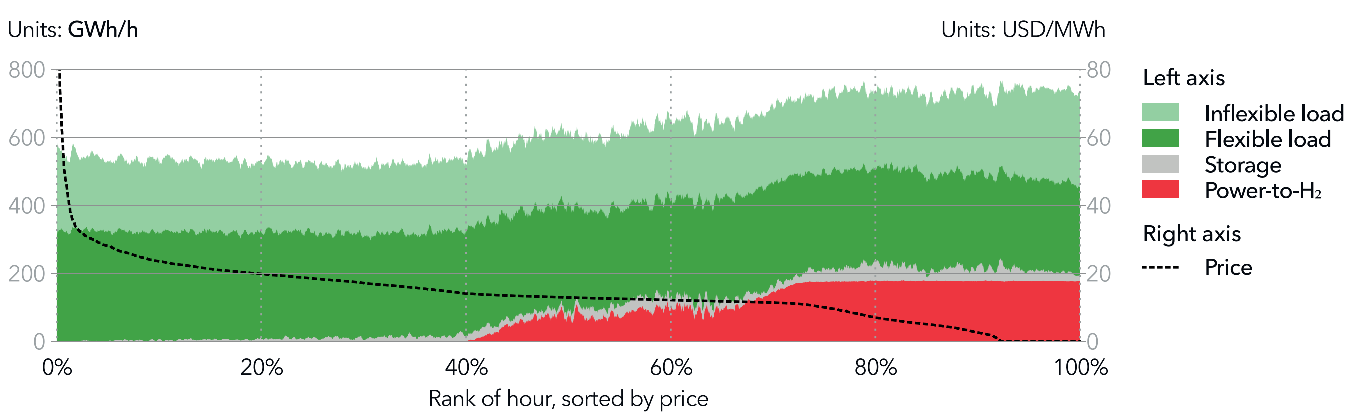
Figure 2.4 and Figure 2.5 illustrate how, using the case of Europe in 2050, a high penetration of VRES would affect the electricity market. Hours of the year are sorted, left to right, according to wholesale electricity price. Flexible load segments are capable of adjusting their demand in response to changes in price. In 2050, a 1% change in electricity price from the average will lead to a 0.12% change in manufacturing, a 0.8% change in residential heating and cooling, and a 0.5% change in EV charging. These segments will constitute, on average, 300 GWh/h in 2050. Other load segments are inflexible, varying between 180 and 280 GWh/h throughout the year. In total, we have modelled 12 categories of end use. Each demand segment has a normalized profile that represents regional demand over a year. These profiles are established on the basis of a representative year and do not change between years.

By 2050, one of the biggest buyers of cheap electricity in the European electricity market will be 178 GW of grid-connected electrolysers. The variable cost of blue hydrogen will be USD 1.54/kg. To break even, grid-connected electrolysers should not pay more, on average, than USD 13 /MWh for electricity. This competition ultimately determines the threshold price for power-to-hydrogen.

Both charging and discharging behaviour of storage is guided by price. Higher price differences from the expected average lead to a stronger incentive to charge or discharge. This can be seen in Figure 2.4 and Figure 2.5, as electricity demand for storage is clustered around low prices and vice versa. Expected price is constantly updated as the simulation proceeds, representing the average price over a fixed period. Storage technologies with longer storage durations use a longer averaging time for their expected price estimates. The behaviour of storage also depends on the state of the charge at the point of decision making.

FIGURE 2.4

Europe's hourly electricity demand by segment in year 2050, sorted by price



Flexible load incudes EV charging, industrial demand, heating and cooling.

We used variable costs, following a normal distribution, to determine willingness to supply for dispatchable power-station types. We ignored constraints, such as start-up times, ramp-up/ramp-down rates, or the heat demand of combined heat-and-power (CHP) plants. 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. This is because we used a statistical distribution of marginal costs of different power plants, simulating differences in efficiency, grid costs, and local circumstances – such as differences in national markets.

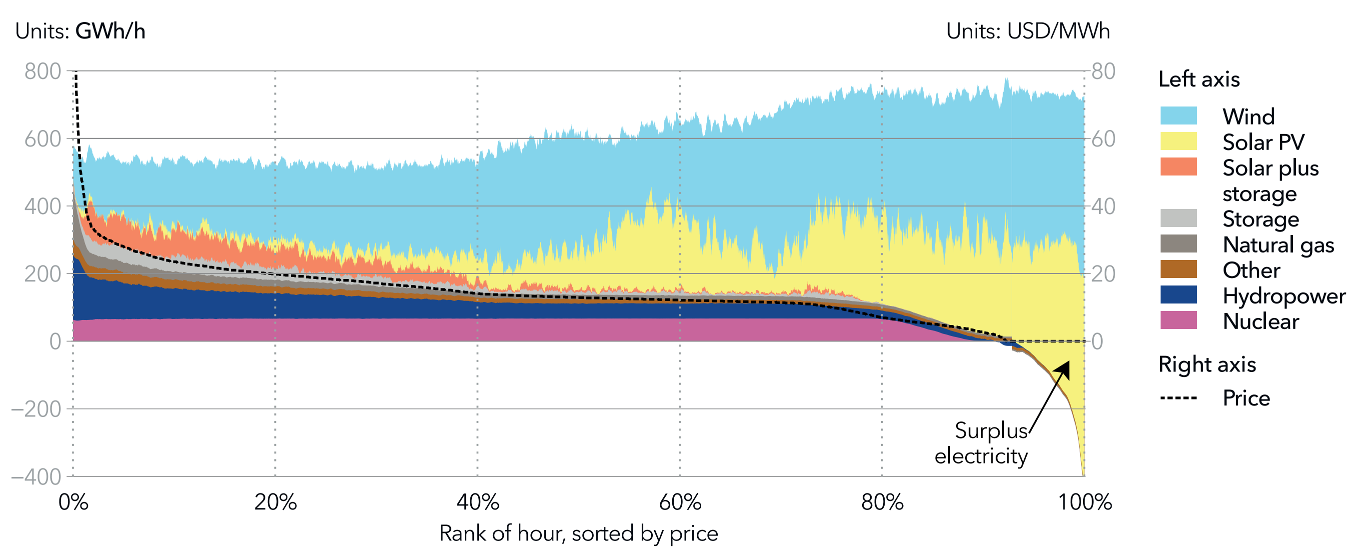
As expected, maximum utilization of dispatchable power stations is reached when the price is highest. But, in the 2050 power system, the maximum price arises when wind and solar supply are at their lowest, contrary to the current power system where peak price would typically be at the time of maximum load. We used normalized deterministic profiles as solar and wind generation patterns. But solar+storage follows a similar heuristic as other storage technologies, discharging when electricity price is high, typically in the evening hours. In this way, they are able to have a better capture price than regular solar PV plants, thereby compensating for its cost disadvantage.

In 2050, the European wholesale electricity price will drop to zero for about 8% of the time within a year, because total supply from solar and wind will exceed demand. Thus, 88 GWh of solar and wind supply would be curtailed, of which 3% is solar generation and 2% wind generation. This amount would be much higher if it wasn't for the flexibility technologies, particularly power-to-hydrogen, which acts like seasonal storage by purchasing excess electricity at times of excessive solar inflow and wind, and converting it to hydrogen for future use as an energy source for heating or transportation.

Our hourly dispatch 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 simplification favours geographically concentrated generation technologies and power-station types that have limited grid connections, particularly solar and wind, by underestimating the curtailment needed. However, neither power stations nor demand are spread homogeneously around the world and, in reality, grid constraints can pose problems with delivering generated electricity to consumers. This could mean more-volatile electricity prices than we forecast, which would create better conditions for investing in storage technologies.

FIGURE 2.5

Europe's hourly electricity supply by technology in year 2050, sorted by price



Cost trajectories

The levelized cost of energy (LCOE) is the cost of producing a megawatt-hour of electricity over the lifetime of a power station, and LCOE has been a primary indicator for the attractiveness of a power-station type as an investment. Figure 2.6 shows the evolution of LCOE of various power-station types for selected regions.

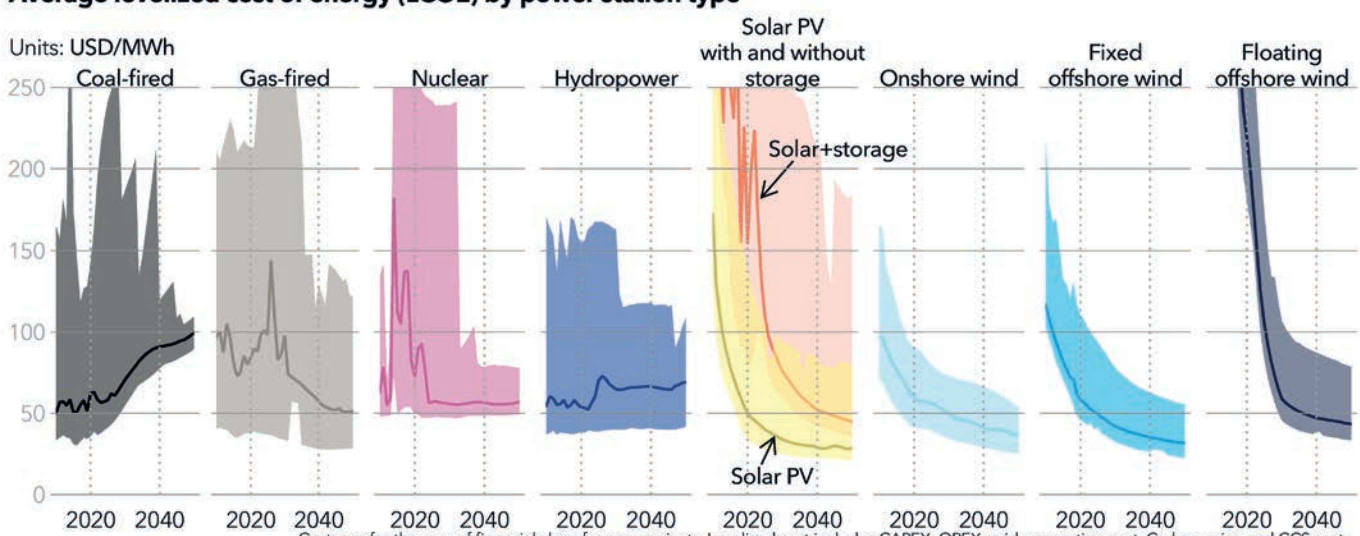
The decline in the LCOE for VRES is due to learning rates in technology costs. The average effective learning rate for the LCOE from 2020 to 2050 is 12% for solar PV, 13% for onshore wind, and 15% for fixed offshore wind. This means that for every doubling of global capacity, the LCOE will decline by these percentages. Solar PV and wind already have the lowest LCOE in many regions, and this will continue. The current discount rate that we use is 7% for 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 will increase to 10% just before 2030.

There is very little room for further technology-driven cost reductions for conventional power stations. Hence, future cost trends for fossil-fired power will be determined by fuel costs, carbon prices, and running hours (capacity factors). The LCOE for coal-fired power stations trends upwards due to declining capacity factors (Figure 2.7), as well as the added cost from carbon prices or from carbon capture and storage (CCS). The LCOE for gas-fired power does not show the same upward trend because its lower carbon intensity makes it a cheaper complement to VRES, balancing out the increasing carbon cost with stable running hours. Moreover, the global weighted-average gas price used for power generation will somewhat reduce, as gas-fired power generation shifts to regions where gas is cheap.

The rise in hydropower costs is linked to lack of resource availability. It is most prominent in China, where widespread buildout of capacity already uses cheaply exploitable sites. The costs of the recent nuclear projects in developed regions are steadily rising due to high safety-related costs and increasing indirect costs, such as engineering, purchasing, planning, and direct labour costs (Eash-Gates et al. 2020). For these reasons, new nuclear development will be mostly confined to Greater China, the Indian Subcontinent, and North East Eurasia, thereby bringing down the world average cost.

FIGURE 2.6

Average levelized cost of energy (LCOE) by power station type



Costs are for the year of financial close for new projects. Levelized cost includes CAPEX, OPEX, grid connection cost, Carbon price and CCS cost. Lines show global weighted average. Shaded areas show spread over 10 regions. Historical data source: GlobalData (2021), WoodMac (2021), IRENA (2021).

Variable renewables

Despite providing cheap electricity, solar and wind are fundamentally dependent on variable weather patterns. Detailed modelling of the power systems highlights the impact of fluctuations on hourly power generation and demand – which, in turn, impact on projected power prices – and the use of flexibility options, such as demand-side response, power-to-hydrogen, and storage.

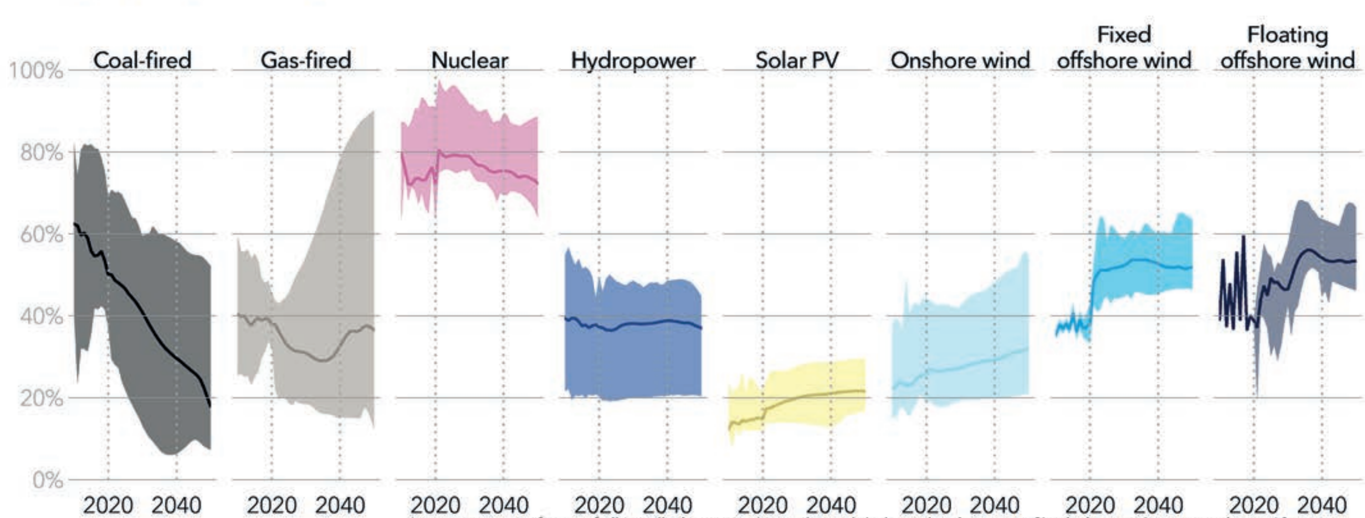
Although there will be a range of flexibility options available in the future, there is still a risk of wholesale power 'price cannibalization' for variable-renewable power plants. This term describes the reduction in the capture price of variable renewables as a result of a high share of solar and wind in the system, as there are more hours within a year in which the price is set by these zero-cost technologies (see Figure 2.5).

Figure 2.8 shows that wholesale power price cannibalization starts to impact solar PV as soon as it reaches 20% of renewable penetration, and it continues to reduce solar-PV capture price as renewable penetration increases. At about 70% VRES penetration, the capture price of solar PV is around half the wholesale electricity price. No clear price cannibalization impact is observed in wind. Opportunistic generation technologies, like solar+storage, along with gas-fired power plants, will experience an increase in their capture prices with respect to the regional average wholesale price.

Price cannibalization will slow the growth of solar PV and delay overall investment levels in some regions with higher penetration. Grid-connected solar-PV capacity additions will peak at 370 GW/yr in around 2030. After 2040, the capture price advantage of solar+storage against solar without storage will be large enough to justify the extra cost of storage. From then on, half of all global solar capacity additions will come with storage.

FIGURE 2.7

Average capacity factor of power stations



Average capacity factor of all installed capacity. Lines show global weighted average. Shaded areas show spread over 10 regions.
Historical data source: IEA (2021), GlobalData (2021), IRENA (2021).

Conventional generation

High renewables penetration will impact the operation of conventional thermal plants. In the short-term, their operating hours will decline as they will not be able to compete with zero-variable-cost solar and wind when there is enough sunshine and wind. On the other hand, as shown in Figure 2.8, their capture price increases. This is because they operate only when solar and wind are unavailable and insufficient to meet demand – which are those hours with a high electricity price. So, over time, thermal generation technologies will transition to becoming complementary to renewables, rather than providing the base load.

Coal

Although we assume a flat trajectory for coal prices, the added cost of carbon, along with fierce competition from gas and renewables, will see coal lose its competitive advantage in many parts of the world. Until 2026, coal-fired capacity additions will be slightly higher than retirements; just enough to keep the capacity flat until around 2030 (Table 2.1). However, subsequent rapid retirements will drop the installed capacity, resulting in it falling to almost 75% of present capacity by 2050. The decline in actual generated electricity from coal is even more dramatic. From 2019 to 2050, the electricity output of coal-fired power stations will fall by 75%. 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 will not be significantly affected.

Gas

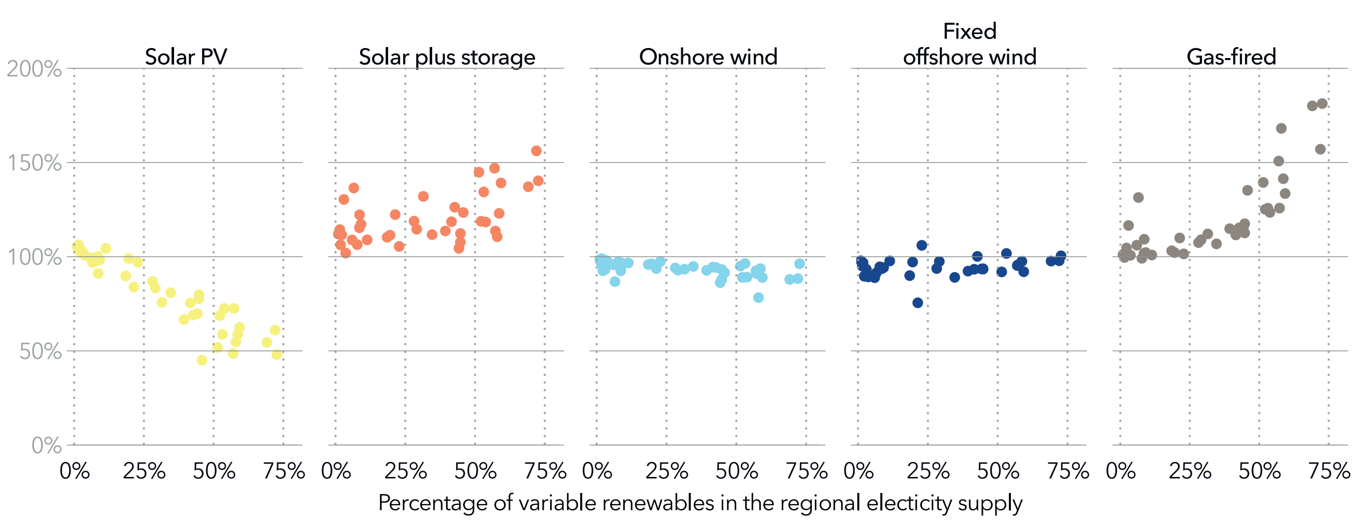
With relatively low carbon emissions, higher flexibility to complement variable renewables, and stable prices, natural gas will stay competitive in the power sector. The installed capacity of gas-fired power stations will decline by 22% by 2050 as old capacity is retired. Gas-fired power generation is most sensitive to gas prices; should gas prices rise by 50% then 2050 gas-fired power generation would fall by 16%. A similar reduction in price would increase the share in 2050 to 13%, rising from 8%, at the expense of renewables.

CCS

The role of CCS in the power sector would be limited. By 2050, the cost of CO_2 avoided by CCS for coal-fired power stations will be between USD 50/tCO_2 in North-

FIGURE 2.8

The ratio of capture price to average wholesale price



Each point represent one of 10 regions at 2020, 2030, 2040 and 2050.

East Eurasia and USD 200/tCO_2 in OECD Pacific, with the difference mainly due to fuel costs. For gas-fired power, the 2050 CCS costs hover between USD 65 and USD 200/tCO_2. These costs are still significantly higher than the carbon price, apart from in Europe where our expected carbon price for 2050 is USD 100/tCO_2. This is just approaching equality with the cost of CCS for gas and coal-fired power. In 2050, 17% of gas-fired power stations will be equipped with carbon capture. Globally, a mere 0.6% of power-sector CO_2 emissions would be captured.

Nuclear

Nuclear-power capacity will stay flat throughout the forecast horizon, with new capacity additions, largely in Greater China, compensating for retirements in Europe and North America. In relative terms, nuclear more than halves its share, dropping from 10% in 2019 to 4.3% 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 technical lifetime, so should countries decide not to invest in life-extension measures, then the decline will be steeper.

With the advantage of having no emissions and providing a reliable supply, we forecast hydropower to grow by 59% 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 12% in mid-century. The use of waste and bioenergy for power production will first grow, and then decline as limited biomass resources will be used in hard-to-abate sectors, like aviation and biomethane production.

TABLE 2.1

Global power-station capacities with additions and retirements

Units: GW

	2019	2020-2030		2030	2031-2040		2040	2041-2050		2050
Power station type	**Installed**	**Add.**	**Ret.**	**Installed**	**Add.**	**Ret.**	**Installed**	**Add.**	**Ret.**	**Installed**
Coal-fired	2 096	+410	−318	2 188	+72	−219	2 041	+8	−470	1 580
Oil-fired	333	+15	−62	287	+0	−47	239	+0	−62	178
Gas-fired	1 914	+414	−35	2 293	+29	−256	2 066	+53	−633	1 486
Nuclear	396	+57	−61	392	+37	−43	385	+50	−39	396
Geothermal	15	+10	−0	25	+1	−0	26	+0	−0	26
Bioenergy	144	+19	−13	150	+4	−32	123	+7	−14	115
Hydropower	1 305	+541	−11	1 835	+240	−5	2 071	+148	−2	2 217
Solar+storage	9	+656	−0	665	+1202	−3	1 864	+2012	−24	3 852
of which off-grid	*0*	*+17*	*−0*	*17*	*+52*	*−0*	*69*	*+64*	*−0*	*134*
Solar PV	601	+2864	−0	3 464	+2437	−95	5 807	+2153	−362	7 597
of which off-grid	*0*	*+68*	*−0*	*68*	*+363*	*−0*	*430*	*+413*	*−8*	*836*
Onshore wind	623	+1386	−48	1 960	+1184	−265	2 879	+1580	−309	4 150
of which off-grid	*0*	*+5*	*−0*	*5*	*+210*	*−0*	*215*	*+493*	*−0*	*707*
Fixed offshore wind	29	+201	−1	230	+458	−12	676	+897	−88	1 484
of which off-grid	*0*	*+1*	*−0*	*1*	*+105*	*−0*	*106*	*+215*	*−0*	*320*
Floating offshore wind	0	+11	−0	11	+94	−0	105	+159	−1	264
of which off-grid	*0*	*+0*	*−0*	*0*	*+0*	*−0*	*0*	*+0*	*−0*	*0*

End of year capacities. Off-grid includes rural solar systems and dedicated hydrogen production facilities.
Historical data source: GlobalData (2021), IRENA (2021)

2.2 GRIDS

Physical developments

More grid connections will be needed as the global grid-connected electricity demand will grow by 2.5%/yr from 2019 to 2050. As Figure 2.9 shows, world transmission lines will increase from just over 6 million circuit-kilometres in 2019 to almost 12 million by 2050. The fastest progress will occur in regions with relatively weaker infrastructure: Sub-Saharan Africa, the Indian Subcontinent and South East Asia. In terms of volumes, the Indian Subcontinent and Greater China will be the regions with the longest new lines, with 42% of all new transmission lines installed in these two regions. Although it could be argued that distributed renewables remove the need for centralized electricity systems, our modelling highlights that transmission infrastructure does not become obsolete in transitioning to a more-decentralized grid despite a shift towards distribution lines, as power plants become smaller. Modern societies require the highest reliability level from their electrical infrastructure, and this can be provided by a greater number of more-widely distributed elements connected via a strong backbone.

Distribution lines will more than double from 2019 to 2050, reaching about 180 million circuit-kilometres globally. As the percentage of VRES grows significantly, integration of renewables and grid modernization will go together to achieve the reliable grids needed for modern societies and successful economies. Modernization of the grid will involve: reinforcement or upgrade transmission and distribution systems, investing in international interconnections, implementing decentralized energy data and information processes, installing advanced grid features (smart meters, sensors, remote controls), changing processes and business models, establishing more flexible energy markets, undergoing regulatory review, and modernizing system operations.

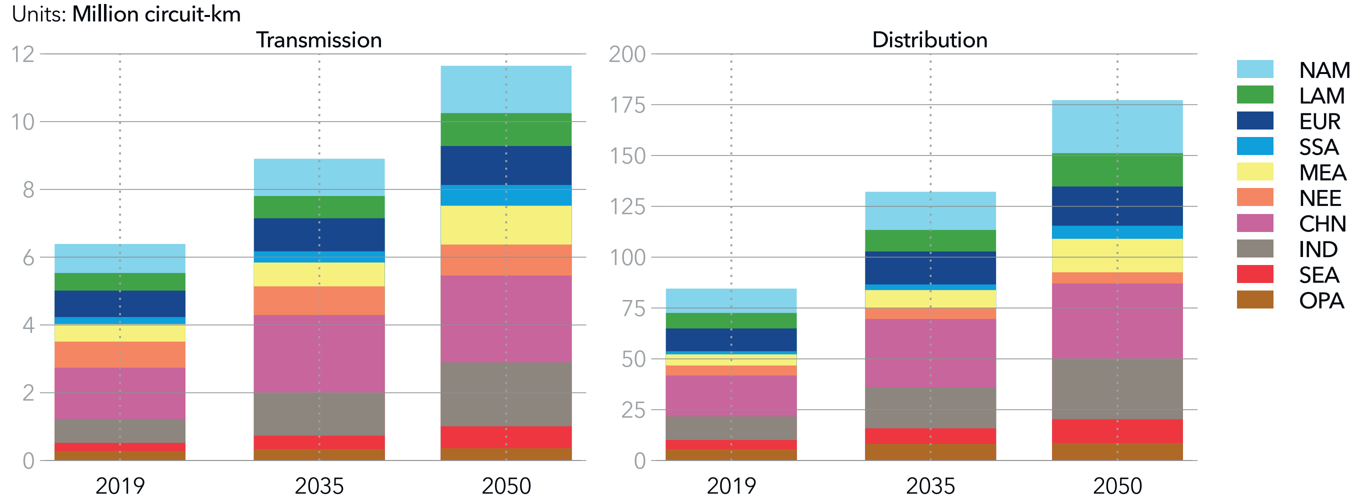
Investments in transmission and distribution infrastructure

Although total grid investments have been hovering at around USD 250bn and 300bn/yr in the past decade, post-COVID recovery and expansion of renewable power will ensure a steady increase in grid investments until the 2030s, reaching levels of USD 400-500bn/yr. The continued growth in investments shown in Figure 2.10 is driven by actions from grid operators accelerating renewables

FIGURE 2.9

Transmission and distribution power-line length by region

Units: Million circuit-km



Historical data source: GlobalData (2021) integration, grid modernization to improve resilience and reliability, and digital transformation. Grid investments are typically reflected to consumers over years. As global power grids steadily expand, this annualized depreciation cost of past investments is higher than the investment expenditures. We estimate global transmission and distribution depreciation costs to be just below USD 500bn/yr. The operating expenditures (OPEX) add another USD 380bn to the bill, bringing the total expenditures (TOTEX) to USD 860bn/yr. The total cost of grid operators includes additional costs, such as tax, levies, dividends, profits, and interest rates. These make up about 40% of the total costs of the grid operators.

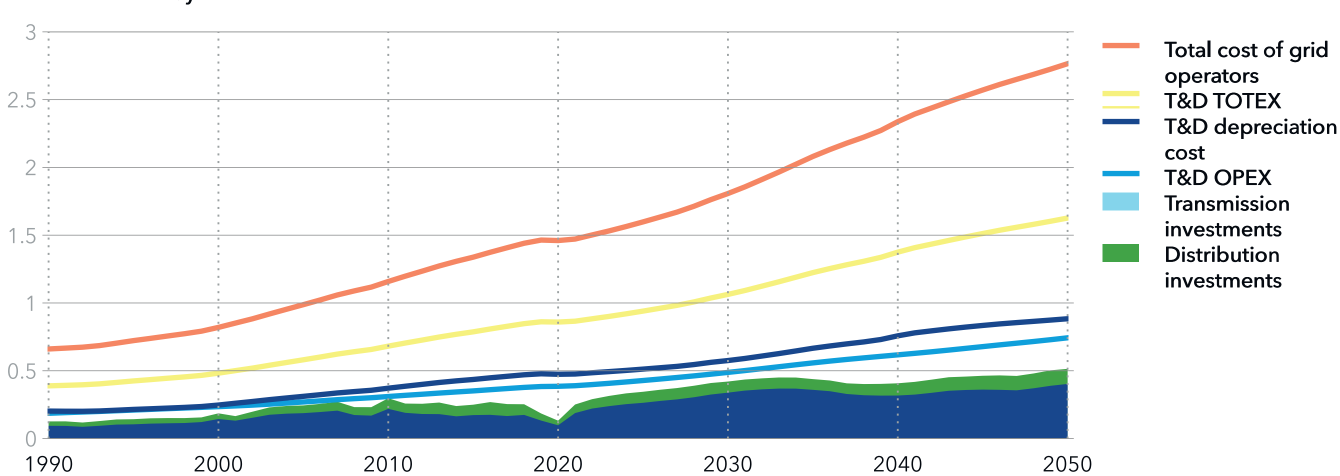
Investments are not only for grid expansion; some 15% of grid investment today goes into digital infrastructure, to address the complexity of a more-decentralized power system and to support decision making in asset management and operations. Investments in digital tools will expand to enable collection of data and information from the grid and feed these to core processes. These tools include: advanced analytical algorithms enhanced with machine learning to translate data from various sources into validated information about market processes, asset conditions, and decision-support functions; IT infrastructure to store and manage data for authorization and data quality; standardized and secure data-communication infrastructure to transfer market and field data, enabling connectivity and interoperability; and sensor arrays, collecting asset data to be utilized by a digitally enabled workforce. This digital ecosystem enables the operation of equipment closer to physical limits, and for optimizing maintenance and replacement plans, as well as integrating distributed energy resources.

By allocating total cost of grid operators to the total electricity consumption, the grid charges in the end users' electricity bills can be estimated. The world average for the unit grid charges has been around USD 66/MWh for the last two decades; we forecast this number to be stable in the USD 61-63/MWh band in the future. Regionally, the picture will vary. In Europe and North America, where strong renewable growth is not accompanied by equally strong growth in electricity demand, unit grid charges will rise and constitute a larger portion of the electricity bill. In Europe, this increase will be offset by decreasing wholesale electricity prices, keeping the average electricity price flat, at around USD 250/MWh for residential consumers and USD 150/MWh for industrial consumers. In North America, stability in 2030 will be followed by a slight increase for residential consumers as electricity-demand growth will not match the grid expansion.

FIGURE 2.10

World power grid investments, expenditures and total cost

Units: **Trillion USD/yr**



Historical data source: GlobalData (2021), IEA (2020)

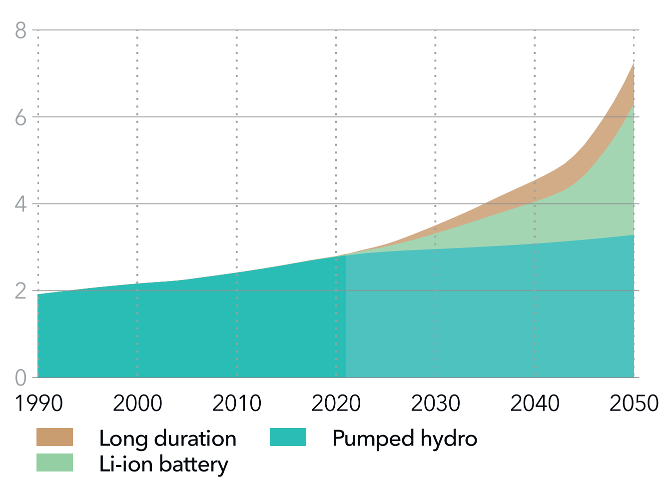
2.3 STORAGE AND FLEXIBILITY

Historically, variability and uncertainty in power systems were due to demand patterns and to failures. As we move towards a carbon-free future, there is both opportunity and need for flexibility. In a future with high shares of solar and wind, several sources will provide flexibility to the power system. Oil- and gas-fired power stations with quick ramp-up/ramp-down rates are already used to match demand on slightly longer time scales. With the value of flexibility increasing, many other conventional generation technologies will seek ways to accelerate their ramp rates and reduce their start times. Better prediction of renewable-power generation levels and demand response will assist with reacting to excess renewables and shifting electricity usage from peak periods to times of lower demand. New technologies and market mechanisms will allow more consumers to provide flexibility in the form of demand response and behind-the-meter storage. Converting cheap electricity from VRES to other energy carriers, such as hydrogen, is yet another option that will provide flexibility. Continued investment in the interconnectors between physical transmission systems, and in the links between generation and load centres, will contribute towards better utilization of excess renewable supply. Implementation of smart grids features (such as smart meters, IoT sensors, remote control and advanced automation) will be able to better address the energy flows, further helping to match energy needs of different areas.

FIGURE 2.11

World utility-scale energy storage capacity

Units: TWh



Historical data source: GlobalData (2021), US DOE (2021)

Energy-storage technologies will also be increasingly used to allow power generation to be decoupled from power demand in time. Storage in today's power system is mostly in the form of pumped hydro. Although limited by geography, pumped hydro is a mature technology, and is set to grow by 20% over the next three decades (Figure 2.11).

Our analysis shows that increased solar and wind, with a higher chance of mismatch between supply and demand at different times, will create a price arbitrage opportunity. Using Europe as an example, Figure 2.12 shows how the daily, weekly, and monthly standard deviations of wholesale electricity prices rise over time as the share of solar and wind in the European electricity mix increases. A higher standard deviation indicates more variability in the price, which makes a better business case for storage. By modelling the storage investments, based on profitability from price arbitrage, we forecast widespread expansion of battery storage. We also foresee batteries being installed as a backup capacity through capacity markets. As conventional thermal power plants start to retire, low-CAPEX power stations and battery-storage systems will be installed as a precaution against times when solar and wind power is unavailable, to avoid blackouts. In the case of Europe, sizable backup of lithium-ion (Li-ion) battery capacity will be added, starting from the mid-2040s. Interestingly, a large amount of battery capacity in the system also helps to reduce price variability (Figure 2.12), by buying the excess cheap electricity and providing it when needed. Through this balancing feedback loop, storage kills its own price-arbitrage business case, thus providing a natural limit on storage-capacity growth.

There are many storage technologies, each possessing different characteristics. Li-ion is today's dominant battery chemistry for utility-scale storage, EVs, and information and communication technologies. Approximately 95% of storage projects in which DNV is currently involved through feasibility assessment, development, and construction, are Li-ion. With a cost-learning rate (i.e., the rate at which costs fall with every doubling of capacity) of 19%, costs for batteries will continue to plunge (Figure 2.13). Further improvements in the cost, energy density, weight, and volume of electric batteries will enable wider use of battery-storage systems. New battery chemistries will have to compete with existing Li-ion energy density, manufacturing infrastructure, and costs. If significantly cheaper batteries, based on Earth-abundant materials, emerge, this could cause a step-change in addressing some existing energy-storage challenges in power production and transport.

Where there are larger markets for utility-scale battery storage (e.g., China, South Korea, Japan, US), a shift in the charge/discharge duration required from projects is already starting to be seen. As storage capacity exceeds 0.5% of grid capacity, the trend is for business models to shift from frequency response as a primary application, often requiring one-hour duration or less, to price arbitrage or, in some markets, capacity provision. Average storage duration therefore shifts from two to four hours. As this trend for longer-duration batteries continues through the ETO period, alternative chemistries and technologies will have increasing value: e.g., vanadium redox flow batteries, zinc-based chemistries, or compressed air. After the second half of the 2030s, these other long-duration storage solutions will enter the market.

EVs will also play a central role in flexibility thanks to advancements in smart meters and smart grids and regulatory changes providing incentives to consumers for installing vehicle-to-grid systems. For one thing, the rapid decline of Li-ion batteries is mainly driven by the EV market. In addition, we expect EV-charging systems that can feed into the grid to lead to 10% of all EV storage capacity becoming available to provide grid flexibility at any time. From 2040 onwards, throughput of vehicle-to-grid systems in the world will be almost as large as that of Li-ion batteries and pumped hydro, reaching 240 TWh/yr globally by mid-century.

FIGURE 2.12

Standard deviation of wholesale electricity price in Europe in different time-scales

Units: USD/MWh

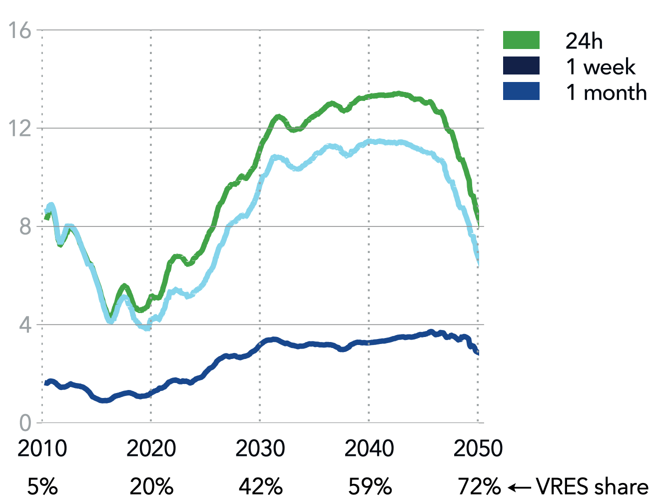
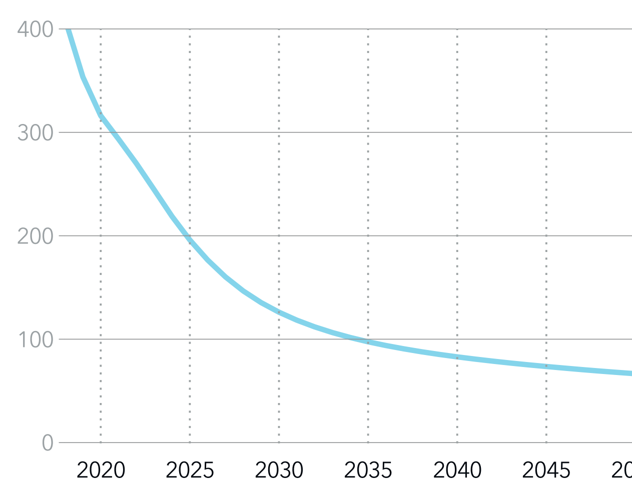


FIGURE 2.13

Utility-scale Li-ion battery system cost

Units: USD/kWh



Historical data source: NREL (2020)

2.4 HYDROGEN

Hydrogen is currently used in refineries for reducing the sulfur content of diesel oil and upgrading heavy residual oils into higher-value oil products. It is also used in ammonia production for fertilizers. These require a pure form of hydrogen. In addition, some applications, like methanol and direct reduced-iron steel production, use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock (IEA, 2019).

Use of hydrogen as an energy carrier has been a point of debate for decades. Hydrogen's strong point is that it can be produced from water and energy alone, and, at the point of conversion to energy, only emits water. Its drawback is that its production requires considerable amounts of energy and thus generates substantial energy losses. There are also concerns about the safety and storage of hydrogen. The high cost of hydrogen currently prevents widespread adoption as an energy carrier. However, with declining costs of production and an increasing push for decarbonization, hydrogen is a major contender for hard-to-abate sectors where electrification is either infeasible due to the low energy density of batteries or very costly.

Hydrogen demand

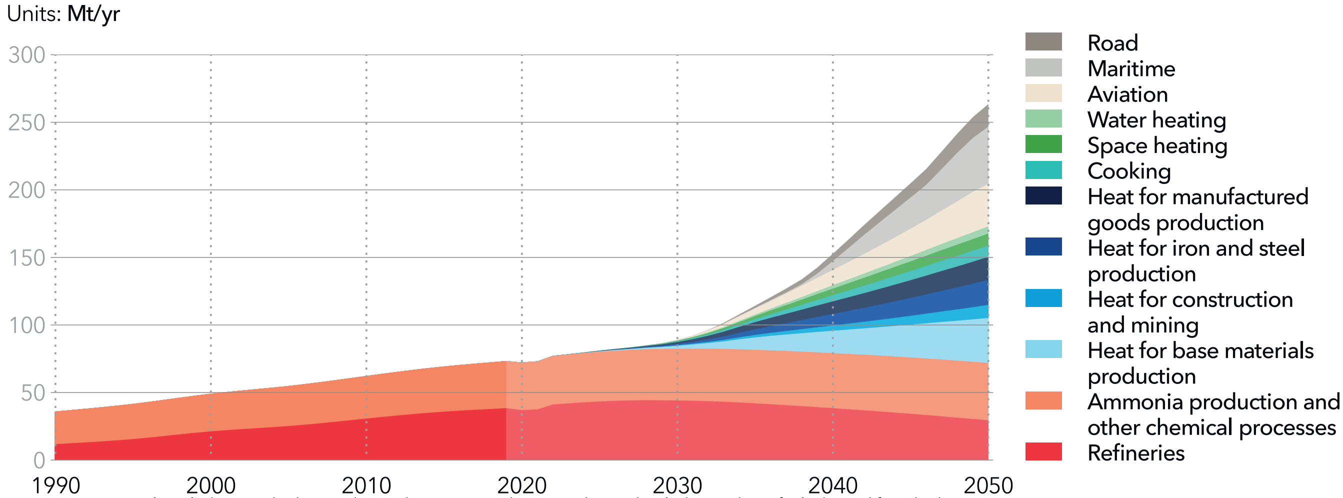
Synthetic fuels, such as e-methanol, e-ammonia, or sustainable aviation fuels, are typically refined from hydrogen using methods like the Fischer–Tropsch process. As they are hydrogen-derivatives, we have included the demand for synthetic fuels under hydrogen and account for their conversion losses. In 2050, all the "hydrogen" demand from the maritime sector and 70% of aviation's "hydrogen" demand are actually in the form of synthetic fuels.

Figure 2.14 shows that 30% of global hydrogen demand and synthetic-fuel demand in 2050 is for industrial heating, 16% for ships, 6% for heavy long-range road transport, 12% for aviation, and 9% for buildings. The remaining 27% is consumed for non-energy purposes. This year we forecast hydrogen and synthetic fuels to have a significant share in the aviation fuel mix in 2050, as large amounts of sustainably produced biofuel is a challenge. We have also explicitly modelled non-energy use of hydrogen in ETO 2021, which last year was included as part of the manufacturing sector's fossil-fuel consumption.

FIGURE 2.14

World hydrogen demand by sector

Units: Mt/yr



Only includes pure hydrogen demand. Maritime and aviation demand includes synthetic fuels derived from hydrogen.
Historical data source: IEA Future of Hydrogen (2019)

Until the end of our forecast period, hydrogen use in buildings will be limited. Hydrogen's main purpose in buildings will be to replace natural gas as a fuel for space heating, water heating, and cooking. We assume that hydrogen distribution can be achieved by retrofitting current gas grids at minimum cost. In the pipelines, hydrogen and natural gas can be blended (up to about 10% hydrogen), and the mixture can be burned, just like natural gas. It will also be possible to pipe pure hydrogen through the network, but this would require an additional total upgrade of appliances. In Europe, Greater China, North America, and OECD Pacific, current and planned gas grids are substantial and will easily accommodate the piping of hydrogen. Nevertheless, hydrogen for heating will represent only 1.8% of energy use in the buildings sector globally, just above coal's 1.7% share. In Europe, hydrogen will represent about 4.4% of energy use in the buildings sector by mid-century, which is the highest regional share, and equivalent to about one tenth of natural gas use. In Greater China, hydrogen use in buildings will be around the global average, whereas natural gas will still represent almost 16% of that sector's energy use.

We see hydrogen as a potential zero-emission energy carrier for applications in manufacturing. To compete on cost, this would require carbon prices to be higher than those envisaged (USD 100/tCO_2 in 2050 in Europe and USD 60/tCO_2 in Greater China). By 2050, about 10 EJ/yr of hydrogen will be used in manufacturing to replace fossil fuels, which represents a share of 7% of energy carriers used in manufacturing. This development is clearly led by Europe and Greater China, and, to a smaller extent, North America. One third of hydrogen use in manufacturing will occur in Greater China by mid-century, one fifth in Europe, and one eighth in North America. Other regions will each have about 5% share. We forecast hydrogen to play a major role in replacing fossil fuels in industrial heat applications, with an almost 90% share. By 2050, around 42% of hydrogen used for industrial heating will be for base-material production, 24% for iron and steel production, 22% for manufactured goods, and 12% for construction and mining. This development will commence in the current decade, accelerate in the 2030s, and speed up even further in the 2040s. Current hydrogen use for energy purposes in manufacturing is very limited, and often in terms of R&D and lighthouse projects.

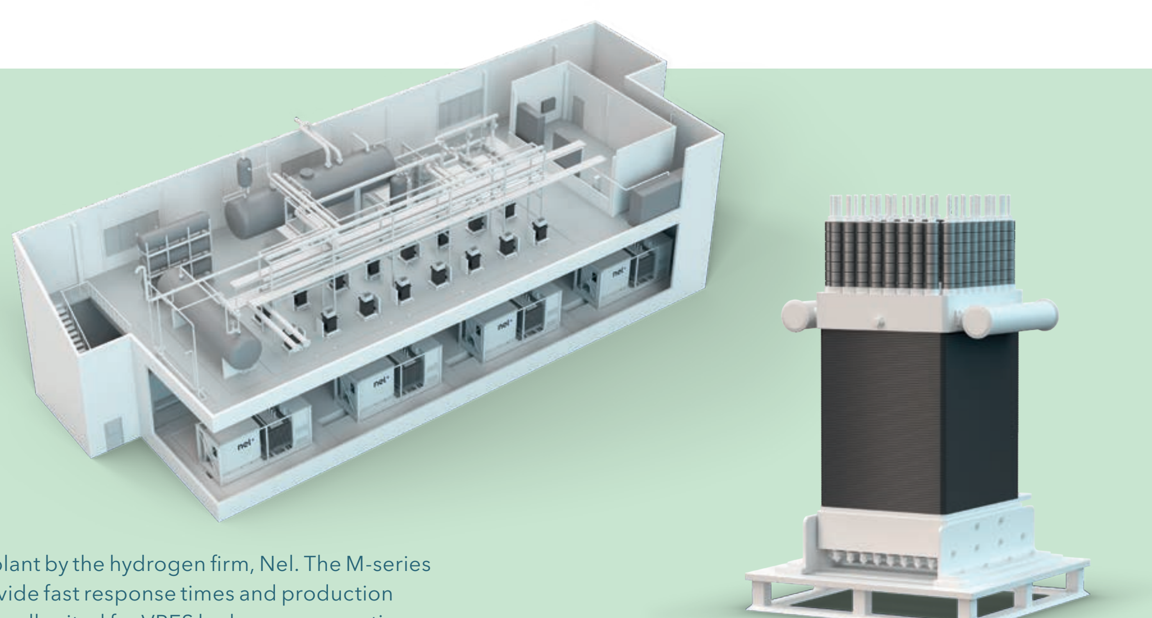


Illustration of M4000 plant by the hydrogen firm, Nel. The M-series PEM electrolysers provide fast response times and production flexibility and are thus well suited for VRES hydrogen generation. (Image: courtesy Nel.)

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 will turn to fuel-cell solutions, despite these being only half as energy efficient, more complex, and more costly. CAPEX support is already available for fuel-cells in passenger and commercial vehicles in all regions. Considering the total available funding and support for hydrogen uptake, Europe and OECD Pacific stand out as leaders. But even with support, less than 3% of road-transport energy use worldwide will use hydrogen, a level similar to the share of biofuels in 2050. Regional fractions vary from as high as 17% in OECD Pacific down to less than 0.5% in Middle East and North Africa and in North East Eurasia.

In maritime transport, the story is different. As we discuss more thoroughly in our Maritime companion report (DNV, 2021c), there is no significant battery-electric option for decarbonization, with synthetic fuels, biofuels, ammonia, and hydrogen the only low- and/or zero-carbon fuel choices available. We see these high-cost fuels, which can also be implemented in hybrid configurations with diesel- and gas-fuelled propulsion, having significant uptake, providing slightly over 42% of the maritime fuel mix by 2050.

We also forecast a significant share of synthetic fuels in the global aviation fuel mix by 2050. Almost one fifth of fuels used by then will be synthetic hydrogen-based fuels. This development is led by Europe and North America, both above the global average, each with a 23% share of e-fuels in aviation sector. We expect the lowest share to be in Sub-Saharan Africa with only slightly more than 10%. Implementing a new type of fuel in a global sector, such as aviation, requires a wide-spread production and distribution system, along with associated infrastructure to allow global refuelling. Hydrogen-based fuels are very likely to be used for medium-haul flights, but, owing to their lasting cost disadvantage compared with fossil-based fuels, significant uptake is not expected before the 2040s.

Non-energy use of hydrogen

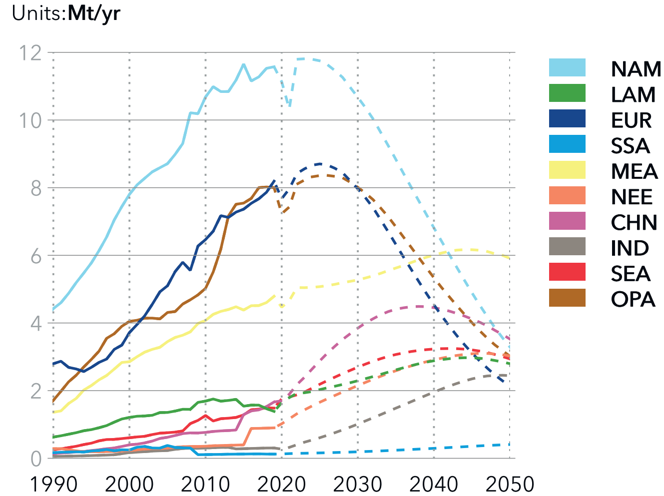
Figure 2.15 shows the hydrogen demand from refineries. As a function of crude oil processed in refineries, there is a clear upward trend in all regions. In Europe, North America, and OECD Pacific, we expect the trend to continue until 2030, as the need for further desulfurization will probably stop. For the other regions, we foresee the trend continuing until 2050, as these regions are still below Europe and North America then. We expect an acceleration in Greater China and the Indian Subcontinent beyond historical trends as they are likely to push sulfur allowances down faster.

World ammonia production has been increasing steadily in line with population growth, as ammonia has been used for fertilizer production. We employed a simple approach to determine the future ammonia demand by assuming that: (1) ammonia demand grows linearly with population (18.9 kgN/person/yr), (2) the effect of increased industrial applications and decreased fertilizer demand balance each other out, (3) 0.24 kg of hydrogen is required per kg nitrogen used for ammonia production (based on 2019 numbers of 38 MtH_2/yr and 150 MtN/yr of ammonia production). This results in a continued increase in world ammonia production and a corresponding rise in hydrogen demand.

FIGURE 2.15

Pure hydrogen demand from refineries by region

Units: **Mt/yr**



Historical data source: IEA Future of Hydrogen (2019)

Hydrogen supply

Currently, the main method for production of hydrogen is via steam methane reforming (SMR), where hydrogen is derived from methane. This method has the lowest overall costs due to low gas prices – but results in CO_2 emissions. Emissions from SMR can be captured to reduce overall emissions; as CO_2 capture and storage costs fall and carbon prices rise, SMR with carbon capture will gain traction. Hydrogen production via electrolysis has also been gaining more momentum for a couple of years and, by mid-2040, will be the dominant method of producing hydrogen. Production costs are currently higher than for SMR-based hydrogen, but economy scale up and systems learning, as well as increased availability of cheap electricity in the long run, will make electrolysis-based hydrogen production more competitive. A third route to hydrogen production is based on gasification of coal and biomass. Coal gasification has a large market share in China due to its low cost, but only a limited presence in other regions.

Figure 2.16 shows the breakdown of global hydrogen production by source. The share of SMR without carbon capture in global hydrogen supply will drop from 81% in 2019 to 63% in 2030, to 32% in 2040, and to 15% in 2050. Coal gasification, which will also adopt carbon capture towards 2050, will keep its absolute production volumes, but lose its relative share from 19% in 2019 to 5% in 2050 as other production methods take off.

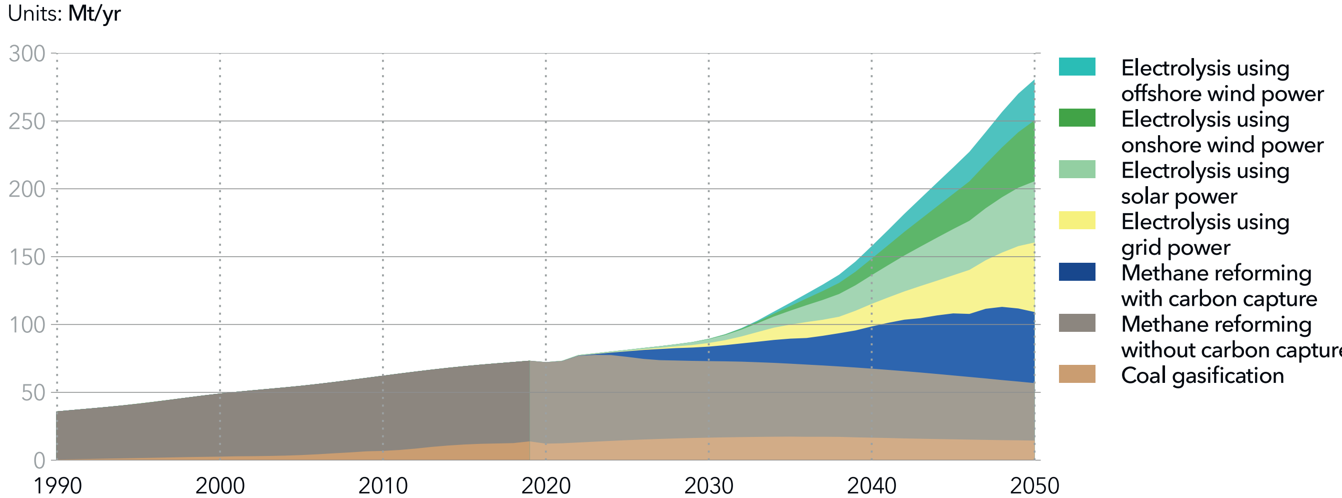
In this report, we make a distinction between hydrogen supplied via electrolysis from grid electricity and via off-grid dedicated renewable-based electrolysers.

Electrolysers using grid-electricity face a trade-off: too low running hours mean more years before investment costs are paid back and a higher CAPEX component in the levelized cost, too high running hours, on the other hand, usually mean higher electricity costs. With the lack of competition, operators can determine their annual operating hours so that total cost is minimized, which is usually in the range of 7000-8000 h/yr. As the current hydrogen market is limited, typical operating hours fall within this range. With increased competition between different providers of hydrogen, electrolysers will need to reduce their variable costs by operating only when the electricity price is very low. Our levelized cost calculations take into account this transition from high utilization rates to low operating hours due to competition. Fortunately, as the share of VRES in the

FIGURE 2.16

World hydrogen production by source

Units: Mt/yr



Only includes pure hydrogen supply. Historical data source: IEA Future of Hydrogen (2019) system increases, the annual number of hours where the electricity price will make the variable cost of electrolysis below the variable cost of SMR ("competitive annual operating hours") will also rise. By 2040, regional averages will increase from a few hundred hours to reach a 1500-2000 h/yr range for most regions. However, there are many takers for such cheap electricity: demand response, pumped hydro, BEVs (storage), and utility-scale batteries. As the volume and influence of these flexibility options on the market increase, they will move from being price-takers to being price-setters. This will prevent annual operating hours from increasing significantly. 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 and curb investments. Grid costs and taxes included in the electricity price, which constitute a significant portion of the operating cost for electrolysers, also affect operating hours. Counting on the fact that some electricity producers will have on-site electrolysis facilities, we assume that average grid charges and taxes for hydrogen production to be half of the average rates of end users.

Some investors will choose to rely on off-grid dedicated renewable generation for hydrogen production. By replacing the variable electricity cost over the operating lifetime with an upfront renewable investment cost, these investors will reduce the risk from future fluctuations in electricity prices. Moreover, hydrogen produced from off-grid renewables can be guaranteed to be fossil-free, unlike grid power, which needs certificates and other schemes to claim to be emission-free. Cost reductions in solar, onshore wind, and bottom-fixed offshore wind will enable dedicated electrolysers using these renewables to compete with SMR and grid-based electrolysers. In 2030, 102 GW renewable-based (mostly solar) and 77 GW of grid-electricity-based electrolysers will provide 8% of world hydrogen supply. Europe will be leading in electrolysis investments, reaching 41 GW grid-based and 4 GW solar-based electrolysis capacity by the end of 2030. By 2050, 61% of world's 281 Mt/yr hydrogen supply will come from electrolysis, split roughly equally between solar PV (16%), onshore wind (16%), offshore wind (11%), and grid-electricity (18%). Total installed electrolysis capacity will reach 3 TW by 2050.

The cost developments for different hydrogen-production methods are summarized in the Hydrogen Infographic.

Hydrogen transport

In principle, hydrogen can be transported in either liquid or (compressed) gaseous form via trucks and ships or in pipelines. Pipeline transport again can be divided into dedicated hydrogen-pipeline transport and blending of hydrogen with methane and use of the existing natural gas grid infrastructure. For hydrogen use in manufacturing and buildings sectors, total hydrogen-demand volumes would be low, and hydrogen will be consumed for the same purposes as methane – mostly for heating. Therefore, we foresee that most of hydrogen demand in these sectors to be in blended form. We assume a conservative 10% maximum for the amount of hydrogen that can be blended in the natural gas distribution pipelines. This is an active area of research and future results might show that higher ratios are possible.

In the transport and power sectors, it is more likely that pure hydrogen will be used, which requires dedicated hydrogen transport. In the 2030s, we will see the first dedicated hydrogen-transmission pipelines around the globe. In 2050, one fifth of Europe's pipeline capacity will be used solely for hydrogen transport. We forecast hydrogen-transportation costs decreasing, with more hydrogen being transported from the 2030s onwards, reaching from USD 0.38 per kg in manufacturing in North East Eurasia to USD 4.7 per kg in buildings in Europe. The average transport cost of hydrogen in 2050 will be between USD 0.4 and 0.7 per kg. These costs represent within-region transport costs, from production sites to the consumers.

Sensitivities

In our analysis, we tested the sensitivity of global hydrogen demand and supply to 47 different uncertainties, ranging from learning rates, to subsidies, to carbon and gas prices.

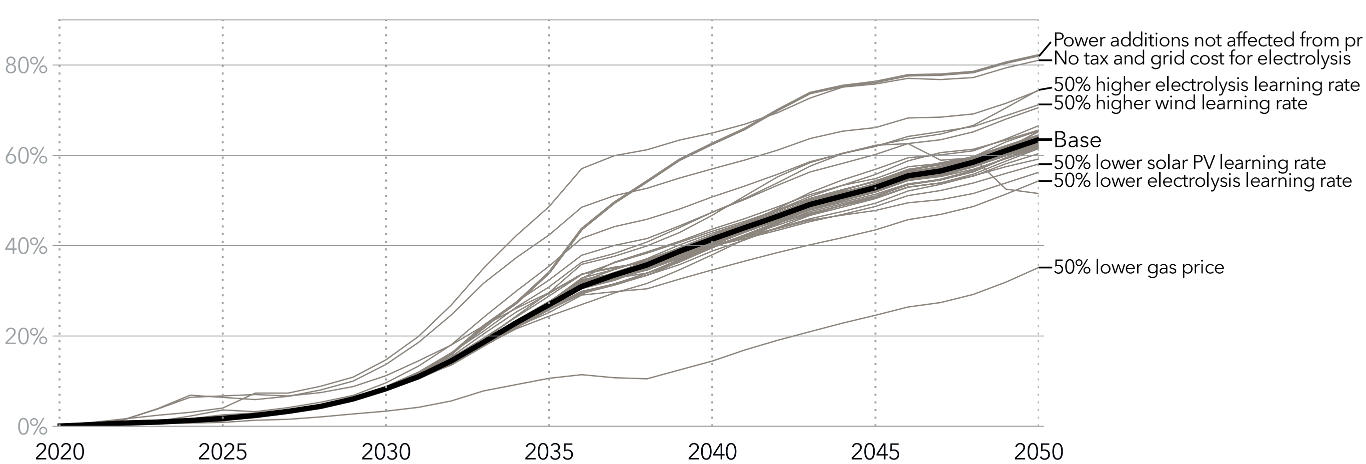
Carbon price is highly significant for hydrogen uptake. The main effect can be observed in the manufacturing and transport sectors, where policies are tied to carbon prices. As we use carbon prices directly as a cost element for fossil fuels in power and manufacturing, and as an indicator for the strength of policy push for decarbonization, a higher carbon price results in a greater hydrogen demand. Quadrupling the carbon price in all regions will more than double the global hydrogen demand. Providing direct subsidies to hydrogen would also be an effective measure for encouraging hydrogen uptake. Should hydrogen prices drop by 50%, then a similar 50% rise in hydrogen demand would occur. Please note that these are conservative estimates as our sensitivity tests do not cover the impact on maritime and aviation sectors, where a separate assessment is provided as an input to the model.

After the 2040s, electrolysis will become the dominant method for hydrogen production. As Figure 2.17 shows, although certain factors might delay this trend, the direction is clear. Lower gas prices would be the biggest obstacle against electrolysis taking over SMR as the main source of hydrogen. Lower learning rates in electrolysis CAPEX and lower renewables costs could also affect the speed of the transition. Removing taxes and grid costs paid by electrolysers using grid-electricity would increase the share of electrolysis in the global hydrogen supply to 80%. Another effective factor was shown by removing the modelled link from declining power-sector profitability to new power-sector investments. This causal link in the model represents a potential reduction in regional power-system safety margins as a result of reduced enthusiasm for investments when capture prices of variable renewables start to fall. Policies that would help investors maintain revenues would also support electrolysis, as high power-sector investments would ensure abundant cheap electricity.

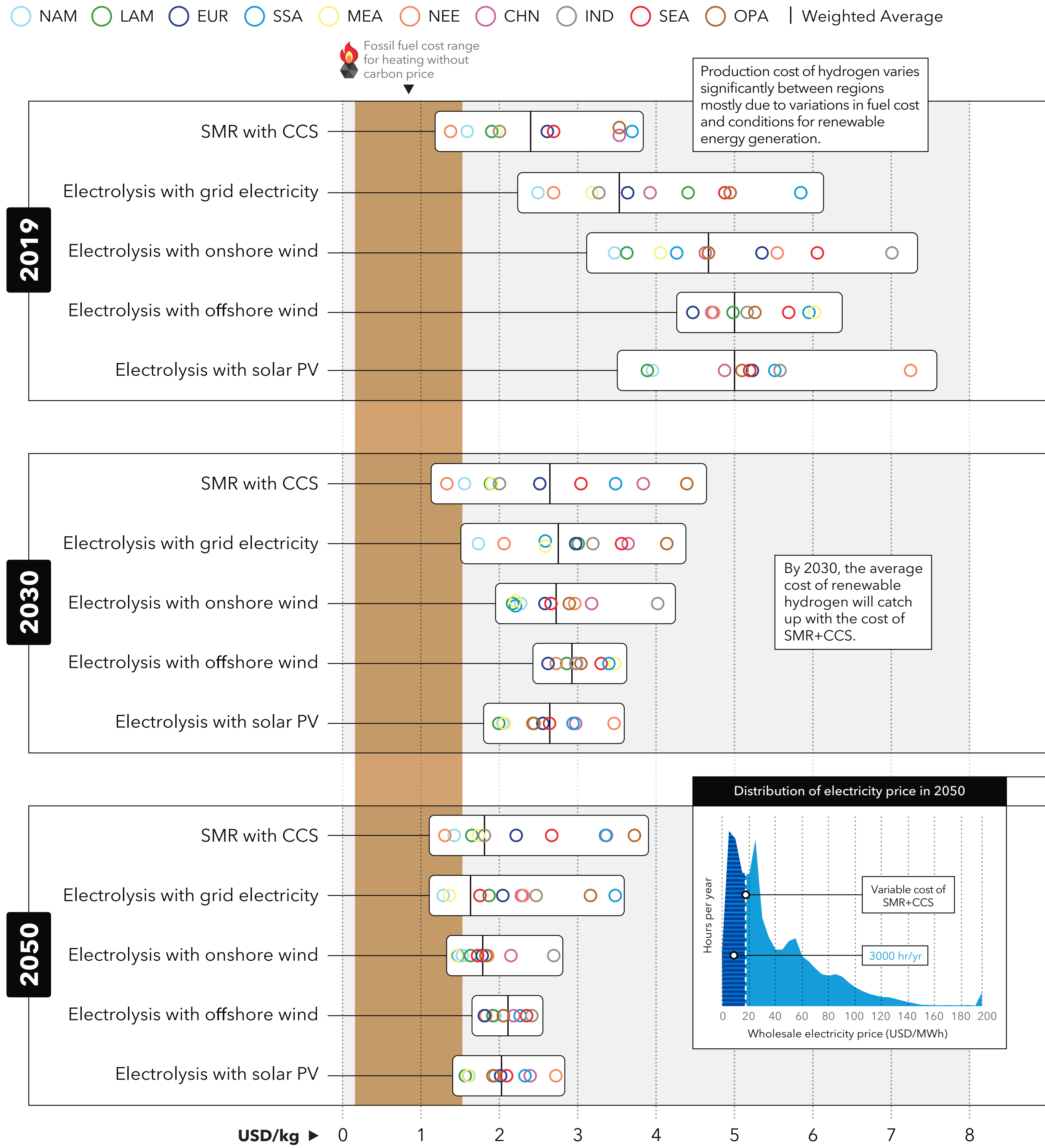
FIGURE 2.17

Sensitivity of electrolysis share in world hydrogen supply

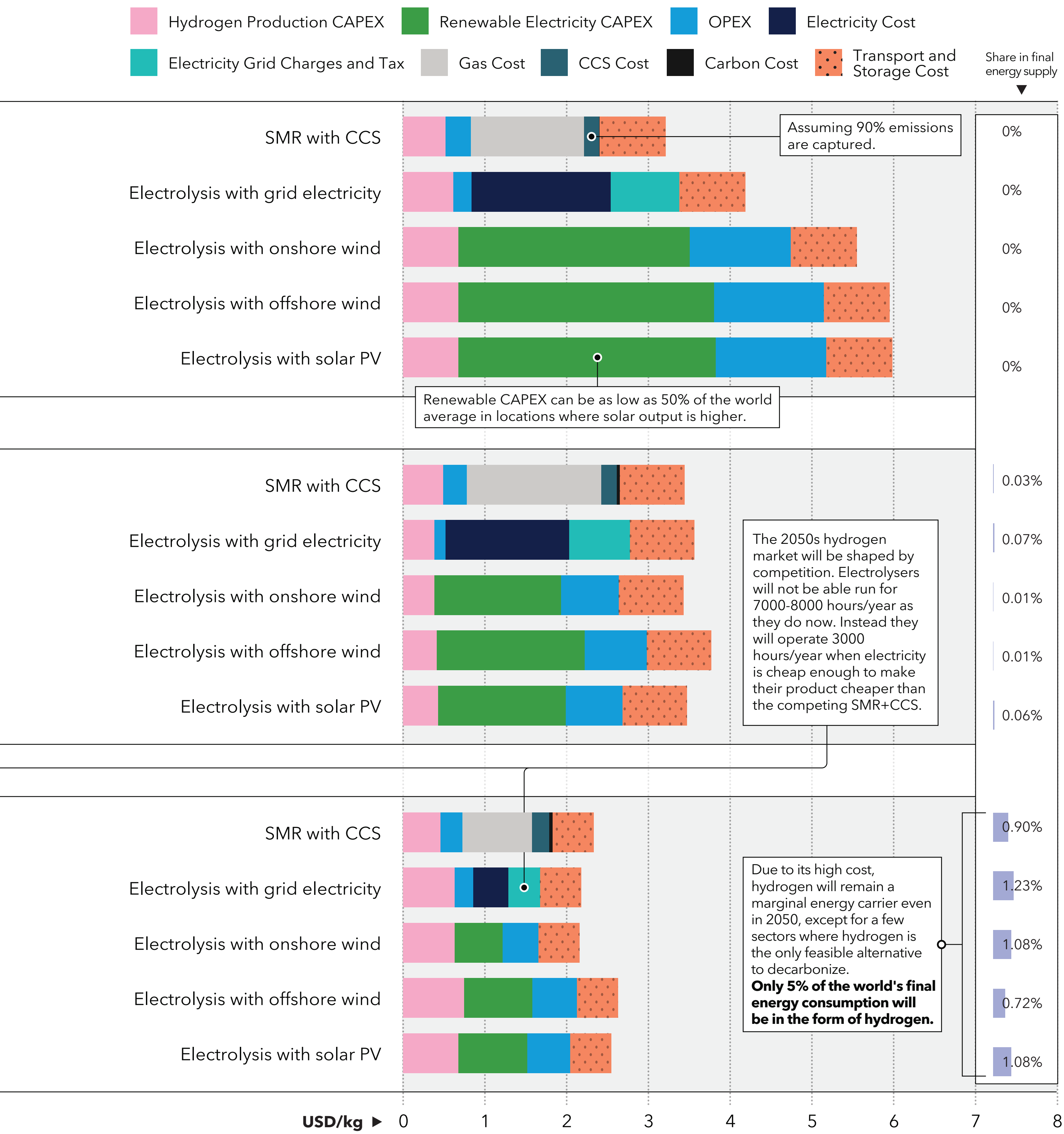
Units: Percentages



LEVELIZED COST OF HYDROGEN PRODUCTION



COST COMPONENTS OF HYDROGEN



2.5 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. Space heating in residential, commercial, and public buildings currently uses 37% of the direct heat globally, followed by 32% by manufacturing, and 7% for water heating (Figure 2.18). 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.

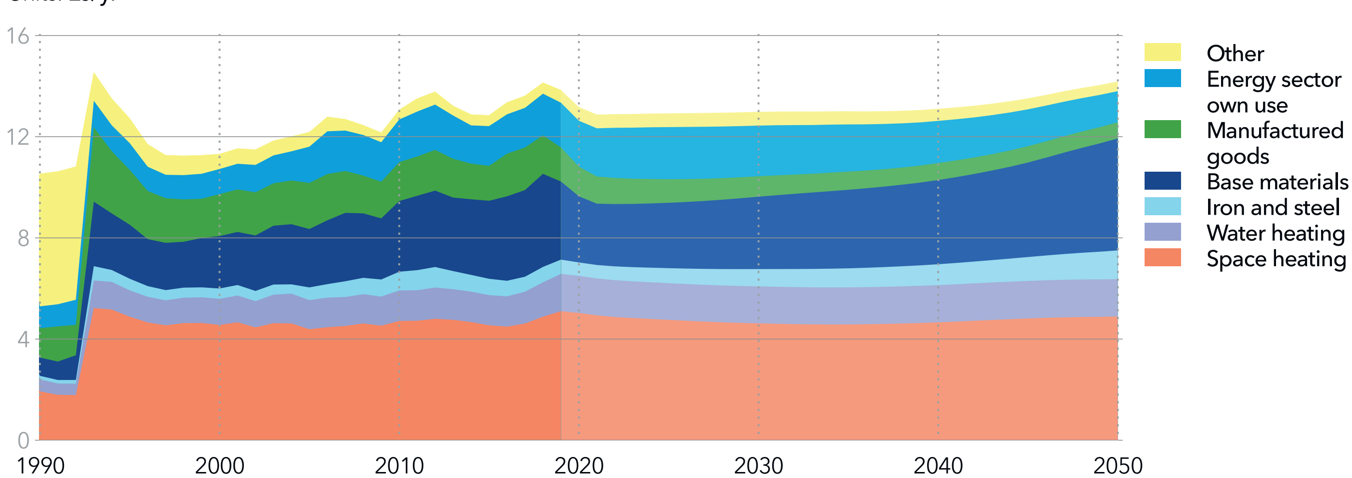
The Russian Federation alone accounts for 37% of global direct-heat demand; 45% for North East Eurasia as a whole, 32% for China, and 17% for Europe, led by Germany. In 2019, coal and gas provided 43% and 47%, respectively, of global direct heat supply. More than two thirds of this came from Combined heat and power (CHP) plants. We envisage a plateauing in the use of direct heat demand due to thermal power losing ground to variable-renewable power supply. Direct heat energy demand will reduce marginally from around 14 EJ/year in 2019 to less than 13 EJ/year until 2030, and will then increase, returning to 2019 levels by mid-century.

By 2030, coal will be replaced by bioenergy technologies, which mostly use municipal and industrial waste as fuel, and natural gas fired technologies, bringing the share of coal in direct heat demand down to 32%. In 2050, bioenergy will provide 21% of direct heat, while coal's share will have shrunk to 9%. Simultaneously, the share of natural gas will increase to 69%. With the exception of the historical expansion in China's share in the 2000s, the geographical breakdown has not changed, and will not change, significantly.

FIGURE 2.18

World direct heat demand

Units: EJ/yr



Historical anomalies are due to changes in reporting from the former Soviet Union. Historical data source: IEA WEB (2020)

Prunéřov power station, Czech Republic. There is very little room for further technology-driven cost reductions for conventional power stations. Hence, future cost trends for fossil-fired power will be determined by fuel costs, carbon prices, and running hours (capacity factors).

Highlights

This chapter covers current developments in and forecast growth of solar PV, wind energy, hydropower, bioenergy and nuclear energy. All of these sources, except nuclear, are set to grow, but at very different rates.

Renewable energy today represents 15% of global energy supply but will expand vastly to make up **45% of global energy supply by 2050**. Adding in 5% from nuclear results in a 50/50 fossil and non-fossil mix by mid-century.

Solar PV will see a 20-fold growth over our forecast period. A high technology cost-learning rate of presently 26% per capacity doubling explains much of this growth. **Solar PV + storage** and the production of green hydrogen will help solar contend with a low capture price for the electricity generated.

Wind energy will expand 15-fold, rising from 5% of global electricity production currently to 33% in 2050, comprising 20% onshore, 11% fixed offshore and 2% floating offshore.

Relative to solar PV and wind, expansion of **hydropower** (74%) and **bioenergy** (28%) seem pedestrian, but they nevertheless play a meaningful decarbonization role and being a non-intermittent renewable source is also an asset.

The future of **nuclear energy** is constrained by cost and safety concerns, and marginal growth in new capacity will be sufficient only to ensure that nuclear retains its 5% share of the primary energy mix through to mid-century.

3 RENEWABLE ENERGY AND NUCLEAR

3 RENEWABLE ENERGY AND NUCLEAR

Renewable energy today represents 15% of global energy supply but will triple in both absolute and relative terms to make up 45% of global energy supply by 2050. Adding in 5% from nuclear, also covered in this chapter, results in a 50/50 fossil and non-fossil mix by mid-century.

Many energy industry professionals currently consider the term 'renewable energy' to include only solar PV and wind. This is a misconception. As illustrated in Figure 3.1, bioenergy is by far the largest renewable energy source at present, and it is only in the 2040s that it will be rivalled by solar PV and wind. However, the final energy delivered by bioenergy is considerably lower than that provided by other renewable sources. That is due to large losses associated with use of bioenergy in inefficient processes like cooking and to the far lower use of bioenergy, relative to wind, solar and hydro, in electricity generation.

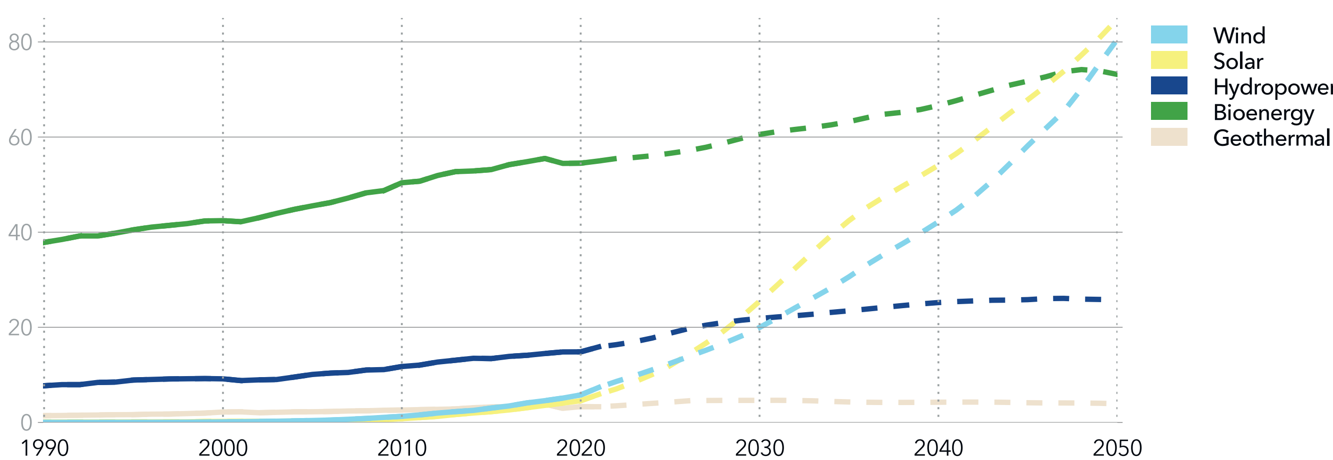
As shown by Figure 3.1 all renewable categories grow throughout our forecast period. However, the 20-fold growth in solar PV and the 15-fold growth in wind between 2019 to 2050, are of a different order of magnitude than the expected 74% growth in hydropower and 40% growth in bioenergy over the forecast period. As detailed in Section 3.5, bioenergy will partly shift to more modern bioenergy forms in the coming decades. Nuclear is not shown in Figure 3.1 but sustains a relatively flat development throughout our forecast period at around 30 EJ.

The very large grid modification and buildout needed to cater for the variability of solar PV and wind is partly dealt with below and also addressed in the previous chapter on electricity and hydrogen.

FIGURE 3.1

World renewable energy supply by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

3.1 SOLAR PV

Although the photovoltaic effect was known to science as early as the first half of the nineteenth century, the first practical application of solar photovoltaic (PV) technology was with the development of silicon solar cells by Bell Labs in the 1950s. These were incorporated into solar panels for earth-orbiting satellites and were initially cost-prohibitive for the general public. Since then, solar PV costs have declined spectacularly, to a level that now makes it the cheapest form of new electricity almost everywhere. The surge to cost leadership has taken place mainly in the last decade, and costs will continue to decline such that new solar PV will be demonstrably cheaper than most existing fossil-fired electricity before this decade is out.

Solar PV comes in many forms, from household installations measured in kW, to commercial-industrial (MW scale) installations on industrial rooftops and car ports designed to reduce corporate energy bills, to multi-GW utility-scale solar farms that tend to be located on remote, unproductive land. Utility-scale production already dominates and will continue to do so, as smaller installations cannot compete on energy cost. Small installations, however, have the advantages of flexibility and local security of supply, which are attractive enough to ensure that rooftop and micro-grid-sized installations will grow significantly in absolute terms, though their market share will decline (DNV GL, 2019).

Cost developments

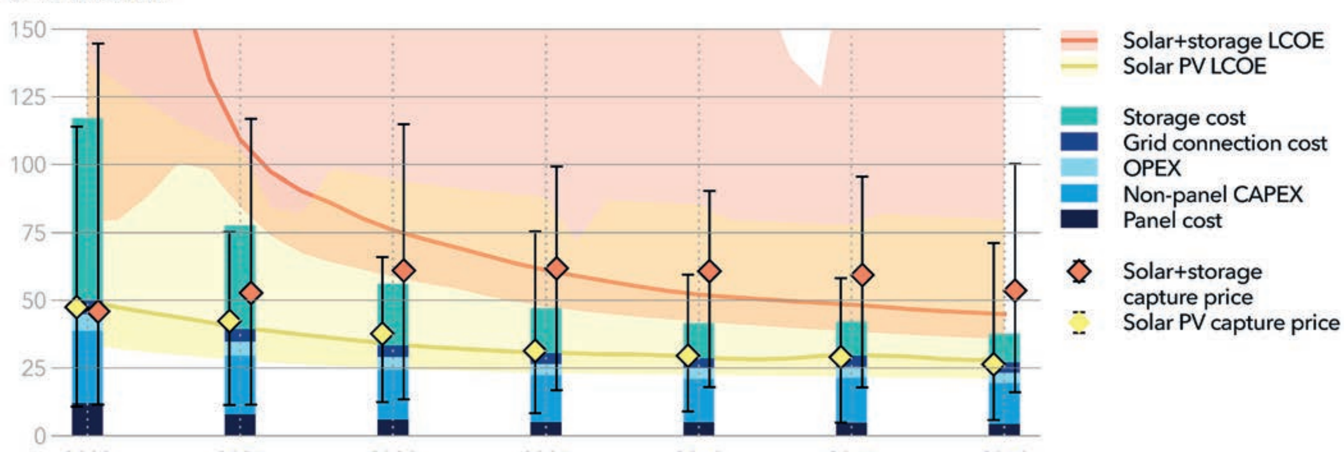
Solar PV costs are dominated by CAPEX, as the operating costs of the PV plants are only about 10-20% of the levelized cost (Figure 3.2). The main driver for continued growth is that unit investment costs, which is just below USD 900/kW as a global average, will fall significantly with every doubling of solar PV installation globally, reaching USD 600/kW in 2050. Currently, the global weighted average LCOE (levelized cost of energy) for solar PV is breaking the USD 50/MWh barrier, with individual project costs well below USD 20/MWh in locations like the Middle East and Latin America.

The panel cost-learning rate for solar PV will remain high throughout our forecast period; it is currently 26% and,

FIGURE 3.2

Global solar levelized cost of energy and capture price, with spread over regions

Units: USD/MWh



LCOE curves and capture prices show the weighted global averages at the investment year, based on the regional average expected capacity factors. Discount rates are 7-8%/yr. Error bars show the spread across 10 regions. Individual projects may lie outside these ranges.

while that rate will decline to 17% in 2050, solar PV will be in unassailable position as the cheapest source of new electricity globally, with exceptions only in unfavourable areas like the high North. The OPEX-learning rate of 9% is expected to remain unchanged until mid-century, as enhanced data monitoring, remote inspections and predictive maintenance continue to drive down the costs. Another factor in decreasing levelized costs is the increasing capacity factors. Greater use of single-axis trackers and bifacial solar cells will continue to boost the average global capacity factor of the new additions from about 19% today to 26% in 2050. In regions with favourable conditions, the capacity factor of new installations will start to exceed 30% within a decade.

The levelized cost of solar PV + storage is currently more than double that of solar PV without storage. However, with a continued drop in the battery prices, the gap between the two will narrow to below 65% by 2030. Despite its higher costs, solar + storage has an advantage over solar PV on capture price. These plants are able to charge their batteries when sunlight is plentiful during the day and sell the stored electricity when the price is high. By 2030, the capture price advantage of solar + storage over regular solar PV plants will surpass the cost disadvantage on a globally averaged basis. Consequently, in Greater China, for example, at least half of new solar capacity additions after 2035 will be in the form of solar + storage.

PV is intermittent: it will only produce electricity during daylight, and mostly during sunny conditions. To work around this, a host of flexibility options are being developed. These include:

- energy storage, such as pumped hydro, bespoke power batteries, and grid-linked EVs;
- connectivity, distributing power through a reinforced power grid with extensive connections that can be used both ways depending on production and demand; and
- demand-response solutions that shift demand to periods with higher production and lower costs, including, for example, industrial hydrogen production through electrolysis at peak production hours.

While flexibility solutions will improve over time, they will have to cope with a rapidly rising share of variable renewables in the power mix. Variability will therefore always be a challenge, and LCOE should not be the sole indicator of solar PV's competitive position. In our ETO model, we allow for various generation technologies to receive different power prices, and hence a levelized profitability accounting for both price and costs is more relevant than only levelized costs. We find that solar PV remains the technology that receives the lowest average power prices due to its variability. These low prices will vary between regions, influenced by the regional solar-PV share, the competing power mix, and the affordability of flexibility options.

Lower received prices will not, however, be a showstopper for the strong growth of PV generation. Increasingly, as discussed above, PV and storage systems are designed as a 'package' that can produce energy on demand, just like hydropower, nuclear or combusting power plants. Solar PV + storage is thus a distinct power station category.

Forecast

The historic growth of solar PV has been remarkable: 1 GW was installed for the first time in 2004, 10 GW in 2010, and 100 GW in 2019. In 2020, despite supply-chain disruptions caused by the pandemic, including to Chinese production which dominates the world market, solar PV again set a new record with 129 GW installed. Annual installations will continue to rise. Installed capacity for grid-connected capacity for solar PV and solar PV + storage, will reach 500GW in 2030, thereafter adding between 300 and 500 GW per year through to 2050. Within a decade, about a quarter of all PV installed will be with dedicated storage, and by mid-century this share will have risen to half.

In 2050, total installed capacity will be 8.4 TW for solar PV and 4.0 TW for PV + storage. Thus, a total of 12.4 TW solar-powered grid electricity in 2050. This is a 20-fold growth compared with the 2019 capacity of 610 GW.

Regions

Figure 3.3 shows that regional solar PV capacity will continue to be dominated by Greater China which will grow its global share of PV from 35% currently to almost 50% the next 10 years. As the rest of the world catches up, this share will recede to 30% in 2050. Greater China will reach the 1 TW installed-capacity milestone in 2026.

By mid-century, the Indian Subcontinent will hold the second-largest share of the global installed capacity of 20% (2.4 TW) while North America, South East Asia, and Middle East and North Africa will each have above 1 TW installed. Europe, which had three quarters of global capacity 10 years ago, and 22% today, will have less than 8% by 2050. One region with a share very much smaller than all other regions will be North East Eurasia, with just 0.5% of global capacity installed.

Off-grid solar PV

In addition to grid capacity, solar PV is also used directly to produce hydrogen, and for off-grid PV production in remote areas in Sub-Saharan Africa and the Indian Subcontinent, which are the only two regions where this is modelled. The overall solar PV capacities for these two regions are considerably smaller than the average across world regions, but still sizeable. Figure 3.4 shows that off-grid capacity for hydrogen production grows to around 40 GW by the mid-2030s, thereafter stabilizing to between 35 and 45 GW per year. Total installed off-grid capacity for hydrogen production will be around 800 GW by 2050, equivalent to 7% of the installed capacity the grid-connected PV.

Off-grid solar in remote areas in Sub-Saharan Africa and the Indian Subcontinent will grow slowly to annual installations of around 6 GW towards mid-century, three-quarters of which will take place in Africa. The global energy contribution of off-grid solar PV will be small even in 2050, with a total of 130 GW installed. But over the next three decades, inexpensive equipment – solar panels supported by limited battery storage – will provide hundreds of millions of less-affluent people in the aforementioned regions with access to energy, as shown in our energy access infographic in Section 1.3. Such equipment adds to the EV infrastructure, as it allows inexpensive, distributed off-grid charging of small EVs.

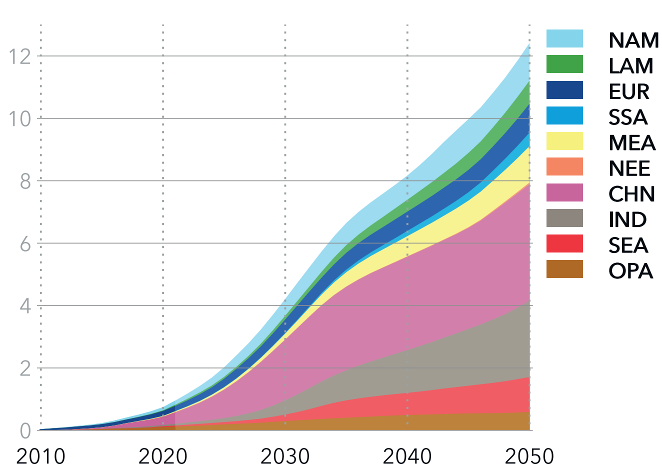
Over our forecast period, capacity installations will be higher for solar PV than for any other energy carrier. Cumulative capacity installed will shortly exceed that of thermal sources.

Solar PV has thus far enjoyed significant preferential treatment through support to PV developers, manufac-turers, and consumers encouraged by feed-in-tariffs.

FIGURE 3.3

Installed solar PV and PV+storage capacity by region

Units:TW

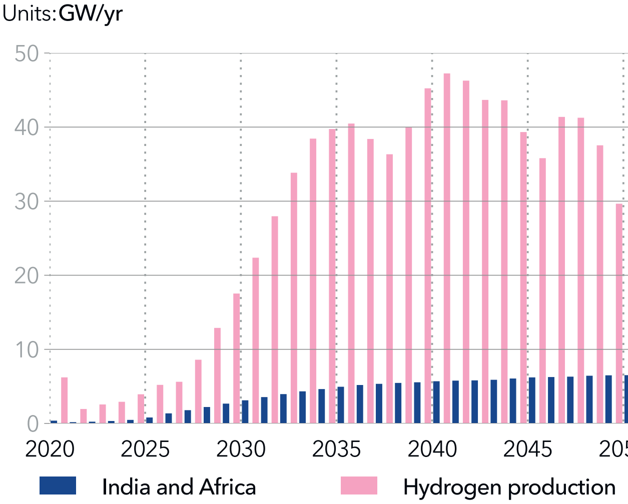


Includes off-grid capacity. Historical data source: GlobalData (2021)

FIGURE 3.4

World solar PV off-grid capacity additions

Units:GW/yr



Such policy mechanisms will recede in importance, with subsidy-free solar and market mechanisms increasingly taking over. Nevertheless, our forecast growth assumes future power market designs that do not place PV generation at a relative disadvantage.

Looking at PV electricity generation (Figure 3.5), it mimics the capacity installed as illustrated in Figure 3.3. But regional factors and differing regional capacity factors produces some variation. Middle East and North Africa, for example, has 10% of global PV capacity but has a higher share (12%) of electricity generated globally due to favourable irradiation.

Total grid-connected solar PV electricity will total 21 PWh in 2050, representing 36% of global grid electricity generation, a slightly larger share than wind at 33%. The sheer magnitude of the growth in solar PV is thrown into perspective when one considers that its share of total grid-connected electricity in 2020 was just 3.2%.

The regional shares of solar PV in power production are covered in detail in Chapter 7. It suffices to state here that the shares will be highest in the Indian Subcontinent with 49% and Middle East and North Africa with 47%, while North East Eurasia has the smallest share at just 3% of power generation.

Over our forecast period, capacity installations will be higher for solar PV than for any other energy carrier. Cumulative capacity installed will shortly exceed that of thermal sources.

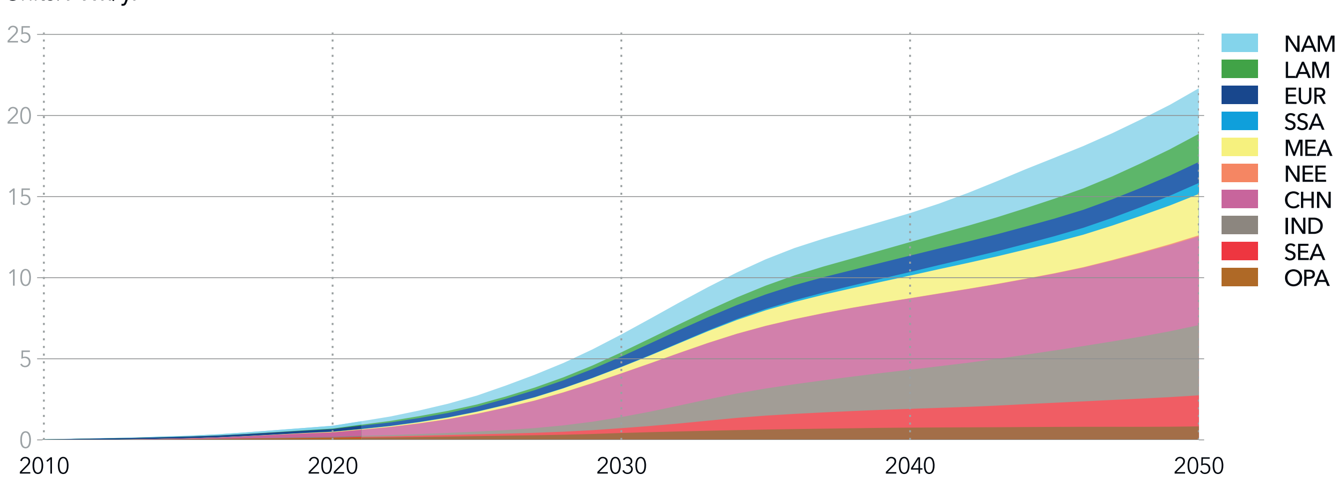
Sensitivities

Solar PV mainly competes with wind and other renewables in power generation and is therefore not so sensitive to carbon prices. Furthermore, future renewable subsidies are of limited importance to the results, as the renewable electricity sources mainly compete with each other. PV uptake is most sensitive to the individual competitiveness of the various power sources, above all wind, and a higher or lower cost learning rate for either solar or wind technologies is therefore very important. For example, were the wind learning rate to slow by 50%, PV generation would increase by 25%. Halving the electricity price in our model would increase solar by 12%, while additional rebound effects, which we have not modelled, are likely to result in a somewhat larger increase.

FIGURE 3.5

Grid-connected solar PV and solar+storage electricity generation by region

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021)

3.2 WIND

Wind power provided 5% of the world's electricity output in 2019, almost exclusively in the form of onshore wind. In some regions, like Europe and North America, its share of electricity generated was as high as 12.4% and 6.7% respectively (Figure 3.6). 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. However, by 2050, Europe and OECD Pacific are going to be the only regions where offshore wind generates more energy than onshore wind.

Electricity generation

We foresee electricity generation from wind increasing from 1,420 TWh/yr in 2019 to 17,840 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 50% of electricity in Europe, 44% in North America and more than 30% of electricity in Greater China, Latin America and South East Asia (Figure 3.6). The share of offshore wind in total wind electricity generation will increase steadily, rising globally from 6% in 2019 to 40% in 2050, 15% of which is floating offshore. In terms of the percentage of regional electricity demand supplied from bottom-fixed and floating offshore wind, Europe will remain in the leading position throughout the forecast period.

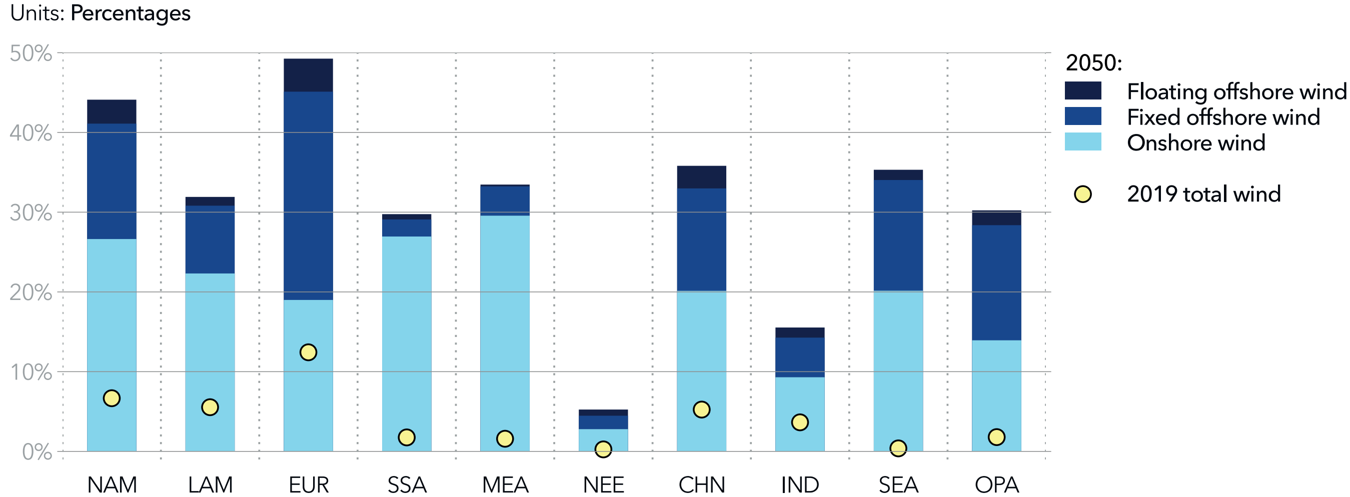
Capacity factors and costs

In 2019, a 1 MW onshore wind turbine generated on average 1.9 GWh/yr of electricity. In other words, the average utilization, or capacity factor, of all onshore wind turbines in the world was 21.5%. As wind capacity expands, new wind regimes will be exploited. Although some farms may have lower average wind speeds, new

FIGURE 3.6

Share of wind in electricity generation by region

Units: Percentages



Historical data source: IEA WEB (2020)

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 50% by 2050.

Figure 3.7 shows where the cost savings will originate. Since onshore wind is the most mature segment, its cost reduction will be limited to 42% over the period 2020 to 2050. The largest reduction in the average LCOE from onshore wind will come from increasing capacity factors and cheaper turbines. As onshore wind projects move to less favourable locations and to regions with higher costs, there will be a slighter decrease in the 'other fixed cost' component, which comprises 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 44% and 80% 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.

Forecast

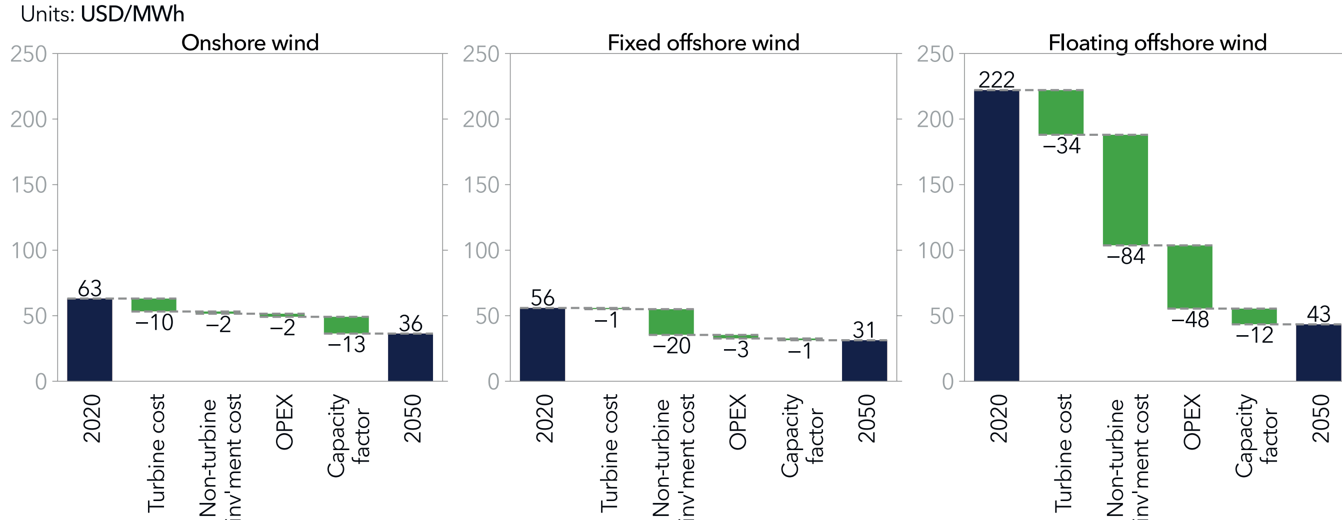
Globally, wind power has been growing steadily since the early installations in the 1980s. Installed capacity reached 709 GW at the beginning of 2020. We forecast 1 TW in 2022, 2 TW in 2029, 4 TW in 2043, and 5.9 TW in 2050, of which 1.7 TW will be offshore (Table 3.1). These developments are linked 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 264 GW of installed capacity by 2050.

Global wind capacity additions will increase from 60 GW/yr in 2019 towards 340 GW/yr by 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 installations that have completed their lifetimes. In our model, we use 23, 28 and 35 years for the lifetime of onshore, fixed offshore and floating offshore wind turbines

FIGURE 3.7

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

Units: USD/MWh



respectively. Because wind technology is still in its early stages of development, 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.

Sensitivities

From our sensitivity analysis 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 15% decline in wind output, a symmetrical 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% decreases wind output by 3% 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 installed capacity. We foresee 9% learning rates for O&M costs of onshore and offshore wind farms. For 'other fixed costs', we project learning rates of 0.5% for onshore wind, 18% for fixed offshore and floating offshore. Raising these learning rates by 50% increases wind output by 10%, while halving the rates reduces output by around 18%. Similar changes in solar PV-learning rates work against wind, indicating significant competition between solar and wind.

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.

TABLE 3.1

Installed wind capacity by region

Units: GW

	2020			2030			2050		
Region	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore
NAM	136	0	0	389	26	1	573	232	47
LAM	33	0	0	81	4	0.1	259	72	9
EUR	183	25	0	250	102	2.6	330	280	43
SSA	4	0	0	8	0.1	0	146	12	4
MEA	13	0	0	61	5	0	417	50	3
NEE	3	0	0	8.5	0	0	16	8	3
CHN	280	10	0	960	58	5	1494	470	102
IND	41	0	0	105	7	0	460	109	27
SEA	3	0	0	26	10	1	331	167	15
OPA	13	1	0	70	18	2	122	82	11
World	**709**	**35**	**0**	**1 960**	**230**	**11**	**4150**	**1484**	**264**

3.3 HYDROPOWER

In many regions of the world hydropower faces competition in terms of LCOE from emerging renewable energy. Additionally, new hydropower dams or improvement projects are typically megaprojects that require high capital investment, government approval, long lead times and the need to consider adverse impacts on biodiversity and on the dwellings and livelihoods of communities in the vicinity of the hydropower projects.

Furthermore, hydropower is dependent on a variable source: rainfall. Climate change is expected to exacerbate rainfall variations. We already see countries such as Sri Lanka struggling to generate electricity due to decades-long drought. This would be less likely in newly planned hydropower projects which have up-to-date hydrology and rainfall forecasts. Yet, uncertainty regarding rainfall variations will persist.

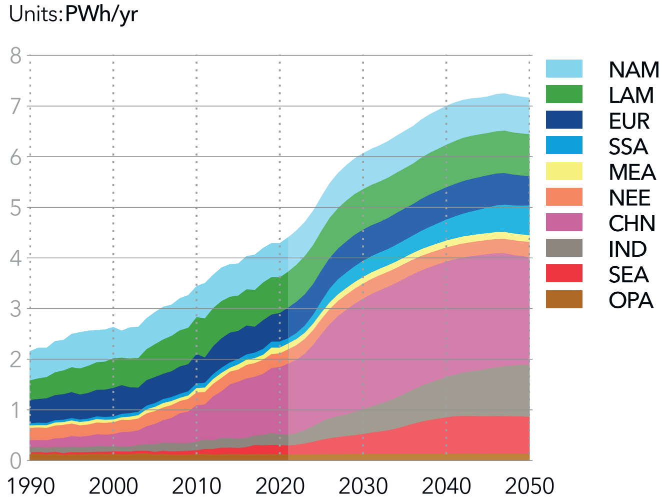
In many parts of the world, VRES (i.e., variable renewable energy sources like solar PV and wind) will be a strong competitor against hydropower, causing average electricity prices to decline, and creating adverse conditions for new hydropower. However, policy continuity for hydropower projects and rising electricity demand will ensure that hydropower projects will continue to be pursued, at least in developing economies.

There is a 'frenemy' relationship between VRES and hydropower. As solar PV and wind energy will grow strongly, hydropower will increasingly complement them, both for daily and seasonal variation management. Pumped hydro, which increases water volumes by harnessing surplus solar and wind energy to pump water back up to the reservoir, will be a part of this picture. However, because pumped hydro requires new investments and involves energy losses, many areas will continue with traditional hydropower, including reservoirs without pumping facilities. Run-of-river hydro, though lacking storage and therefore resembling PV and wind energy, will also continue to play a role. Compared with wind and solar power, dammed hydropower production can be withheld on sunny and windy days. This enables hydropower to receive much higher average prices and ensure profits, despite hydropower having higher LCOE than wind and solar PV.

FIGURE 3.8

Hydropower generation by region

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021)

There is a 'frenemy' relationship between VRES and hydropower. As solar PV and wind energy grow strongly, hydropower will increasingly complement them, both for daily and seasonal variation management.

Forecast

World hydropower generation has doubled over the last 20 years, but future growth will initially slow down (Figure 3.8), and peak in 2047 as suitable resources in prime locations will be exploited. After 2040, only Sub-Saharan Africa will see growth in generation from hydropower, while regions such as Greater China, North America and Latin America will plateau. In a world seeing doubling of electricity generation by 2050, hydropower generation will provide 12% of that, down from 16% in 2019. This loss of share is transferred to solar and wind, worldwide.

The mid-2020s will see expansion of hydropower capacity in Greater China of about 35 GW/year, which will taper off by 2030. This will be followed by capacity additions in the 2030s and 2040s in the Indian Subcontinent, South East Asia and Sub-Saharan Africa.

Sensitivities

We have investigated how sensitive hydropower generation is by comparing the most likely base value electricity generation in 2050 with the same values under conditions of changing carbon price, natural gas price and changing learning rates of solar PV and wind. Overall, we find that hydropower generation is not significantly sensitive to most of these changing factors. Of the sensitivities we have analysed, hydropower generation is most sensitive to a reduction in natural gas price: a 50% reduction in natural gas price leads to a 4% decrease in hydropower generation in 2050.

3.4 NUCLEAR POWER

Nuclear power provides reliable, carbon-free electricity via large, centralized power stations, but its future will be determined by its cost and potential environmental impact. In the 1970s and 1980s, nuclear power benefitted from energy security concerns. Then, 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 absence of long-term, viable solutions to nuclear waste management, 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. Moreover, increasing competition from (much cheaper) renewable energy technologies as a faster-to-market option for meeting the rising energy demand in developing countries has created a new challenge for nuclear energy.

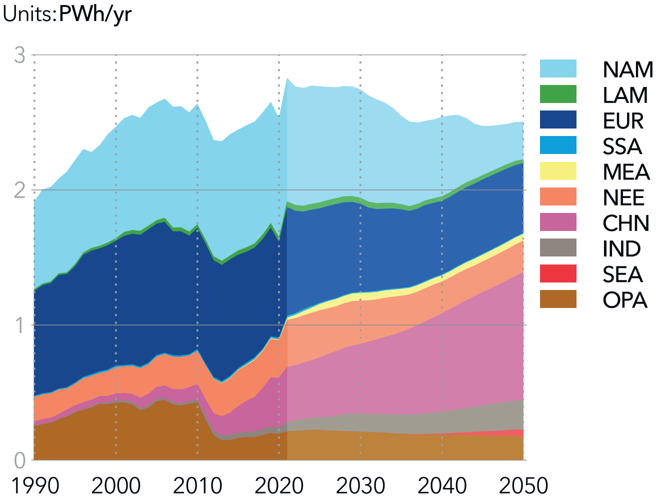
Forecast

Our Outlook reflects the impact of these roadblocks to nuclear (Figure 3.9). Our forecast shows nuclear peaks in 2021, followed by a long, slow decline arriving at a nuclear power output of 2.5 PWh in 2050, slightly lower than 2019 output. North America, Europe, and North East Eurasia are currently the top three nuclear-energy producers. They will be joined by Greater China as a major nuclear energy power within a decade, followed by the Indian Subcontinent and South East Asia in the 2040s.

FIGURE 3.9

Nuclear power generation by region

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021)

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 what happens to existing power stations.

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 decommissioning. 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 through upgrades and life-extension measures. While some countries, like France, are advancing their nuclear shutdown plans, Japan is working towards bringing its reactors back online, subject to improved safety demonstration, after the Fukushima disaster led to suspension of operations.

Small modular reactor (SMR) technology is not expected to scale significantly in our forecast. SMR faces a number of hurdles, including cost, safety, non-proliferation policy, and it could eventually – beyond our forecast period – make an important contribution to the decarbonization of hard-to-abate sectors, including shipping. In this year's *Technology Progress Report* (DNV 2021a), we discuss both fission and fusion technology in greater depth.

Sensitivities

We investigated sensitivities of nuclear electricity generation in our forecast by comparing electricity generation from nuclear in our most likely base case to the values resulting from changing carbon price, natural gas price, and learning rates of solar PV and wind, for the year 2050. Our analysis shows that nuclear electricity generation is sensitive to natural gas prices. When the natural gas price decreases by 50%, nuclear generation reduces by 12% in 2050. On the other hand, when natural gas price increases by 50%, nuclear generation increases by only 4.3% in 2050. Nuclear electricity generation is also sensitive to the learning rates of both solar PV and wind, and to an increase in carbon price as well. While a reduction in carbon price has almost no effect on nuclear generation in 2050, a 50% increase in carbon price leads to a 7% reduction in electricity generation from nuclear in 2050 as wind-generated electricity benefits.

Half the world's installed nuclear capacity is over 30 years old, and many reactors are approaching the end of their original design lifetimes.

3.5 BIOENERGY

Bioenergy – derived from many forms of biomass such as organic 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 and one of the key options to supply our energy needs towards 2050. Bioenergy applications are as diverse as its many forms. Solid fuels such as wood or charcoal are used for heating and cooking. Gaseous forms of bioenergy, such as 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 viewed as promising options in hard-to-abate sectors such as aviation and maritime.

Carbon neutral?

Combustion of biomass, including biofuels, is considered carbon neutral, and thus no carbon emissions are counted. This is in line with the Intergovernmental Panel on Climate Change (IPPC) assumptions that carbon in biomass is eventually absorbed from the atmosphere by photosynthesis, assuming that the burned plants are replaced with new plants. We note that while biofuels are broadly considered renewable, the view that their use is carbon neutral is contested by many scientists, mainly due to the timing of CO_2 reabsorption by replacement growth which is much slower than the sudden release of CO_2 via combustion (Scientific American, 2018).

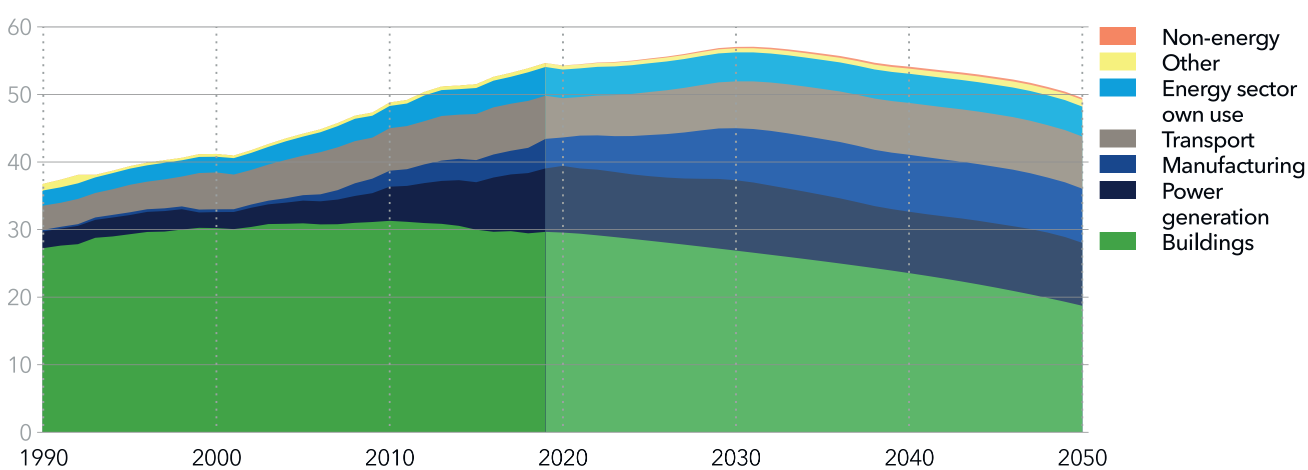
The types of biomass used in the future will differ from today, favouring biofuels derived from waste. Third and fourth generations of biofuels are likely to be subject to close scrutiny before they are approved for use and labelled as sustainable and carbon neutral. Between now and 2030, while the next generation of biofuel infrastructure 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

FIGURE 3.10

World bioenergy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2020)

land-use (AFOLU) emissions. Emissions during transport of biomass are accounted for under transport. Neverthe-less, we still adhere to the overall view that biomass and thus biofuels, is carbon neutral over time. Biomass-based value chains can also be carbon negative – such as the use of organic waste as feedstock for energy production rather than being left to rot, thus producing methane. However, we will follow this subject closely and update our calculations should research conclude otherwise and expect support and policies to also focus on better use of biomass residues and waste.

Forecast

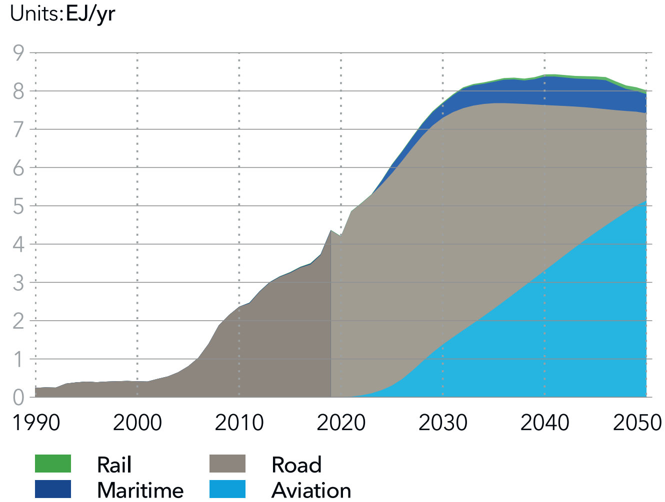
Global bioenergy demand supplied from biomass has almost doubled since 1980. Figure 3.10 shows biomass for energy use will keep growing until the early 2030s and level off towards the end of our forecast period. The transport and power sectors will be the main contributors to the growth. The overall share of biomass in primary energy supply grows marginally to about 12% in 2050 compared with the current share of 10%.

As seen in Figure 3.11, the use of bioenergy in the trans-port sector, mainly in the form of liquid biofuels with gaseous biofuels having a smaller share, will experience significant growth. With a predicted doubling between 2018 and 2050, bioenergy will become an important energy source used for decarbonization of transport, accounting for 8% 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.

FIGURE 3.11

Bioenergy use in transport sector

Units: EJ/yr



Historical data source: IEA WEB (2020)

Today, the overwhelming part of bioenergy use in the transport sector takes place in road transport (99.5%), mainly in the form of blends to gasoline and diesel, with a very small amount used in the form of gaseous energy carriers like biomethane. This is going to change towards 2050. Aviation and maritime transport will increasingly use biofuels to diversify their fuel mixes and foster decarbonization in specific areas where electricity or other renewable fuels are currently not an option, such as long-haul flights or deep-sea shipping. By 2050, road transport will see a 70% reduction of its current share due to ongoing electrification and thus a lower demand for blended fossil fuels. Maritime will by then account for 6% of biofuel use in the transport sector. The majority, namely 64% is going to be used in aviation. Rail transport is responsible for about 1% of transport's bioenergy demand.

Bioenergy use in buildings will reduce by a third, mainly due to diminished use of so-called traditional biomass in less-developed regions to supply space heating and cooking fuel. Even so, bioenergy use in buildings will retain its leading role with a third of bioenergy being used in buildings by 2050, from 55% in 2019. Power stations will use an amount of bioenergy roughly equivalent to current use throughout the forecast period (including all forms of waste) increasing its share by 2%. In 2019, 12% of world's bioenergy was used in the manu-facturing sector, and this share will grow slightly (by 4%) during the forecast period.

Regional developments

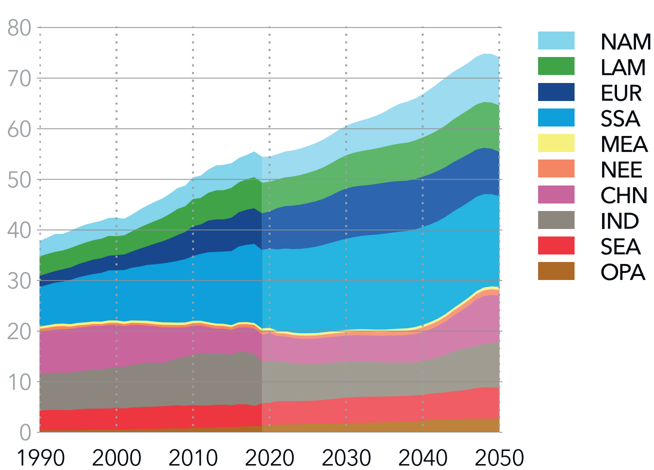
As seen in Figure 3.12, the regional share of demand will not change dramatically over the forecast period for most regions. Greater China (+70%), North America (+88%), and OECD Pacific (+117%) will see a significant increase in their bioenergy use. More modest growth is expected for Europe (+21%), South East Asia (+37%), Latin America (+50%) and North East Eurasia (+57%); slower growth is anticipated in Sub-Saharan Africa (+15%), Middle East and North Africa (+10%) as well as the Indian Subcontinent (+10%).

Over the forecast period, Sub-Saharan Africa will maintain its position as largest user of biomass, but its global share will reduce from 28% to 24%. As shown below, overall demand for biomass will increase, and the composition of biomass used globally will also change considerably from the traditional forms such as wood or charcoal (used, for example, in cooking) to a greater share of modern biofuels derived from waste (being used, for example, in aviation and maritime). 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 for some regions.

FIGURE 3.12

Bioenergy demand by region

Units: EJ/yr



Historical data source: IEA WEB (2020)

This year, we added a structure to our model that allows us to forecast regional developments in biomethane production and use. Biomethane, a gaseous energy carrier chemically equivalent to natural gas but with biogenic origin, has gained a lot of recent attention. It is produced either from upgraded biogas derived from several types of biomass or through gasification of lignocellulosic biomass (wood, straw). In our forecast, we exclude the gasification pathway, as this technology is expected not to have a significant share of biomethane production towards mid-century. We forecast 2050 biomethane production at around 450 Gm^3 per year, a hundredfold increase from present levels. This development is mainly driven by North America, Europe, Greater China and the Indian Subcontinent. We do not expect a significant uptake in North East Eurasia and Middle East and North Africa, because low natural gas and carbon prices in those regions render biomethane uncompetitive. As described in the fact box overleaf, biomass is not an infinite resource, and sustainable biomass is even more limited. Our model therefore increases the price of biomass as its use for biomethane intensifies. Nevertheless, biomethane will replace about a fifth of natural gas demand in North America and Europe.

Over the forecast period, Sub-Saharan Africa will maintain its position as the largest user of biomass, but its global share will reduce from 28% to 24%.

Sensitivities

Our sensitivity analysis indicates that high carbon prices will hinder biomass end use because biomass combustion will be subject to a carbon tax. Doubling the carbon price, however, will decrease biomass use by 3%. 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.

Is there enough biomass to supply demand across many sectors?

Biomethane is currently in vogue as a carbon-neutral fuel, and many cities require a significant share of their buses run on such fuels, which is mainly derived from organic waste. For the different transport 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. Demand is amplified by the use of pure biofuels in aviation transport (SAFs). For green shipping, however, the big increase in propulsion fuels will be in synthetic fuels and ammonia although there will be a minor share of biofuels in the transition period. Bio-based fuel demand will extend beyond transport to other sectors such as manufacturing and buildings. A decarbonized economy in 2050 clearly has an array of biofuel requirements – and by then the emphasis will fall on sustainable bioresources, potentially limiting supply.

Our forecast of the most likely energy transition towards 2050 expects a biomass use of around 70 EJ in 2050, a 27% increase from today's 55 EJ. To supply such an enormous quantity of biomass, three main feedstock classes will be prominent: (1) dedicated energy crops, (2) waste and residue streams and (3) aquatic resources. Estimates of the total available potential from these three sources differ widely, ranging from 100 EJ to 1500 EJ. However, applying sustainability constraints narrows the most likely range of total available potential to 200 EJ – 500 EJ per year (EC, 2010 and IEA, 2007). More conservative assumptions bring the potential down further to about 150 EJ per year (WBA, 2016). This potential would still be sufficient to supply the 70 EJ per year we forecast, but that does not mean an absence of constraints everywhere. Biomass used for energy purposes needs to be produced without compromising other important land uses such as food production; dedicated land-use change for biomass production should also avoid additional carbon releases, and further sustainability issues such as biodiversity need to be considered (ETC, 2021).

As we detail in Chapter 8, our most likely forecast does not meet the Paris Agreement temperature goal, which requires a net zero emission global economy by 2050. This, in turn, has implications for the biomass demand. It might be that sustainable biomass is not able to meet the demands of a net zero emission economy. Biomass use would thus need to be prioritized for sectors where there are few or no alternatives for deep decarbonization. A deeper insight into this topic will be presented in our forthcoming report – *Pathway to net zero emissions* (DNV 2021d).

Workers with elephant grass biomass fuel

3.6 OTHER

Other renewable energy sources are likely to remain marginal on a global scale towards 2050. For example, solar thermal and geothermal combined provide less than 1% of world primary energy by mid-century.

In this Outlook, 'solar thermal' refers to heat generated in solar water heaters. Globally, primary energy supply from solar thermal energy will start declining from today's 1.4 EJ in 2019 to reach a level of 0.5 EJ in 2050. Most such energy heats buildings, and Greater China responsible for most of the decline as heating water from electricity takes over. Section 1.3 discusses more in detail how buildings use energy for heating water.

Geothermal energy from the Earth's crust originates from hot springs or other low-temperature sources and has many potential applications, ranging from power generation to driving heat pumps. As of 2019, geothermal energy provided 4 EJ, or 0.7% of the world's primary energy supply. Although geothermal energy has the technological potential to grow in some applications, high costs in most of the world will limit its expansion. South East Asia is the leading region for geothermal energy, with more than a third of global supply and use. With a small growth in future geothermal production, South East Asia's 4% share of global geothermal energy will remain stable through to 2050.

Solar water heating thermal collector system

Potential future energy sources

As stated 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 Technology Progress Report 2021 (DNV, 2021a) provides more detail of improvements in technologies that are expected to have a meaningful 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 technology. Several methods for capturing energy from oceans have long been pursued (OES, 2018), including wave energy (shoreline and open-sea devices); tidal energy (stream and range devices); ocean currents; and ocean thermal energy. 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. That is not to deny that there are attractive niche opportunities. However, ocean energy is often confined to sites where the conditions are particularly favourable to their operation, making the solution cost effective, but not enough to scale globally. Ocean-energy technologies have existed for almost as long as wind and PV technology, but have seen none of their growth. We conclude therefore that the global contribution from such technologies will be insignificant.

Nuclear fusion is a similar case. For several decades, nuclear-fusion technologies have been discussed as a carbon-free source of energy. Several promising research projects focusing on smaller fusion systems are currently being piloted. Advances in computing power, material science, and manufacturing, together with the rising availability of venture capital, have enabled recent progress in fusion technology. Once the domain of governmental research labs, private companies are now bringing expertise in other areas, and stronger commercial focus as they seek to realize the potential of this technology (See details in our Technology Progress Report 2021). Yet, no plant has produced useable energy beyond that required to initiate and sustain a fusion reaction. The availability of fuel – primarily deuterium – is almost limitless. However, there are large uncertainties as to if and when successful operation of nuclear fusion will occur. Even with a breakthrough, there will still be a significant time delay before energy on a scale comparable to other power sources will be provided, and therefore we confine our nuclear forecast to traditional fission technologies.

During the period covered by this Outlook, one or more of the emerging energy technologies may achieve a breakthrough, such that they become cost competitive. However, to have significant impact on our forecast, they would need to grow much faster than incumbent renewable technologies. We do not see this happening at scale and have therefore excluded emerging technologies from the forecast.

Illustration of a Tokamak fusion reactor

Highlights

By 2050, the fossil share of primary energy will have declined to 50% from its current share of more than 80%. This is due to rapid electrification, decarbonization and accelerating energy efficiencies.

Coal has already peaked, and its use is expected to decline rapidly in our forecast period to just above a third of its current level by 2050.

Oil use is on the rise again after a sharp reduction of 9% in 2020. Our analysis shows that crude oil demand in 2025 will almost reach 2019 levels, but from that point it will decline slowly to 2030 before beginning a steep fall to reach 55% of current levels by 2050.

The electrification of transport is the main driver of the decline in oil demand.

Natural gas use will grow slowly this decade, have a flat development in the 2030s, and thereafter tapering off by some 10% to 2050, as it is edged out by renewables in power generation, by biomethane scaling, and as electricity replaces direct gas end-use. Along the way (early-2030s), natural gas will surpass oil the largest energy source. The oil and gas industry is under pressure to decarbonize natural gas. However, our forecast is that, by 2050, only 15% of gas will be carbon free – reflecting the late, and slow, scaling hydrogen production.

4 ENERGY SUPPLY AND FOSSIL FUELS

4 ENERGY SUPPLY AND FOSSIL FUELS

Fossil fuel presently supplies more than 80% of global energy, and this has been the case for decades. However, this share is set for dramatic change as the renewable energy sector is growing rapidly. The fossil slice of the pie will decline by around one percentage point per year, and we forecast that the split of fossil and non-fossil will be 50/50 in 2050.

Fossil fuels are undergoing a fundamental transition. Historically, coal was first to power the Industrial Revolution, followed by oil and then gas. The coming phase-out of fossil fuels will follow a similar sequence, largely driven by the CO_2 footprint of gas being much lower than coal (see Chapter 8 for a more detailed discussion on emissions and emission factors). Figure 4.1 illustrates how the composition of the various fossil energy sources, and the non-fossil share, will change over the coming decades.

Fossil fuels are competing with each other, first and foremost coal versus gas as they are both used extensively in power production, in industry, and in the heating of buildings. They also compete with renewable energies, including solar PV and wind, that are changing the electricity sector rapidly. Oil is used mainly in the transport sector and there it has little competition from coal and gas. The number of EVs on the road are multiplying rapidly, and electricity is an up-and-coming competitor to oil in road transport. In aviation and shipping, biofuel or electricity-based fuels will eventually challenge oil's supremacy.

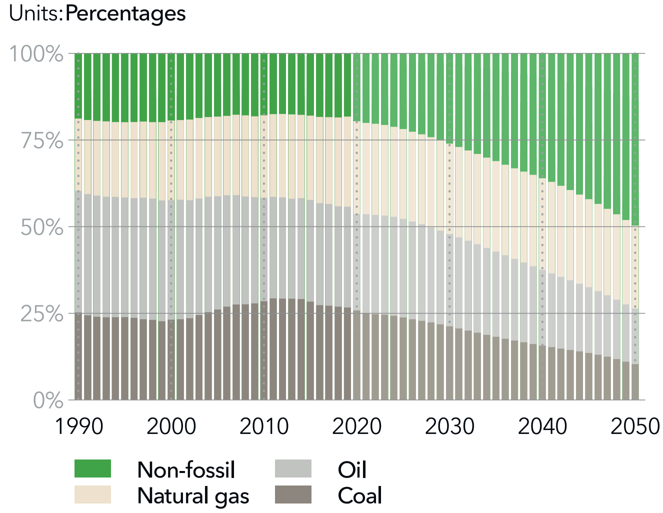
Oil's position as the world's largest energy carrier is now being challenged by gas, and we forecast that, in about 10 years' time, natural gas will have taken over as the largest energy source.

However, in DNV's best estimate for the energy future, which this forecast represents, low- and zero-carbon energy sources do not outcompete fossil fuels anytime soon. The latter will remain a major part of the energy industry over the coming decades albeit at a steadily declining share.

FIGURE 4.1

Fossil versus non-fossil in primary energy supply

Units: Percentages



Historical data source: IEA WEB (2020)

Oil's position as the world's largest energy carrier is now being challenged by gas, and we forecast that, in about 10 years' time, natural gas will have taken over as the largest energy source.

4.1 COAL

Once an energy sector favourite, global demand for coal grew rapidly from 4.7 Gt/yr in 2000 to peak at 7.9 Gt/yr in 2014. But from that point onward, total demand for coal has been on a bumpy ride.

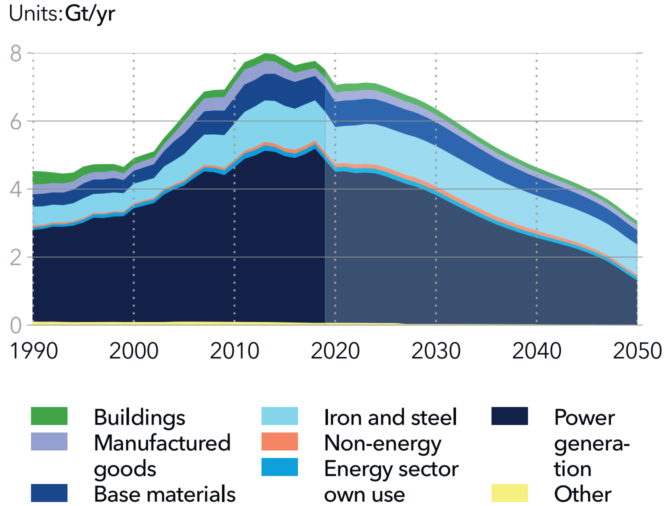
The economic and trade contraction associated with the COVID-19 pandemic reduced coal demand by 7% in 2020. Coal demand will rebound but will not reach its previous peak. A brief recovery to 2024 will soon give way to a decline, with coal demand falling almost two-thirds from its current level by 2050.

As a cheap and reliable source of power, coal has been the preferred technology for electricity generation in many countries. Power generation was thus the primary driver for coal demand, accounting for nearly 63% of coal consumption in 2019. However, 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, are signs of a shift towards wind and solar power generation.

FIGURE 4.2

World coal demand by sector

Units: Gt/yr



Historical data source: IEA WEB (2020), US DOE (2010), Heat Roadmap Europe (2015)

Coal is also used as a heat source in manufacturing, and as a carbon source for iron ore reduction in steel production. For low-heat processes in production of manufactured goods, direct coal use will decline and be replaced by electricity. Additionally, coal being a source of local pollution is a main reason why China, for example, will continue to switch from coal to gas for industrial processes. In other regions, heat demand will increasingly be met by gas boilers and electricity, thereby contributing to the phasing down of coal.

For higher-temperatures processes (such as cement or iron and steel), the switch will be more difficult, and coal will remain a favoured option despite its high carbon emissions. Coal demand for high-heat processes will first increase slightly and then fall rapidly after 2030. The global coal demand in the iron and steel sector will decrease almost a third by 2050. Today's biggest coal consumer, Greater China will see a larger reduction of 59%, mainly due to steel production declining by even more than that (down 65%). Coal demand for iron and steel in the Indian Subcontinent will double by 2050, overtaking Greater China's appetite for the fuel.

Total coal use has already declined strongly in North America and Europe, driven by shifts in the power sector. Low gas prices have been at the forefront of the fall-off in North American coal use, whereas renewables growth is the main factor in Europe. Coal use has flattened in China recently, supported by policies to curb air pollution in manufacturing and power supply. Over the last decade to 2019 only the Indian Subcontinent (38% growth) and South East Asia (150%) have shown uninterrupted increases in coal use.

All regions will show a long-term reduction in coal consumption, but not necessarily in the short term. Before 2030, coal use in the Indian Subcontinent and South East Asia will grow. By mid-century, coal use in OECD regions, notably North America and Europe will have declined by 85% and 80%, respectively. Coal's decline in coal-rich OECD-Pacific will also be substantial, at 62%.

In near-term power generation, coal will lose out to gas and renewables in OECD countries, but expand in many developing nations. After 2030, stricter emission policies, increasing competition from renewables, and ramping-up of storage and other sources of flexibility technologies will make renewables more dispatchable and reduce the competitive position of fossil fuels in general and coal in particular. Consequently, capacity additions will gradually fade away, retirements increase, and capacity utilization will decrease. Our analysis confirms the coal death spiral feedback-loop: as plant utilization declines, coal power will become more expensive, thus further reducing its competitive position, making coal power less affordable, and thus its use declines yet further. China and India have recently added capacity and more coal-fired power stations are planned along with greater coal use in manufacturing. This inertia will result in Greater China and the Indian Subcontinent continuing to retain their current share, 70%, of global coal demand in 2030. Greater China will however see a large decline after 2030, resulting in total coal use falling to 21% of its current level by 2050. But the Indian Subcontinent's coal use will grow, such that the two regions combined will consume 65% of global coal supply in 2050

Almost all brown coal, and a significant share of hard coal, is consumed within its region of production. However, Figure 4.4 shows that in 2019, 8% of demand was not satisfied regionally, but had to be imported. This share will continue to grow, reaching 16% in 2040. Four of the 10 regions are net importers of coal, namely Europe, Greater China, the Indian Subcontinent, and Middle East and North Africa. China, the largest producer and consumer of coal, is also the biggest importer. However, the phasing out of coal-fired power plants in China, and reduced use of coal in manufacturing, will progressively reduce its demand for coal, but imports will remain high. Driven by India's efforts to increase self-sufficiency, the Indian Subcontinent will reduce its share of imported coal. Australia, Indonesia, Russia, and South Africa will continue to be major exporters, albeit each with diminishing shares.

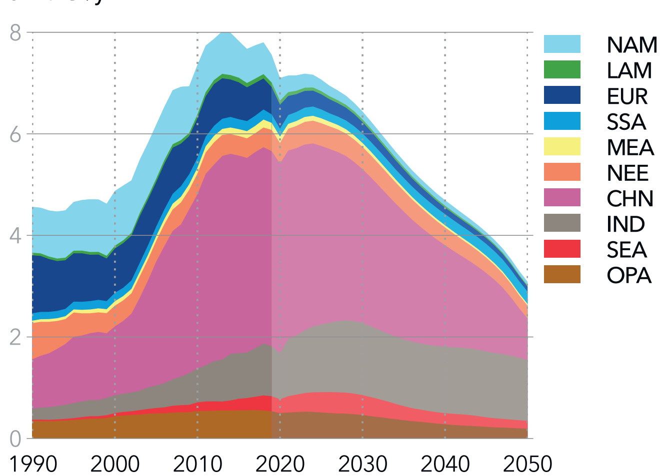
Sensitivities

Sensitivity analyses suggests that the phasing out of coal is unstoppable, even with policies less favourable to renewables. Carbon pricing could be one of the more important factors. Relative to our forecast, a 50% lower carbon price would lead to only a 13% increase in global coal consumption in 2050, while doubling the carbon price would reduce coal use by only a quarter between now and mid-century.

FIGURE 4.3

Coal demand by region

Units: Gt/yr

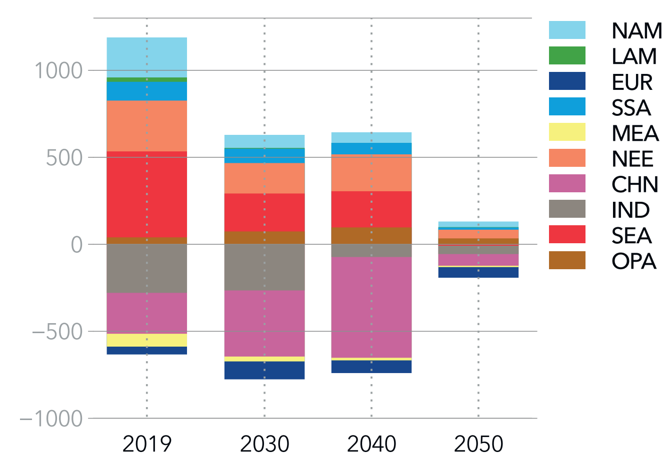


Historical data source: IEA WEB (2020)

FIGURE 4.4

Net difference between coal production and demand

Units: Mt/yr



Historical data source: IEA WEB (2020)
Positive value: net export / Negative value: net import

4.2 OIL

Global oil demand has grown steadily at slightly over 1% per year for decades, with a minor bump related to the 2007/2008 financial crisis. In 2020 this steady growth came to an abrupt halt. Above all, oil is used for transport, and global transport in the months after the COVID-19 outbreak plummeted. The oil industry is still tackling the consequences of the pandemic, and while some subsectors and regions have returned towards normality, others have not.

Driven by a growing population and economy, and an ever-increasing demand for transport services, oil has been the world's leading energy source ever since it took over from coal in the early 20th century. In 2019, demand for oil was at 166 EJ or 88 mn barrels per day (b/d). (See fact box at the end of section 4.2 for a discussion of oil vs. natural gas, and crude oil vs. oil products.)

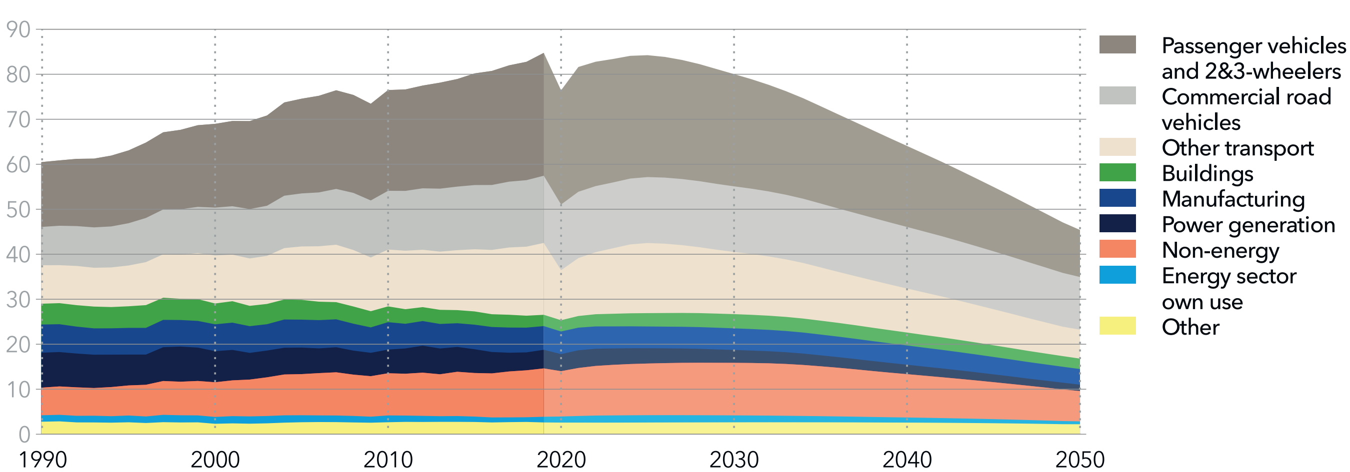
Figure 4.5 shows global oil demand may have reached its all-time high in 2019, or there may be another small peak in a few years' time, before entering steady decline. In DNV's forecast, the difference in demand between 2019 and 2025 is about 1%. Demand will reduce slowly towards 2030, but then the decline becomes relatively steep, averaging -2.8% per year over the following two decades. This means the reduction rate is much faster than the average growth of about 1% per year that we have seen historically. 2050 global oil demand will be 45% lower than today.

The transport sector's share of oil demand in 2019 was historically high at 68%, but will now gradually reduce as the aviation industry returns to normal only slowly after the pandemic, and road transport starts to electrify. The transport sector will continue to dominate oil use, however, retaining a share of 61% in 2050, with the road subsector taking the largest part, which, again, is evenly split between passenger and commercial vehicles. Electrification of the passenger segment will come first, and its oil demand will more than halve over the next 30 years; oil use in the commercial road segment will hold up a little longer. The global number of ICEVs will peak in 2029 at 1.4 bn vehicles. ICEVs are also improving their average efficiency annually, as described in Section 1.1.

FIGURE 4.5

World oil demand by sector

Units: Mb/d



Does not include natural gas liquids and bioliquids. Historical data source: IEA WEB (2020)

Oil use in aviation and shipping (termed 'Other transport' in Figure 4.5) will grow at first but then reduce significantly towards the end of the forecast period when biofuel, e-ammonia, and other e-fuels decarbonize the fuel mix.

Oil is also used as petrochemical feedstock, where its present share of 13% will grow, in both absolute and relative terms, during the next decade. However, owing to higher rates of recycling and use of bio-derived feed-stock, our longer-term outlook for petrochemical feed-stock is at odds with that of several other forecasts, with ours indicating a reduction of one third from 2035 onwards.

The third largest sector is manufacturing, which will retain its 7% share in oil demand. This means that oil use in the manufacturing sector will slowly decline between now and 2050 as the relative weight of oil diminishes in the global energy mix. Oil, or its products, are also used in buildings, power, and 'other' sectors, and for producing the oil itself. However, these uses are small and will remain so in our forecast.

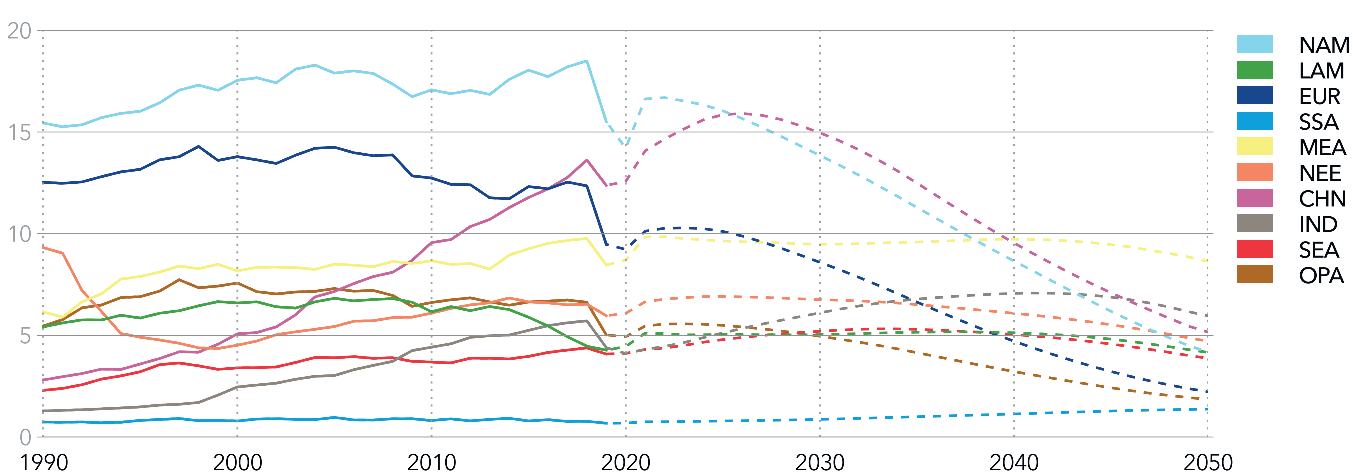
Looking at regional demand, North America has been the region with the highest demand for many decades, but Greater China overtook Europe as second largest in the last half of the previous decade. Figure 4.6 shows North America and China will continue to be the largest users over the next 20 years. However, both will be surpassed by Middle East and North Africa and the Indian Subcontinent in the 2040s, as rates of electrification of the road transport subsector in these two regions lags behind EV uptake in North America and Greater China, as illustrated in Figure 1.7.

Peak oil will come at very different times in the various regions. As with energy demand in general, global oil demand will shift eastwards and southwards. Europe's 2050 oil demand will be only 21% of its present level, and, together with OECD Pacific, the lowest oil demand of all regions. Driven by electrification of the transport sector, North America will see oil use drop to 24% of its present level. In Greater China, an increasing number of vehicles on its roads, will mean that oil use grows initially before peaking in 2026, at 10% higher than today. Thereafter, fast uptake of EVs will result in China's oil use entering a rapid decline, and its demand in 2050 will be only one third of what it is today. In contrast, Indian Subcontinent's oil use will peak in around 2040 and will still be nearly a third higher in 2050 than it is today. Sub-Saharan Africa's oil use will not peak within the forecast period and will almost double between now and mid-century.

FIGURE 4.6

Crude oil demand by region

Units: Mb/d



Does not include natural gas liquids and bioliquids. Historical data source: IEA WEB (2020)

No other energy commodity is transported around the globe to the same extent as oil, and the centres of global oil production are generally not the main areas of consumption. Middle East and North Africa is already the largest oil-producing region, and Figure 4.7 shows that its share in global crude-oil production will rise from today's 34% to 52% in 2050. The main reason for this is its abundant reserves of relatively cheap oil. However, absolute production in the region will be 23% lower in mid-century than today.

We do not have a stance regarding whether the potential political repercussions from one region producing more than half of the world's oil are acceptable, but this is worth mentioning as a risk. However, security of supply is generally improving as the share of energy produced locally or regionally increases with a growing share of renewables, and oil's role in the geopolitical picture will diminish in the coming decades.

Our model also separates between offshore, onshore conventional, and onshore unconventional oil production. Globally, the distribution remains almost constant over the forecast period, with onshore conventional at just above 50% of production, offshore at 30%, and onshore unconventional increasing its share from 16% to 18%.

Naturally, there are large regional variations, with onshore dominating in Middle East and North East Eurasia, whereas in North America the lead is now taken by onshore unconventional.

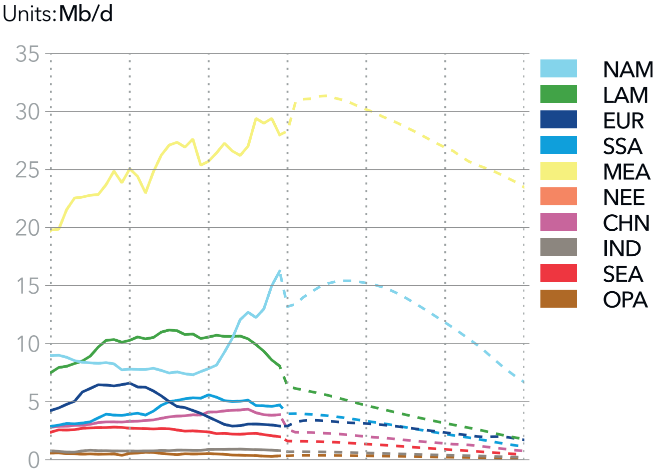
It should be added that uncertainty over where oil will come from is high. In the DNV ETO model, oil production equals demand, and regions do not develop their oil resources if cheaper oil can be supplied by other regions. Although global oil production will always equal demand over time, as storage is limited, regional distribution might not follow the same disciplined pattern as used in our model. In a future in which oil demand levels off and declines, the oil industry is entering unfamiliar territory, with significant risks of volatile and lower oil prices for suppliers. OPEC decisions on curbing oil production to maintain a certain price level, or similar political decisions have not been included in our model.

In our forecast, new oil-production capacity will be developed through to 2050, but, as shown in Figure 4.8, annual capacity additions will reduce by three quarters globally over the next 30 years. As unconventional capacity has a shorter average lifetime than the capacity of conventional, both onshore and offshore, regional distributions of capacity additions are not directly

FIGURE 4.7

Crude oil production by region

Units: Mb/d

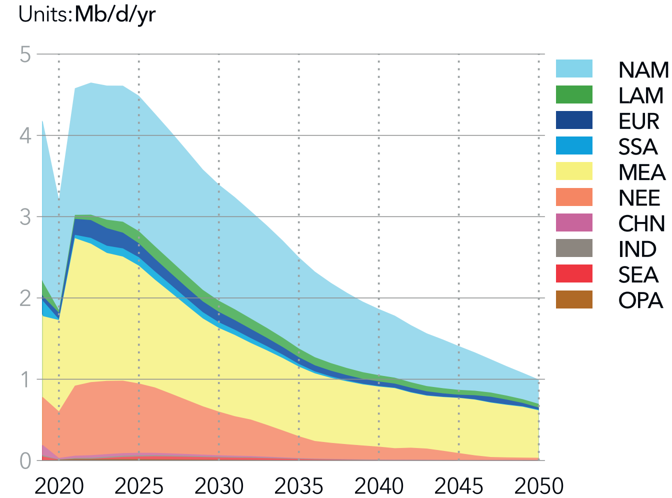


Does not include natural gas liquids and bioliquids.
Historical data source: IWA WEB (2020)

FIGURE 4.8

Crude oil production capacity additions by region

Units: Mb/d/yr



Does not include natural gas liquids and bioliquids comparable. Thus, North American capacity will dominate in the first decade, before the share of Middle East and North African capacity additions increases, as a growing proportion of oil production moves to this region. The reduction in oil demand will make it less attractive for the industry to expand production into challenging environments, such as deep water, high pressure, and/or remote locations such as the Arctic.

In Section 5.3 on energy expenditures, Figure 5.5 shows that oil was previously capitalized in the report. CAPEX will reduce by 80%, reflecting the decrease in capacity additions.

Sensitivities

The most decisive factor in the rate of decline in oil demand is the speed with which EVs will take over from ICEVs. Battery costs are the most important determinant of EV competitiveness; battery learning rates, i.e., how fast batteries are falling in price, are therefore of key importance. If we model a halving of battery learning rates over the next 30 years, we find oil demand in 2050 rises by 14%, from 90 to 103 EJ. A similar reduction in demand occurs with a battery learning rate raised by 50%. Over time, technology learning is more important for oil demand than the level of EV subsidies.

As oil demand from the power sector is low, sensitivity to changes therein, including those occurring with solar PV and wind, is relatively low. Electricity price itself is a factor, and halving/doubling electricity prices will result in oil demand varying by around ±7% from our base case.

The most decisive factor in the rate of decline in oil demand is the speed with which EVs will take over from ICEVs.

Finally, if we look at oil price itself, our analysis indicates that should the oil price halve then demand for oil will increase by some 17%, whereas doubling the price will reduce demand by 10%. The numbers might well be higher than these, as significant rebound effects that are not included in the model, e.g., on transport services themselves, would occur in addition to changes in the energy mix.

In this sensitivity discussion, we have considered changing individual parameters one-by-one. However, combinations of changes could also happen simultaneously.

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 others sometimes categorize them as 'oil'. This is one reason for differences between the absolute values of oil vs. natural gas for historical numbers.

Crude oil, as extracted in its natural form, is also composed of various hydrocarbons, and must 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.

4.3 NATURAL GAS

Natural gas, the least carbon-intensive fossil fuel, will usurp oil to become the world's largest energy source in 2032. There will be new uses for natural gas, particularly with increasing use in maritime transport, but also as a source for blue hydrogen (Figure 4.9). Slightly less than half of the demand for natural gas will derive from final use – in buildings, manufacturing, and transport. The other half of the demand will come from transformation to other final uses, such as electricity, non-energy use such as for petrochemicals, from own use (demand from the oil and gas and energy industries during production and distribution) and from hydrogen production.

Demand for natural gas and biomethane (both are thereafter referred to as gas) is set to slowly increase to 2041, and thereafter decline towards 2050. In Europe and OECD Pacific, gas consumption already peaked over a decade ago, and its decline will continue. In Greater China, it will peak in the early 2030s. After a five-year respite to 2025, gas growth in the Indian Subcontinent will continue, climbing to a level by 2050 three times higher than its 2019 level.

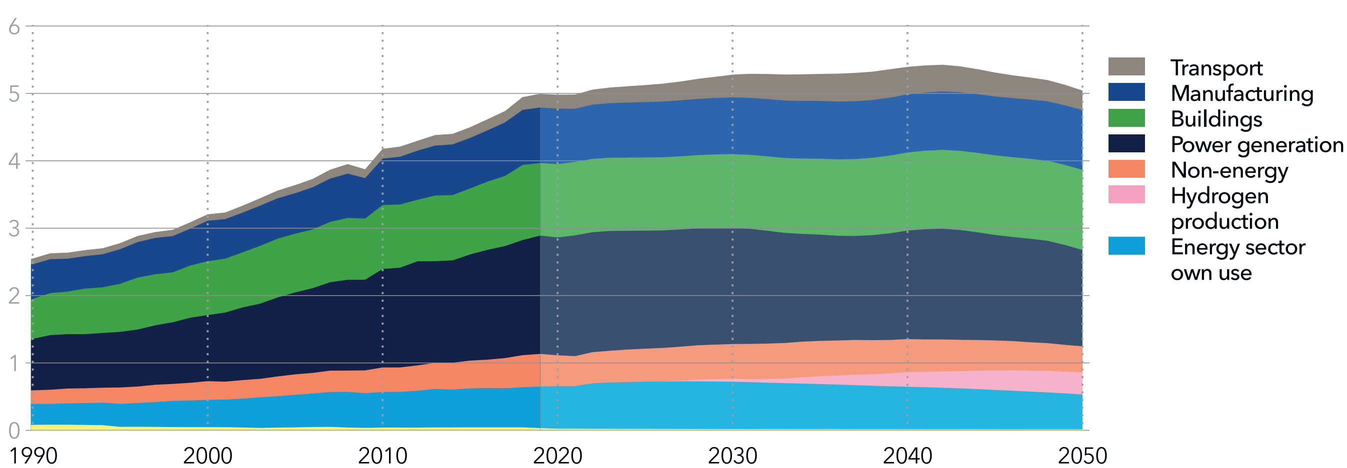
Use of gas in power generation will decline from 35% to 29% by 2050, but still accounting for the greatest share among sectors. In real terms, its use in power generation will already have plateaued in 2025 and will start to decrease from the 2040s as a result of growth in renewables.

From a relatively low starting point, gas demand in the transport sector will more than double to 2040, before dropping by almost a third to 2050 as it is increasingly displaced by the rise of hydrogen in transport. Manufacturing's appetite for gas will increase to 2050, ensuring its share increases from 16% to 18%. Similarly, demand for gas from the buildings sector will see a slight growth to 2050, expanding its share from 22% to 24%. Non-energy (largely petrochemicals) will decline from 10% to 8% as demand for products that use gas as a feedstock falls and hydrogen is increasingly used. Own use (demand from the oil and gas and energy industries during production and distribution) will grow over the next five years but will fall from 14% to 10% by 2050. Decreases in own use will likely arise from efficiency gains, from the electrification of production facilities, and from less flaring. Some of this

FIGURE 4.9

World natural gas demand by sector

Units: Tm^3/yr



Includes natural gas liquids and biomethane. Historical data source: IEA WEB (2020) use in the energy sector will be for liquefaction and regasification of gas that is transported as liquefied natural gas (LNG).

Among the regions, primary demand for natural gas in the Indian Subcontinent will triple to 2035, whereas Greater China will experience a 50% growth towards 2035, followed by a steep decline, returning to 2019 levels by mid-century, but then still accounting for 8% of world natural gas demand (Figure 4.10). Together, these two regions accounted for 13% of total natural gas demand in 2019. This will rise to 21% by 2035 and continue at that level to 2050. Both regions are set to see strong policy support for natural gas consumption in the short term, with local pollution prevention as a main driver. As both regions have limited natural gas resources, they will together account for 55% of net natural gas imports in 2035 and 70% in 2050.

South East Asia will see a slight natural gas growth from 2023 to a peak in 2032 before returning to 2010 levels in 2050. The region will continue to export more than it imports, although its gross imports will decline. Strong demand for natural gas from Middle East and North Africa, North America, and North East Eurasia regions will continue, collectively accounting for 56% of global demand today and keeping this share to 2050. Within these big-user regions, demand from North America will decline, from a 25% global share in 2023 down to 16% in 2050, as the power sector there, in particular, totally decarbonizes. North East Eurasia will see much less decarbonization in any of its demand sectors and its share will grow by half, to over 21%. Only marginal growth will be seen in the Middle East and North Africa. These three regions will remain as the main natural gas production regions and will also continue to be the main net exporters of natural gas.

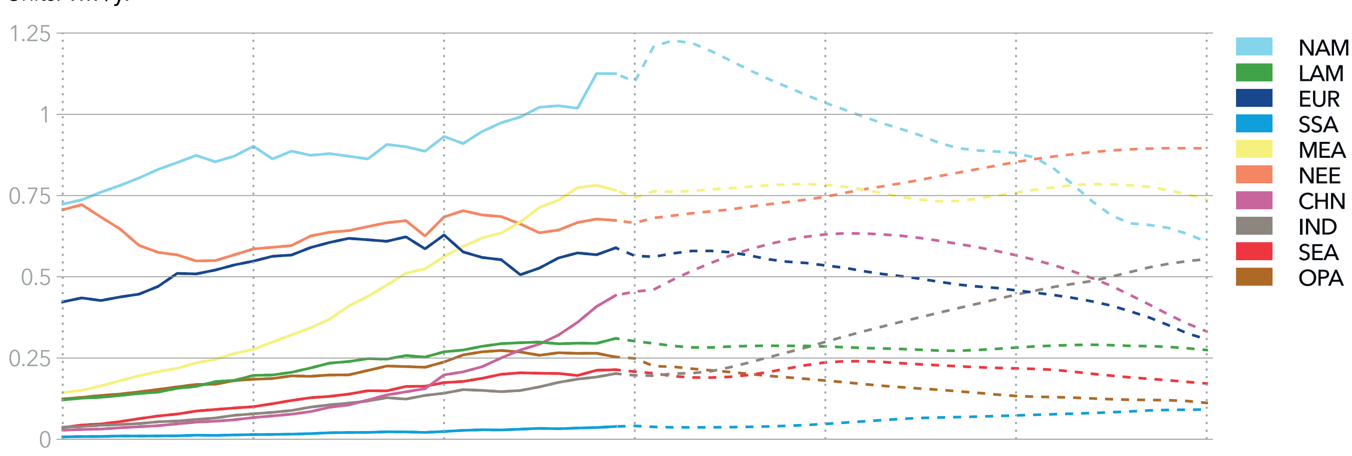
Europe and OECD Pacific are decarbonizing faster than other regions and, as their own natural gas resources are limited, both will therefore see declines in natural gas demand to 2050. Latin America, however, will see little change in its demand. Combined, these three regions accounted for 24% of demand in 2019 and will account for 19% by 2050 and will remain natural gas importers throughout the forecast period. Sub-Saharan Africa will see continued growth, albeit from a low level, doubling its global natural gas share to 2% in 2050.

Declines in natural gas use occur for three primary reasons. Firstly, gas-fired power generation meets stiff competition from carbon-free renewables. Secondly, in

FIGURE 4.10

Natural gas demand by region

Units: Tm^3/yr



Includes natural gas liquids. Historical data source: IEA WEB (2020) sectors where it is feasible, direct gas use is hit by electricity growth. In other sectors, hydrogen – increasingly green – will be a fossil-replacement option in hard-to-abate applications in a world steadily more eager to decarbonize, and with carbon prices implemented worldwide. Thirdly, biomethane, being organic in origin and chemically identical to natural gas, but additionally accounted for as "carbon free", will increasingly replace fossil (aka natural) gas in all demand sectors.

In 2050, 15% of gas will be carbon free (Figure 4.11). This follows rapid growth in converting natural gas to hydrogen as an energy carrier (current use of hydrogen and ammonia from natural gas is simply classified as 'non-energy feedstock'), natural gas with CCS in power and industry as well as growing production and use of biomethane. By mid-century, biomethane production will see a hundredfold increase from today`s levels, with more than 80% of the production capacity in North America (30%), Europe (20%), the Indian Subcontinent (17%) and Greater China (15%). Global production capacities buildup accelerates significantly in the 2030`s and reaches 450 Gm^3 in 2050 (see Section 3.5 for more information). In 2050, 30% of hydrogen will be produced from fossil fuels, exclusively from natural gas, and 70% will originate from electricity, predominantly from renewable sources and much of it in bespoke electrolyser facilities. Carbon-free gas developments will be spearheaded in those regions with the most ambitious transition policies, and consequently high carbon prices, namely: Europe, Greater China, North America, and OECD Pacific.

In the coming decade, global natural gas production will remain largely unchanged (4,510 Gm^3 in 2019 and 4,520 Gm^3 in 2030) before decreasing to 3,979 Gm^3 in 2050 (Figure 4.12). Middle East and North Africa and North East Eurasia will together account for more than half of global output in 2050. North American natural gas production will halve, reflecting a 50% reduction in its own demand. However, smaller levels of production in the higher cost regions of Europe and OECD Pacific will experience the most dramatic reduction, falling by 42% and 47% respectively from 2019 to 2050.

Compared with our forecast for oil (see Section 4.2), offshore natural gas production will be more resilient than offshore oil. This is partly due to a more pronounced fall in oil demand, such that more-expensive offshore capacity will lose its oil market share.

FIGURE 4.11

World natural gas and decarbonized gas supply

Units: Tm^3/yr

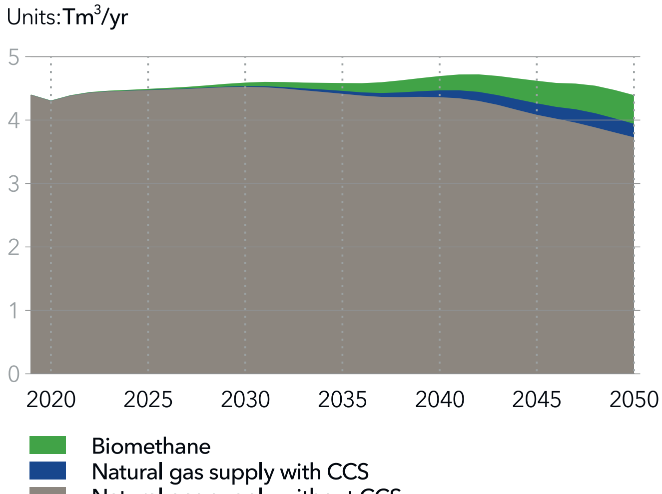
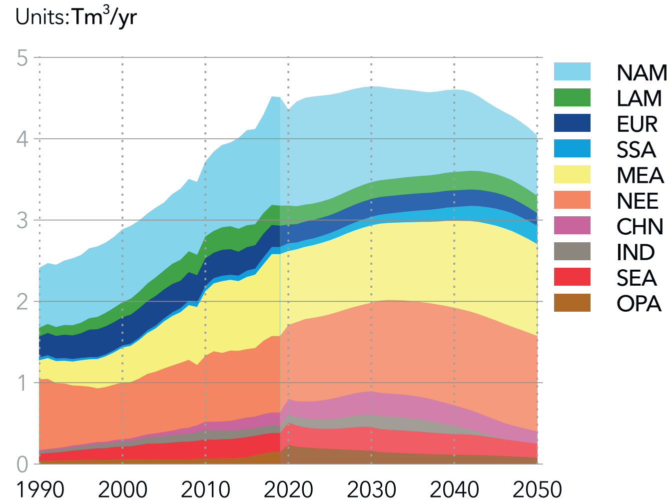


FIGURE 4.12

Natural gas production by region

Units: Tm^3/yr



Includes natural gas liquids and refinery output. Does not include biomethane. Historical data source: IEA WEB (2020)

As the demand for natural gas grows more pronounced in importing regions, LNG and pipeline transport will increase even when global gas demand does not. Gas transport is expensive and accounts for a significant proportion of the cost of delivered energy. Piping is cheaper than shipping for transport over shorter distances and will expand as production sites and consumption sites move further apart. Global capacity for regasification grows by only 10% to 2050, while liquefaction more than triples. The big producers are also the big exporters, and North America – which is distant from its natural gas customers – will see the largest growth in liquefaction, accounting for 38% of global capacity by 2050. Middle East and North Africa will be second largest, representing about 19% of global liquefaction capacity. By mid-century, nearly half (47%) of global regasification capacity will be in the Indian Subcontinent and Greater China (Figure 4.13).

Greater China is one of the main importers of natural gas, and will increase its imports in the coming decade, followed by a steep decline to 2050 values as its consumption of natural gas reduces (Figure 4.14). In a few years' time, Europe's natural gas imports will begin a steady decline to about half of current volumes by 2050. Despite the decreasing imports from Europe and Greater China, North East Eurasia will continue to be a major gas exporter during the forecast period, and while the region will see some increase in liquefaction capacity, pipelines are likely to distribute much of the exports. The Indian Subcontinent will significantly increase its imports to satisfy its almost tripling natural gas demand which necessitates significant increases in LNG regasification capacity in the region. Middle East and North Africa, will continue to be amongst the most important suppliers of global natural gas demand and towards the end of our forecast period replaces North East Eurasia as the biggest natural gas exporter.

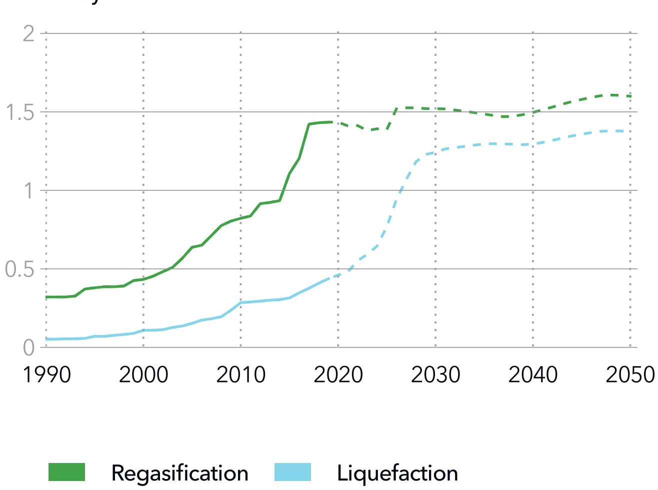
Sensitivities

Although the energy transmission cost per GWh delivered is lower for gas than for electricity, it is more expensive than electricity and the price differential offsets lower gas transmissions costs. The cost advantage of gas-grid replacement compared with that of power-grid newbuilds is assumed to be relatively minor. In contrast to the minor transition role of gas in providing heat, 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 biofuel category.

FIGURE 4.13

World LNG trade capacity

Units: Gt/yr

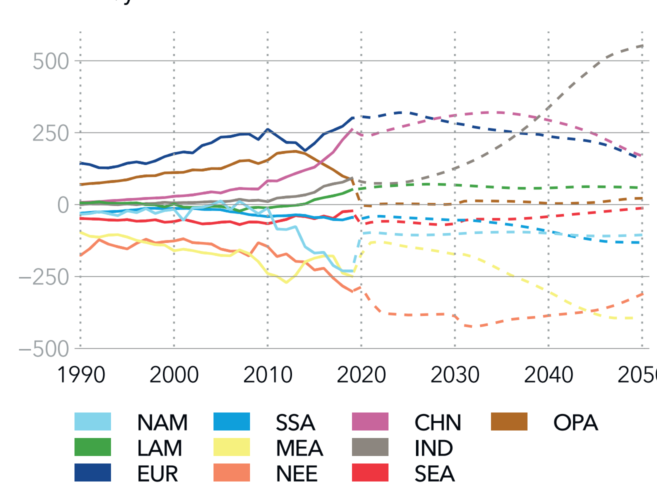


Historical data source: IGU (2019)

FIGURE 4.14

Net natural gas imports by region

Units: Gm^3/yr



Historical data source: IEA WEB (2020)

Which factors might threaten our conclusions regarding the future of gas? Gas demand is sensitive to price. A reduction in the gas price of 50% will increase the 2050 demand for gas production by 40%. However, the equivalent increase would result in a 20% drop in gas demand in 2050.

Neither a 50% lower nor a 50% higher carbon price compared with our base case significantly alters gas demand in 2050. With gas positioned between more carbon-intensive coal and zero-carbon nuclear and renewables, changes in carbon prices will bolster or hinder, depending on the competition. Similarly, cost-learning rates for wind and solar power will have limited effects on gas-fired power stations. Higher carbon prices will, however, benefit green gas.

Hydrogen fueled truck

4.4 SUMMARIZING ENERGY SUPPLY

Here, we summarize the primary supply of energy, not only from fossil fuels, but from all energy sources.

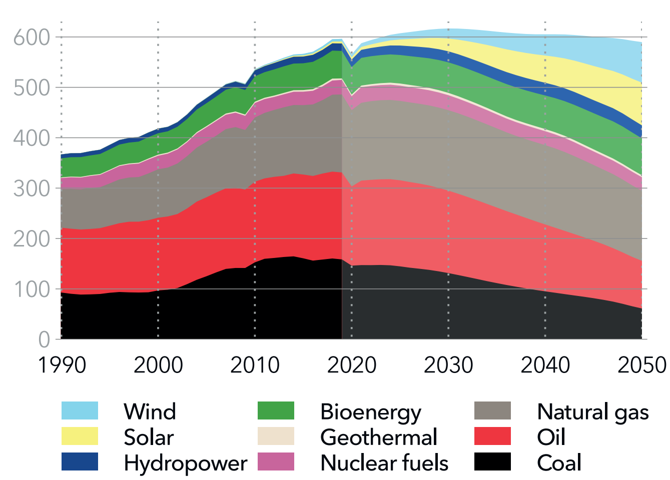
Primary-energy supply is the total amount of energy behind the provisioning of useful energy services. There are several ways in which primary energy can be measured, as we detail in the fact box on Energy Counting at the end of this chapter. In this Outlook, we use the Physical Energy Content Method.

Considerable losses occur in the global energy system. 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.

FIGURE 4.15

World primary energy supply by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

The historical and forecast world energy supplies, derived from various primary-energy sources, are shown in Figure 4.15 and Table 4.1. A key result from our analysis, as shown in the figure, is that global primary-energy supply will peak within the forecast period. This will occur despite the expansion of the global population and economy (albeit at steadily slowing rates) throughout the forecast period. Although a more populous and prosperous world will be demanding 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. This is due to the steady electrification of the world's energy system and due to cumulative advances in energy efficiency.

Although we will see a peak primary energy level in 2030, this will not necessarily last. One main reason why energy consumption will decline to 2050, is the increased energy efficiency associated with continuous energy-efficiency improvements and a steady rise in the use of renewable electricity. Once this transition is complete, further efficiency improvements must come from other sources. Towards the end of the century primary energy supply might well start to increase again.

Primary energy, which was 594 EJ before the pandemic, will return to 2019 levels in 2022, but will then only increase by a further 4% percent and peak at 617 EJ in 2030 before slowly reducing 4% to some 590 EJ in 2050.

The energy mix will change significantly over this period. As described in the introduction to this chapter, the fossil share will fall from 80% today to 50% in mid-century. Nuclear will be stable at 5% over the entire period, while renewables will triple from 15% today to 45% by the end of the forecast period.

Within renewables, the large increase will be driven by solar and wind, which will see 20-fold and 15-fold increases, respectively. The sources represent 14% each of the global primary energy mix in 2050, with further growth expected. Bioenergy and hydropower will also grow, in both relative and absolute terms.

Contributions to changes in the primary-energy supply are shown in Figure 4.16. In the forecast period, renewables will constantly be adding to the primary-energy supply, while fossil fuels will be reducing, except for natural gas that will only decrease in the 2040s. Note that we have intentionally used 2019–2025 for the first period to avoid the effect from large short-term fluctuations caused by the pandemic.

TABLE 4.1

World primary energy supply by source

Units: EJ/yr

Source	2019	2030	2040	2050
Wind	5	20	42	81
Solar	4	25	54	85
Hydropower	15	22	25	26
Bioenergy	54	61	67	73
Geothermal	3	5	4	4
Nuclear	29	30	28	27
Natural gas	155	160	157	139
Oil	173	164	133	94
Coal	158	131	95	61
Total	**596**	**617**	**605**	**590**

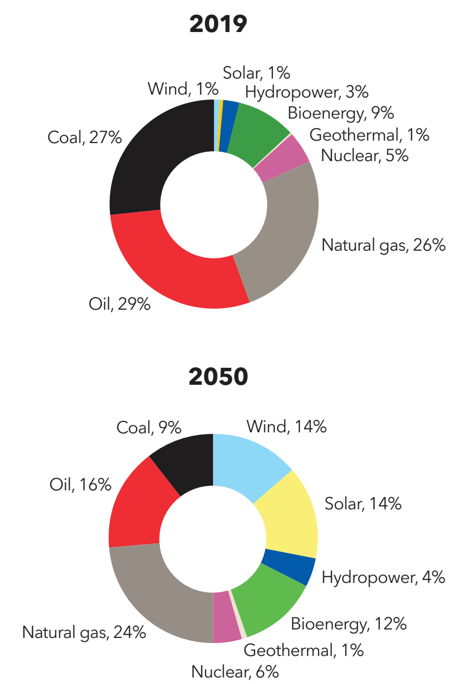
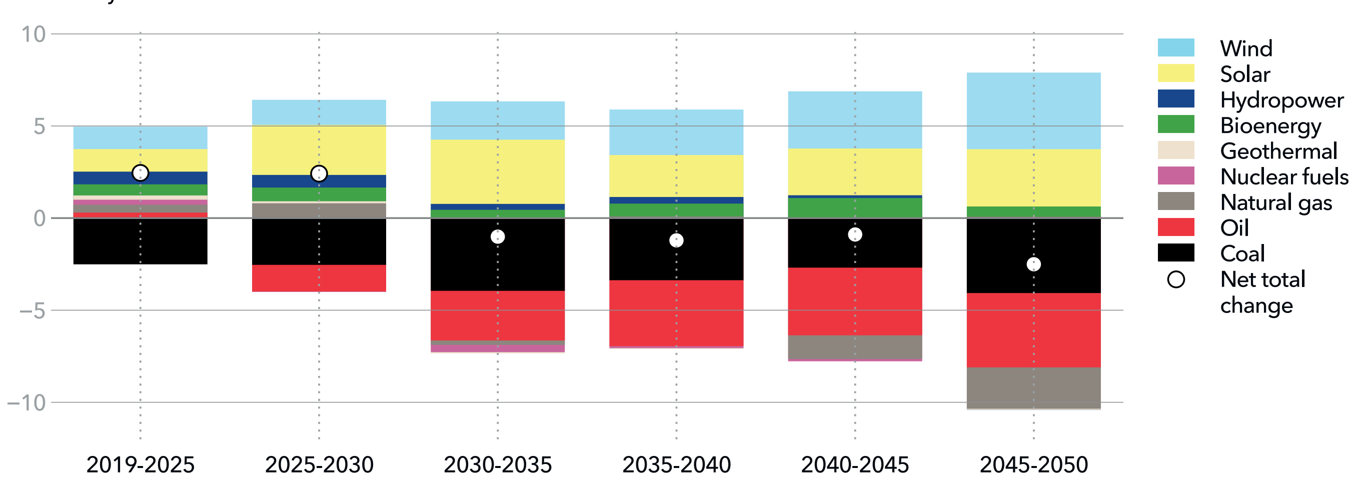


FIGURE 4.16

Net change in primary energy supply by source

Units: EJ/yr



Net change of primary energy between 5-year intervals. 2019 used to avoid effect of COVID-19. Historical data source: IEA WEB (2020)

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, differences between the methodologies also increase, and it is important to understand what we are counting.

The primary energy of combustible sources, such as fossil fuels and bioenergy, 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, e.g. solar irradiation, is neither captured nor extracted, nor is it traded. Therefore, it is assumed to be outside the boundary of the energy system.

Other analysts, however, assign a low conversion efficiency to renewables 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 methods of counting primary energy: 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 hydropower, 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, for example, by the IPCC – resembles the Physical Energy Content Method, whereas 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).

The different energy-counting methods produce quite different results, and using the one instead of the other gives a different set of conclusions.

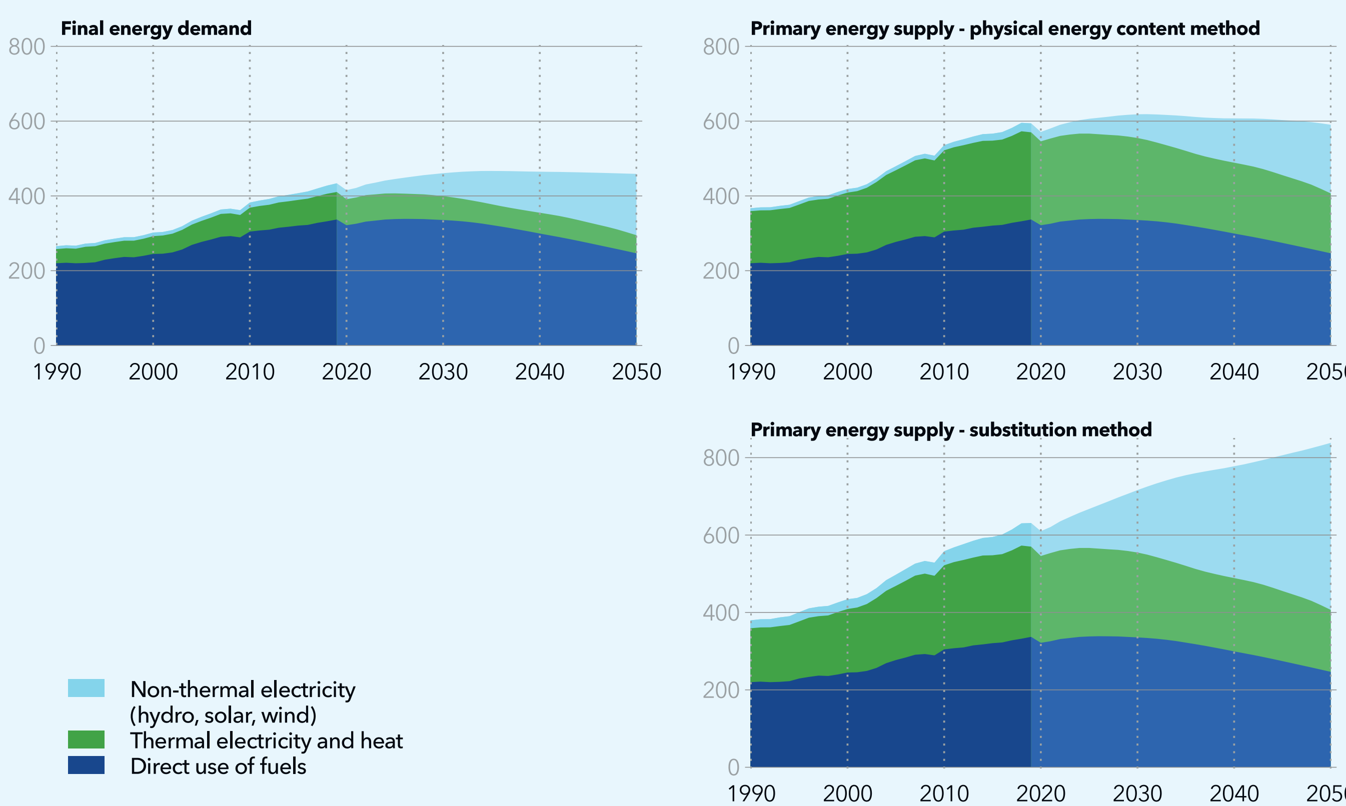
How would an alternative method affect our forecast?
The choice of energy-counting methods significantly affects energy forecasts. When the renewables share of the energy mix was low, this hardly mattered. However, as the share of renewables is now growing rapidly, and will continue to do so, the different energy-counting methods produce quite different results, and using the one instead of the other gives a different set of conclusions.

Figure 4.17 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 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.

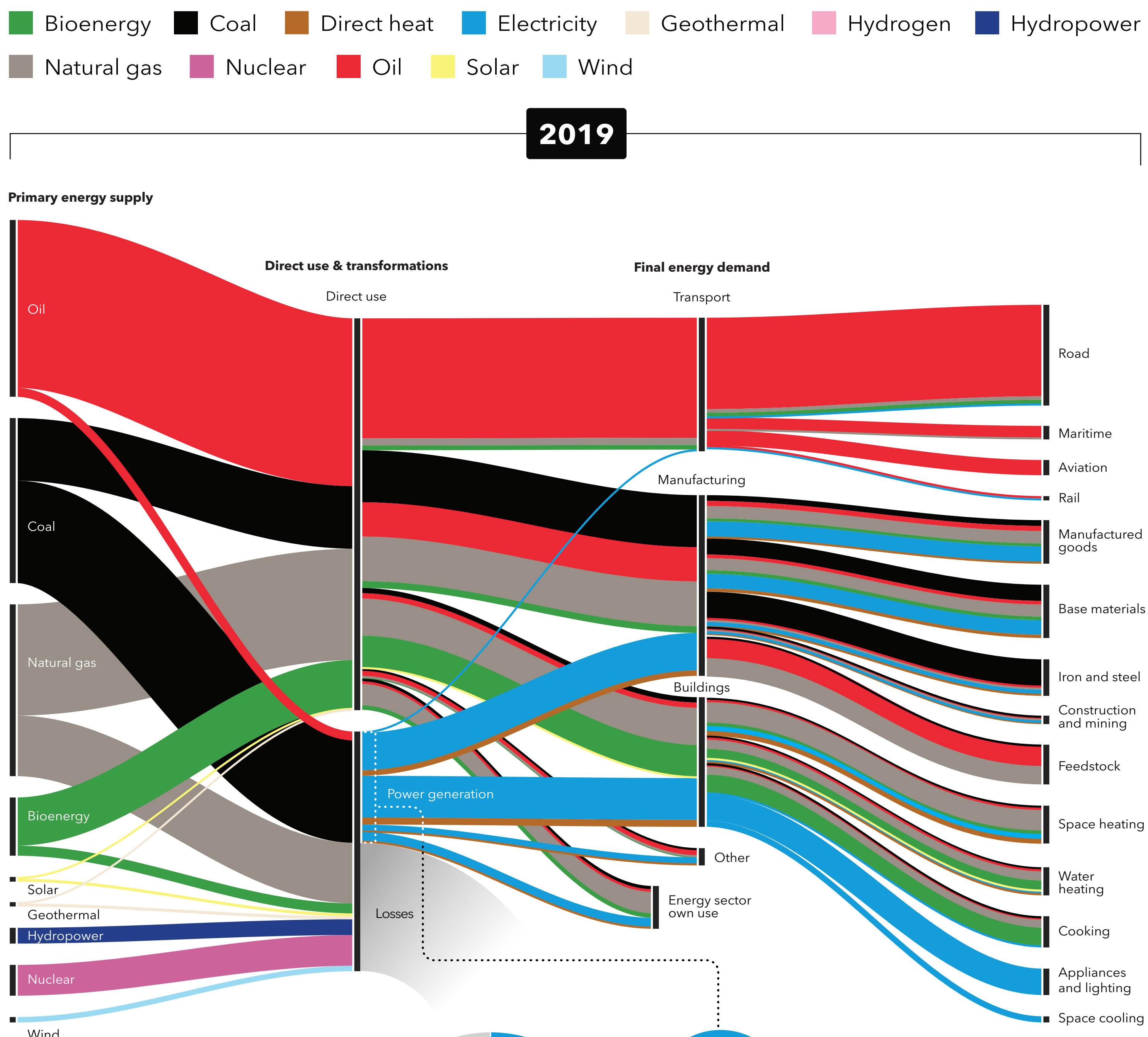
FIGURE 4.17

Primary energy supply using the two different methods of primary energy accounting

Units: EJ/yr

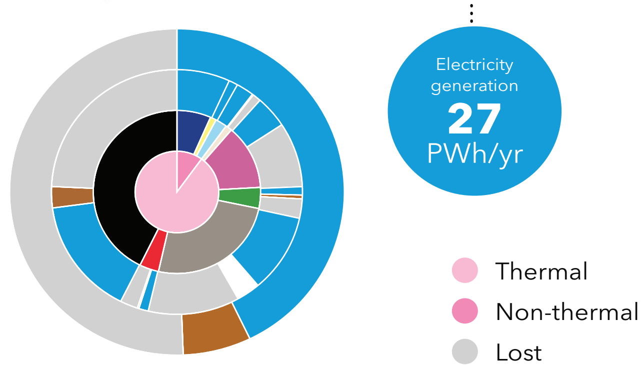


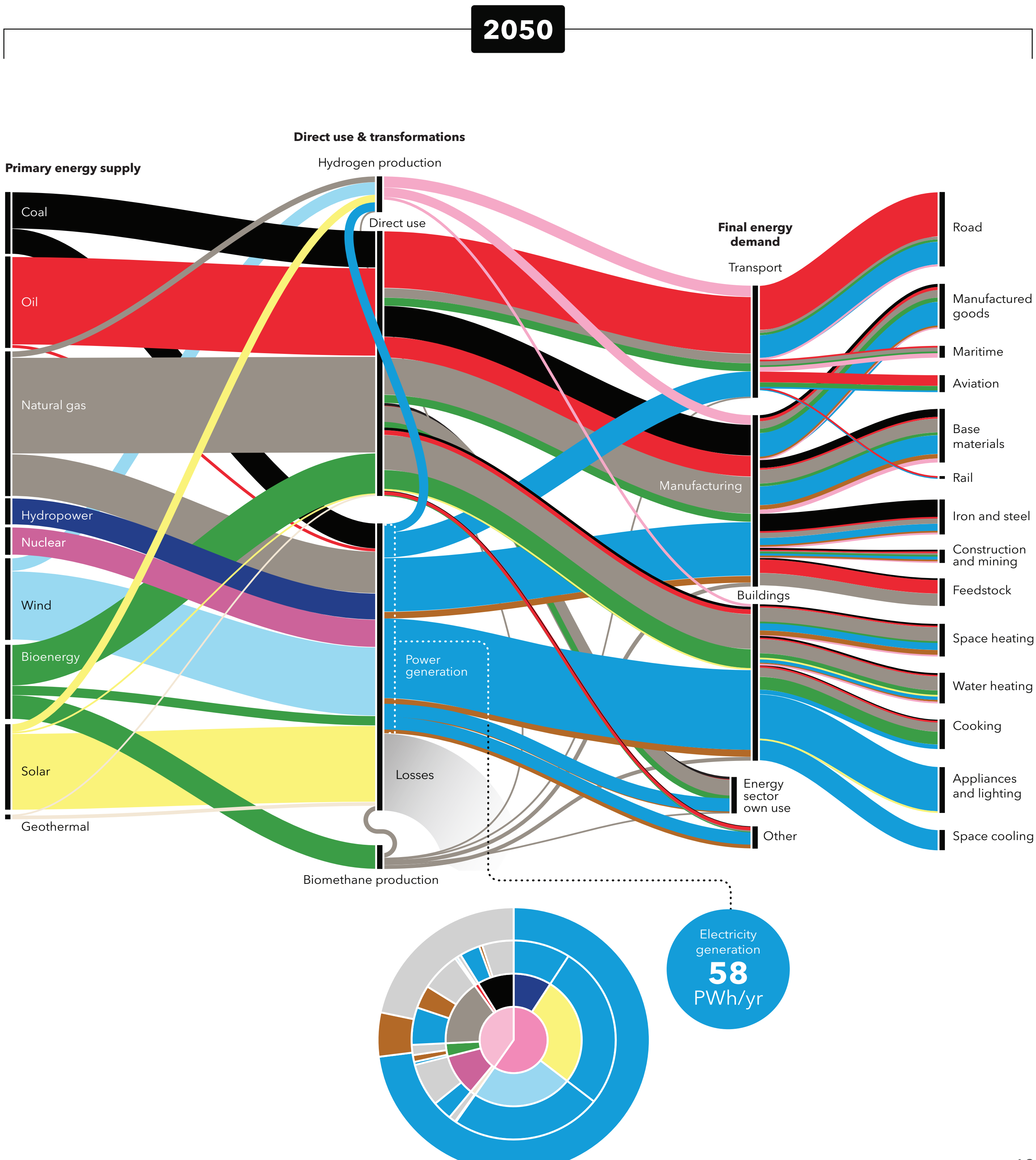
COMPARISON OF ENERGY FLOWS: 2019 AND 2050



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
Direct use & transformations
Primary energy supply
Hydrogen production
Coal
Direct use
Final energy demand
Transport
Oil
Natural gas
Hydropower
Nuclear
Wind
Bioenergy
Solar
Geothermal
Power generation
Losses
Biomethane production
Manufacturing
Buildings
Energy sector own use
Other
Road
Manufactured goods
Maritime
Aviation
Base materials
Rail
Iron and steel
Construction and mining
Feedstock
Space heating
Water heating
Cooking
Appliances and lighting
Space cooling
Electricity generation
58
PWh/yr

Highlights

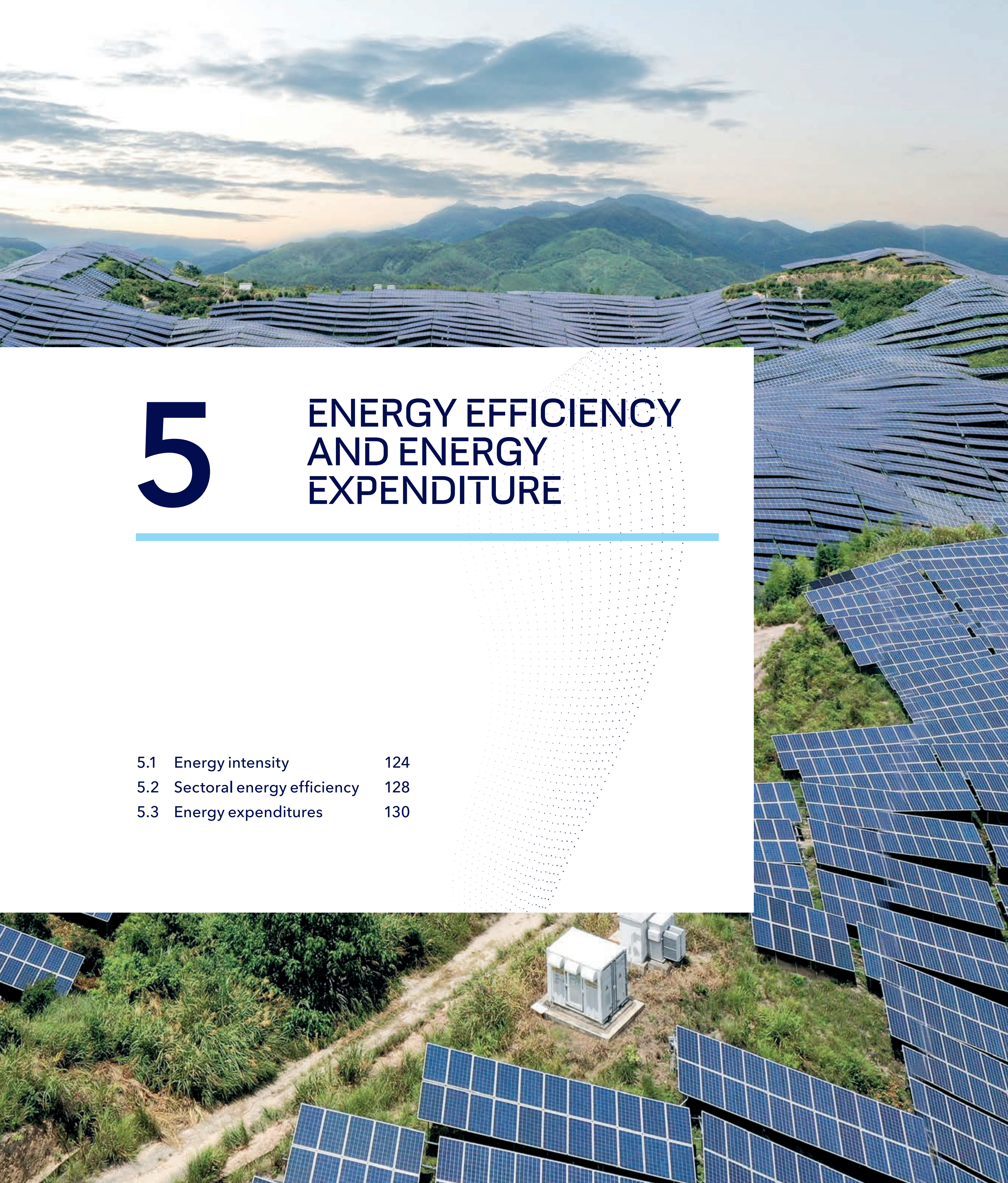
Accelerating efficiencies in the production and use of energy are key to the transition. Energy efficiency is our greatest transformational resource and should be a top priority for any entity wanting to transition faster.

Energy intensity (i.e. unit of energy per dollar of GDP) has reduced by 1.7%/yr on average for the last two decades but will reduce an average of 2.4%/yr over the next 30 years. The rate of this reduction is higher than GDP growth, with the implication that, from the early 2030s, the world's energy use will start declining.

Rapid electrification powered by renewables is the core driver of these rapid energy-intensity improvements.

We quantify expected energy efficiency gains in the main demand sectors – transport, buildings, and manufacturing – and show that without these gains, energy demand would be 65% higher than we forecast for 2050.

Affordability: Global energy expenditure will increase by only 4%, from USD 4.5trn in 2019 to USD 4.7trn 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 3.2% to 1.6%. This implies considerable surplus is available to fund faster progress towards the ambitions of the Paris Agreement.



5 ENERGY EFFICIENCY AND ENERGY EXPENDITURE

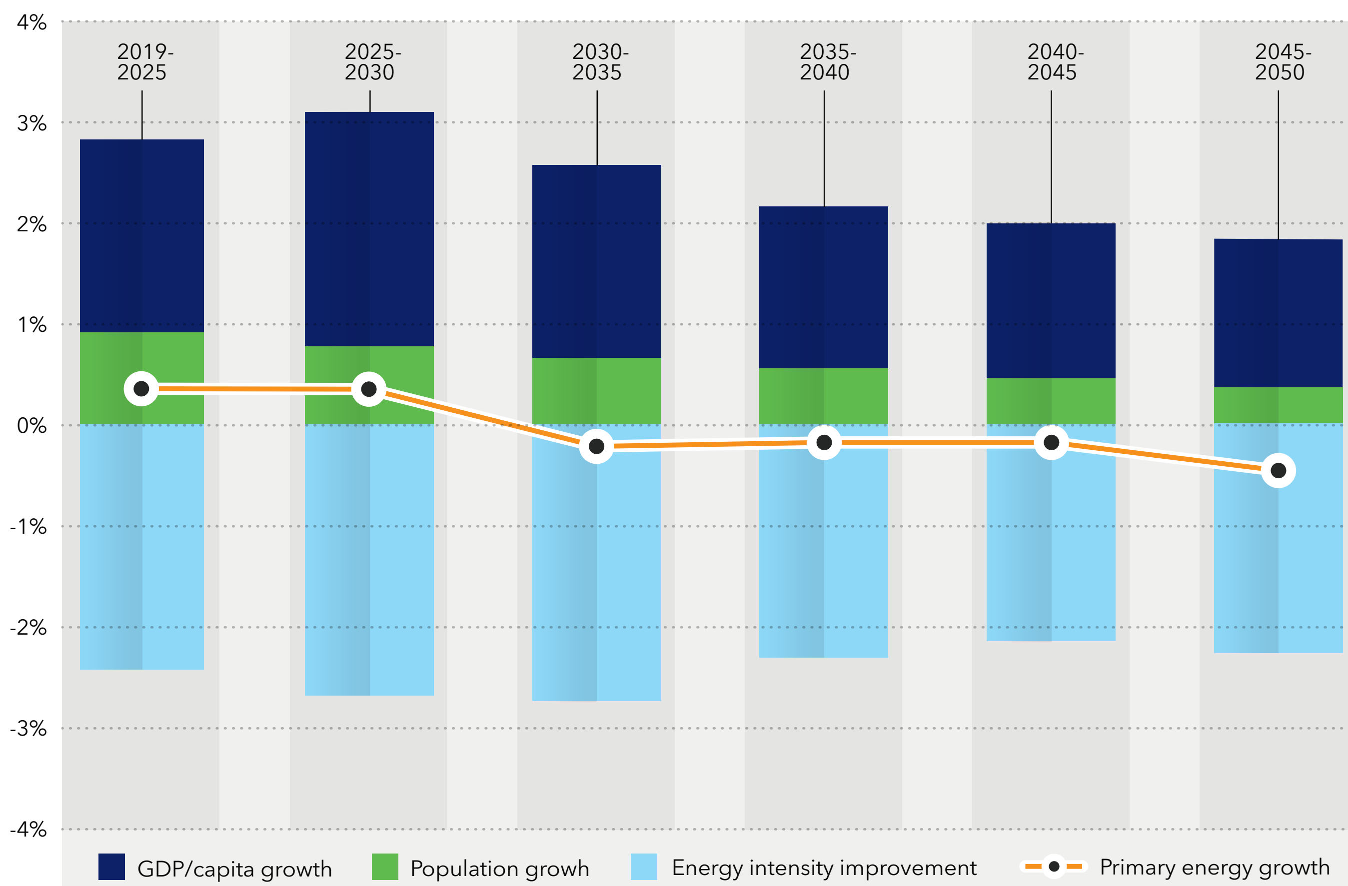
5.1 ENERGY INTENSITY

Accelerating efficiencies in both the production and use of energy will be a key feature of the transforming energy system in the coming decades. Energy efficiency is the silent – but dominant – part of the energy transition, and our greatest transformational resource. Using less energy should therefore be the top priority for individuals, companies, and governments focused on transitioning faster.

FIGURE 5.1

World energy intensity and annual reduction rate

Units: Percentages/yr



The development of energy intensity can be plotted together with the growth of population and GDP/person, as shown above 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 and primary energy supply peaks in the early 2030s.

Energy efficiency can be measured in several ways, and in the engineering sense the ratio of energy input to output is the key metric. Economist are more likely to use the term 'energy intensity', which compares energy use to the size of an economy.

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. Primary energy intensity will also, together with population and GDP/capita growth, shape how global energy use develops, as illustrated in Figure 5.1. When the multiples of the three developments fall below zero, primary energy use will start to fall, and the world will start to use less energy.

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 introduced further short-term spikes, with varying fluctuations in both energy consumption and GDP.

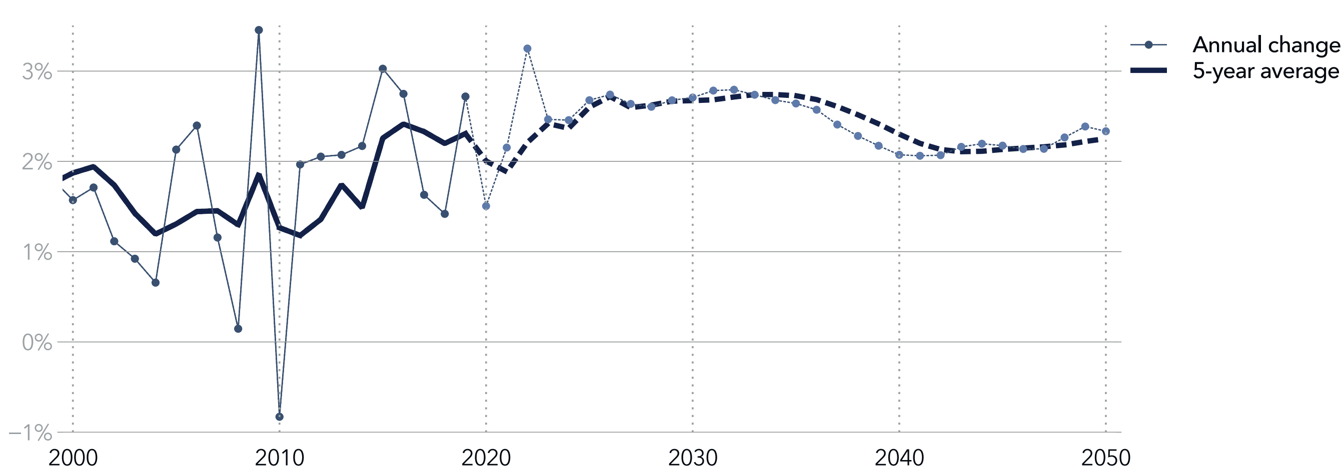
Over our forecast period, in which we foresee a doubling (111%) of global GDP and a 1% reduction in overall primary energy consumption, energy intensity will be more than halved, falling from 4.3 MJ/ USD in 2019 to 2.0 MJ/USD in 2050. Irrespective of the short-term impacts of the pandemic, energy intensity will continue to decline faster than in previous decades, dropping by 2.4%/yr on average over the next 30 years, as illustrated in Figure 5.2. In the 2040s, the intensity improvement tapers off somewhat, as, by then, most electricity will be generated by renewable sources, and the opportunity to reduce heat losses from fossil-fuelled generation reduces.

Energy intensity will continue to decline faster than in previous decades, dropping by 2.4%/yr on average.

FIGURE 5.2

Annual rate of energy intensity improvmenents

Units: Percentages/yr



National economies that are dominated by services (the tertiary sector) often manage to grow without increasing energy use. If regional changes in energy intensity are measured as the sum of national energy intensity changes, the results are often flawed, as they do not consider trade. Hence, regional decoupling of energy consumption and economic activity fails to account for actions such as manufacturing being largely outsourced from Europe and North America to Asia over the last few decades. We therefore choose not to focus on regional energy-intensity forecasts.

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 2.4%/ yr from 2015 to 2030 is higher than, but not double, the historical 1.6%/yr seen between 2000 and 2015.

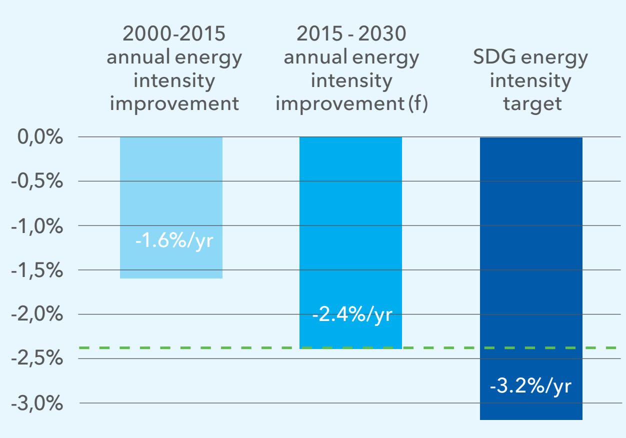
Electrification and reduced energy losses

Efficiency can be measured at each stage of the energy system, i.e. during production, energy transport, and end use. These efficiencies are described below as sectoral efficiencies.

Energy losses, resulting from conversion processes (e.g. burning coal to produce electricity) or energy transport (e.g. heat losses from power lines), essentially make energy output smaller than the input. However, it is more relevant to look at 'useful energy'. Some of the heat generated by a power plant, for example, can be used for district heating. The point is to avoid or minimize energy forms that are either unusable or not needed – e.g., heat from a light bulb. The Sankey diagram at the end of Chapter 4 illustrates energy losses to heat in the generation of electricity – they will be substantially lower in 2050 than today.

Double the global rate of improvement in energy efficiency?

The SDG #7 target to double the rate of improvement in energy efficiency for the 15 years to 2015 vs the 15 years from 2015 … will not be met.



National economies that are dominated by services (the tertiary sector) often manage to grow without increasing energy use.

The acceleration of electrification, especially renewably-generated electricity, is the main driver of energy-intensity improvements in the future. Accelerated electrification leads to accelerated efficiencies throughout an energy system. As the renewable 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. In comparison, solar PV and wind generation are 100% efficient according to our method of counting energy. A discussion on calculating primary energy can be found in Chapter 1.

That electrification itself is a main driver explains why efficiency improvements in the energy system as a whole taper off once the rate of electrification slows (in the 2040s).

5.2 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 delivered.

Such improvements are the result of activity, technological advances and structural changes:

- **Activity changes:** More people, more buildings to heat and cool, and longer distances travelled all increase the total amount of activities. Some changes in other factors also reduce activity levels and/or contribute to slower rates of activity increase.
- **Technology efficiency improvements:** in the various energy-demand sectors, several technology efficiency improvements continuously drive down energy use per service delivered. Examples include more-effective engines or improved hull hydrodynamics and vehicle aerodynamics.
- **Structural shifts** take three principal forms:
  - Technology shifts: Occasionally, services are better delivered by replacing one technology with another. Examples are replacement of a combustion engine with an electric motor or abandoning traditional solid biomass for cooking in favour of gas or electric stoves. 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.
  - Service shifts: Sometimes, there are structural changes in the service delivered, such as bigger cars. These shifts can be connected with rebound effects; e.g., setting a higher temperature threshold in your house because heating is cheaper or more effective. These shifts may counter technology-led improvements and lead to higher energy use; in other cases, they might reduce energy use.
  - Regional shifts: 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.

In our overview (overleaf), structural shifts are grouped, as it is often impossible to separate one effect from another.

Standards and policies

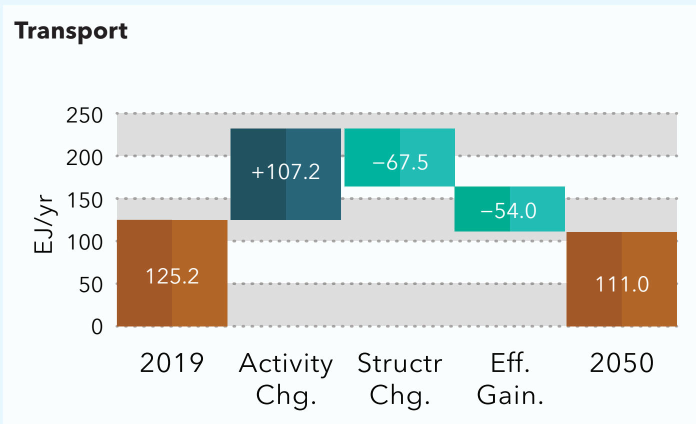
Efficiency improvements reduce energy use and/or costs. The 'cheaper and/or better' mantra has always been the main driver for technology innovation. But sometimes policy interventions, in the form of efficiency and performance standards (e.g., technical retrofits, building codes, fuel-efficiency standards) play an important role, as discussed in Chapter 6. We note that in countries with mandatory efficiency policies, growth in energy use or emissions is subdued. Policy frameworks help to direct investment towards energy-efficiency initiatives that otherwise tend to be overlooked by investors. There are several reasons why such initiatives are neglected, including the difficulty of calculating direct returns and the possibility that benefits accrue to parties other than the investor.

The present technology and policy momentum are leading to growth in efficiency improvements across all sectors. 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 for the main demand sectors in Figure 5.3.

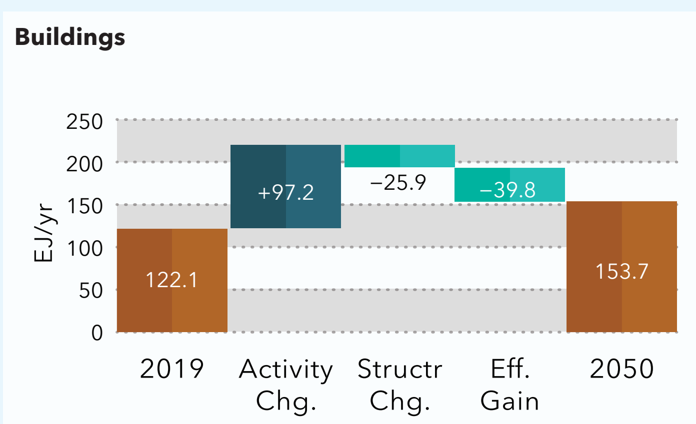
The potential to improve efficiency yet further is huge and sorely needed to achieve a faster energy transition that is closer to the Paris Agreement. This will be dealt with in more detail in the forthcoming *Pathway to net zero emissions* report (DNV, 2021d).

FIGURE 5.3

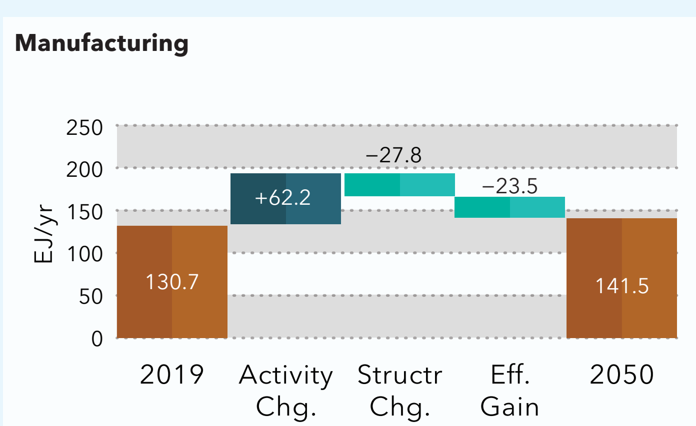
Sectoral energy efficiencies in transport, buildings and manufacturing



Transport is dominated by road transport, with vehicle kilometres almost doubling over the next thirty years (shown as **activity change**), but aviation also grows 150% and maritime transport 33%. In 2050, EVs account for 70% of all passenger km and 40% of the cargo km, and this **structural change** drives energy use down dramatically. **Efficiency** improvements in remaining combustion engines, aerodynamics in aviation, and vessel utilization also contribute to the overall 11% energy reduction.



Activity-wise, total buildings floor area grows 60% in the forecast period, but the increase in energy services in buildings varies considerably, from cooling which grows almost seven-fold to heating which grows by a quarter. More modern heating technologies (e.g. heat pumps), and water heating and cooking upgrades (e.g. traditional biomass to gas or electricity) in various regions contribute to the **structural** improvements, while **efficiency** gains are largest in cooling and lighting. However, overall building sector energy use still grows 26% over the forecast period.



Over the forecast period, the **activity** change for manufacturing includes a 70% increase in base materials, construction and mining, and a 60% rise manufactured goods (measured in $ output), and a 17% reduction for steel and iron (in tonnes of steel produced). **Structural changes**, in e.g. regional shifts, give a reduction in energy use, while **efficiencies** in all the manufacturing processes also contribute to a total energy use growth of only 8% for the manufacturing sector over the coming three decades.

5.3 ENERGY EXPENDITURES

The energy transition we are forecasting is not only affordable but leads to considerable savings at a global level. Some aspects of the transition, like the roll-out of renewables or storage and grid buildouts, will require very large upfront investment; this is why some consider the transition to be 'unaffordable'. Our results suggest the exact opposite. Whilst global GDP will more than double by 2050, global energy expenditures will almost plateau. This is thanks to the improvements in energy efficiency and in renewable energy technologies.

As shown in Figure 5.4, world energy expenditures will shift from fossil to non-fossil sources, and the annual sum expended will increase by 4%, from USD 4.5trn in 2019 to USD 4.7trn in 2050.

Expenditure definition

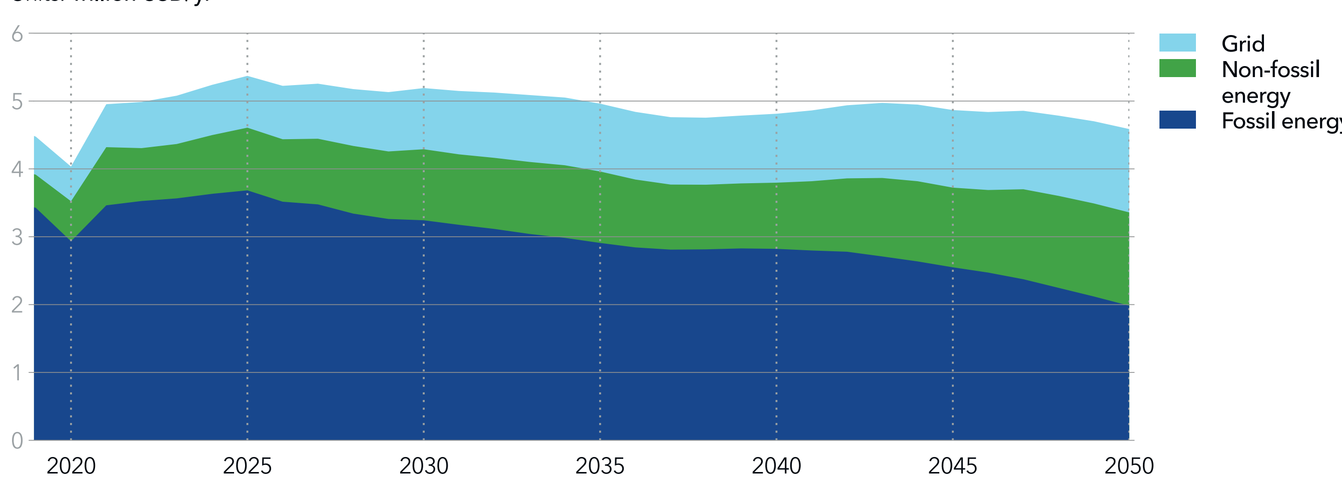
Contrary to other modelling frameworks, such as the IEA's TIMES and the EU's PRIMES, our approach does not ensure the global optimality of solutions. However, in many sectors – such as power production, upstream oil and gas, and energy use in manufacturing – we use a merit-order, cost-based algorithm.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

There are various definitions of 'energy expenditure', and we have chosen to use a strict definition. We have therefore included only fossil-fuel extraction, transport, and refinement such as liquefaction, regasification, refineries, and conversion to hydrogen and electricity. Similarly, all costs in the power sector are incorporated (including power grids and the installation and operation of renewable energy plants). However, we have excluded investments in energy-efficiency measures, as well as in downstream carbon-mitigation costs. Nor do we incorporate costs related to end-use spending (in manufacturing, transport and so on.)

FIGURE 5.4

World energy expenditures by source

Units: Trillion USD/yr



What actually constitutes a subsidy deserves a chapter in its own right, and we have decided to adopt a simplified approach. The modelled subsidies that we report in this Outlook are seen as support that benefit consumers and are not counted as energy expenditures. Likewise, fuel taxes are not included.

Although the simulated decision making in our model discounts 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 5.4 that global energy expenditure will increase by 4%, from USD 4.5trn in 2019 to a little less than USD 4.7trn in 2050. The fossil-energy share will decline by more than a third of today's 76%, dropping to 42% by mid-century.

OPEX and CAPEX

Upstream oil and gas expenditures will decline by 46% through to 2050. Figure 5.5 shows that it is composed of different dynamics. Oil investments will drop while gas investment will remain constant before slightly decreasing in the 2040s. On the other hand, given the long lifetimes of installed capacity, OPEX will, remain quite high, only decreasing by 35% for oil and remaining flat for gas.

Fossil fuel-fired power investments will decline spectacularly by 96% over this same period, to a mere USD 5bn. Operating and maintenance of fossil power stations (excluding fuel) will remain at around USD 350bn due to the inertia of long-lifespan installations.

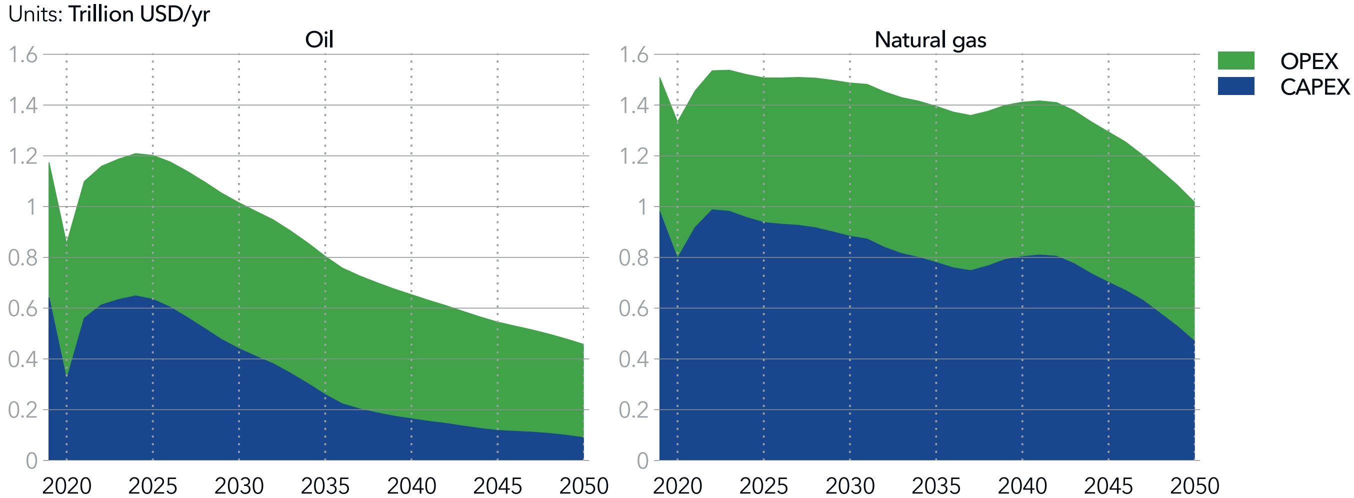
The progressive decline of fossil fuel-related investment contrasts sharply with higher expenditures in low-carbon power generation (Figure 5.6). The increase in electricity demand will lead to an almost doubling of non-fossil power expenditures by 2050. The rise is particularly visible for solar PV and wind power. Together, they will represent a fifth of global energy expenditures in 2050, an almost four-fold increase compared with 2019.

> The energy transition is not only affordable but leads to considerable savings at a global level.

FIGURE 5.5

Oil and gas upstream expenditures

Units: Trillion USD/yr



The overall picture for power generation is that costs shift from OPEX, dominated by the cost of fuel, to CAPEX in renewable power installations. Figure 5.6 shows the rapid rate of growth in non-fossil capital investments compared with the steadier and lower rate of growth in OPEX.

The doubling of electricity production and decentralization of power generation, coupled with a large amount of new VRES capacity, necessarily leads to strong investment in grids. Grid expenditures will consequently represent about one third of energy expenditures in 2050, versus 13% today.

FIGURE 5.6

World non-fossil power expenditures

Units: Trillion USD/yr

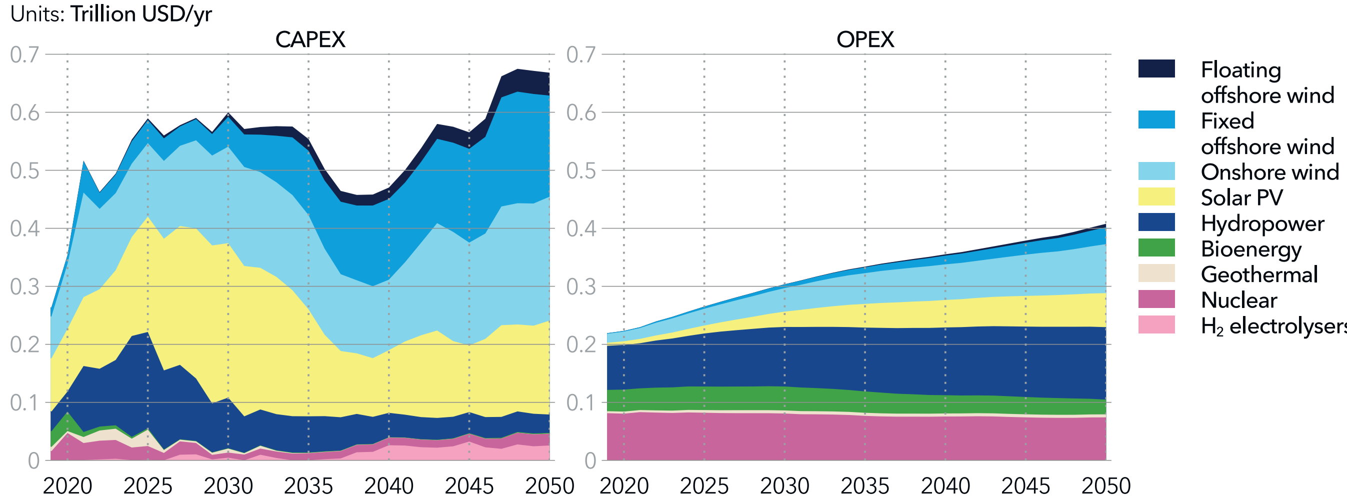


FIGURE 5.7

Total power grid costs by region

Units: Trillion USD/yr

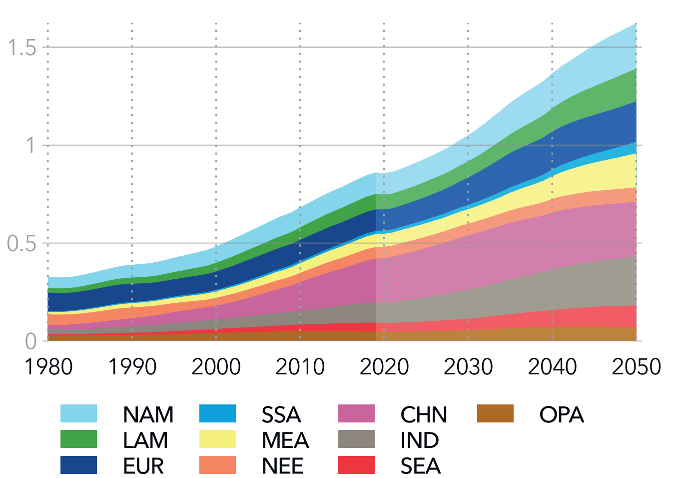
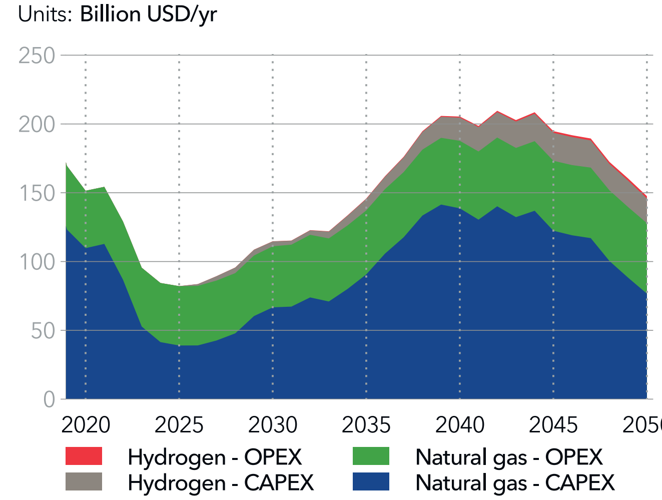


FIGURE 5.8

World pipeline expenditures

Units: Billion USD/yr



Hydrogen blended with natural gas is included under natural gas pipeline expenditures.

Globally, grid OPEX will almost double (+94%) from today's level to reach USD 748bn in 2050, while grid CAPEX rises 112% to USD 515bn.

Figure 5.7 shows regional grid costs. Greater China will account for 21% of accumulated grid-related expenses to 2050. The rest will be distributed among Europe (15%), North America (14%), the Indian Subcontinent (13%), and other regions (37%).

Low-voltage and medium-voltage grids will be the largest expenditure category in 2050, accounting for almost three quarters of the grid funding. Considering grid costs differently (by AC or DC), we see a tremendous surge in the share of DC expenditure, rising from 2% now to 20% by mid-century.

Underground and underwater installations will grow twice as fast as overhead lines.

Natural gas demand will remain high, and hydrogen demand will grow, and consequently investments in pipelines will continue, as shown in Figure 5.8. The larger part of pipeline expenditures will be devoted to natural gas networks, with a yearly CAPEX fluctuating between USD 50bn and USD 140bn in the period. Around 38% of investments in this period will be devoted to addition of new capacity. OPEX will remain constant over the period at around half the size of the CAPEX.

Four regions will represent two thirds of the investments for gas pipelines: the Indian Subcontinent (20%), North East Eurasia (17%), Europe (16%), and Latin America (15%).

On a more modest scale, dedicated hydrogen pipelines will progressively be installed, reaching an accumulated USD 300bn investment by 2050.

The share of GDP devoted to energy expenditure will halve, dropping from its current level of 3.2% to 1.6% by mid-century.

A declining share of GDP

Despite massive investments in high capital-cost renewables and electricity networks, the share of global GDP allocated to energy expenditures will decline steadily. Figure 5.9 shows that the share of GDP devoted to energy expenditure will halve, dropping from its current level of 3.2% to 1.6% by mid-century. This is a significant finding from our forecast; by mid-century, energy will be both relatively cheaper (in terms of % GDP) and absolutely more affordable, given that the energy system itself will be substantially more efficient.

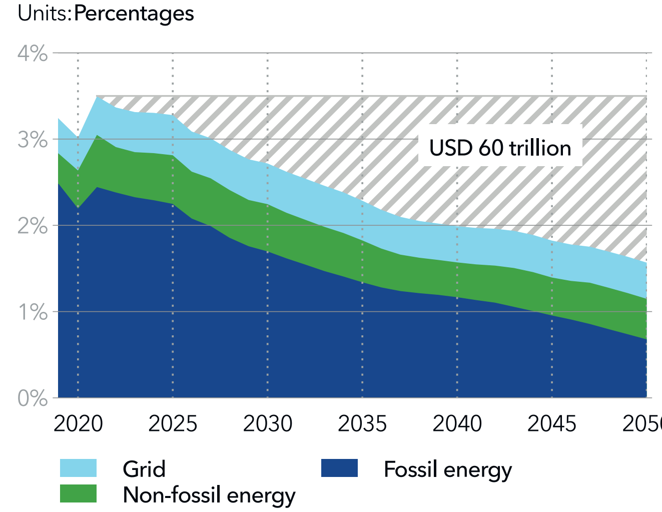
This leads to a thought experiment: If the world decided that the current ratio of energy expenditure to GDP were to stay constant, then a climate change war chest would be created that would grow, on average, USD 2trn each year, reaching close to USD 63trn by 2050. Although impressive, USD 63trn represents less than 0.9% of cumulative global GDP to 2050.

The question is whether a war chest of this magnitude would cover the costs of a faster transition – one that is compliant with the Paris Agreement. Our short answer is, yes it could. We will explore this line of thought in greater detail in our forthcoming *Pathway to net zero emissions* report (DNV, 2021d).

FIGURE 5.9

World energy expenditures as a fraction of GDP

Units: Percentages



Highlights

In this chapter we explore the role of policy in the energy transition and describe **12 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 need to protect planetary boundary conditions, not least biodiversity.

We discuss a series of **drivers** of, and **barriers** to, the energy transition. These create uncertainty over the speed of transition. However, mission-oriented policy, along with rapid developments in technology and costs, suggests that change will hold sway over continuity. **Policymaker dilemmas** are discussed by extending the well-known energy trilemma with energy transition trade-offs.

We outline our view on a policymaker's 'toolbox' to activate the advancement of low-carbon energy. This is followed by **highlights on key policy developments** from our forecast regions since last year's ETO.

We address specific energy system challenges including **penetration of renewables in power systems, hard-to-abate sectors and sector coupling**, and illustrate the **policy response** and activation of the policy toolbox through real-world cases.

6 POLICY AND THE ENERGY TRANSITION

6.1 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.

This is a mission-orientated energy transition in the sense that it aims to address planetary, economic, and human development risks. DNV anticipates an intensification of policy efforts to shape markets in the direction of energy system change. We also expect that opportunities in low-carbon sectors and technologies advancing decarbonization will hold primacy.

Signs that the energy transition is picking up speed are abundant. Economist Rudiger Dornbusch is known for the statement: "In economics, things take longer to happen than you think they will, and then they happen faster than you thought they could."

A multitude of converging factors signals acceleration. The competitiveness of cleaner technologies builds confidence among policy makers to act. A surge in capital allocations towards sustainability-aligned energy activities and investors is pushing governments into a global race-to-the-top on climate policy (The Investor Agenda, 2021). Financial regulators are sharpening their focus on climate-related financial risks and compelling policymakers to create an enabling environment that accelerates the transition. Climate risk awareness is growing and governments find themselves under pressure to act.

Many converging factors signal an acceleration of the energy transition.

During COVID-19, governments have shown the important role of the state in the economy, but fiscal recovery stimulus has not converged exclusively with decarbonization efforts and other sustainability objectives. Decisive interventions are very much needed to prevent existential threats posed by climate change. Given the insufficient progress so far on global objectives, DNV expects a deepening of orchestrated regulatory approaches to propel energy-system evolution. Figure 6.1 presents a snapshot of the policy factors in the analysis.

Key issues for all governments will be increased ambition levels, and policy frameworks that ensure timely implementation of emission reductions in alignment with the Paris Agreement and other goals. DNV also notes that three key topics are gaining prominence in governmental transition agendas since last year's ETO.

1. A new reality for hydrocarbon producers

The picture of profound geopolitical consequences of the energy transition (as described, for example, by GCGET, 2019, and CSIS & Bloomberg, 2021), became ever clearer after IEA launched its net zero report (IEA, 2021). The IEA pathway finds that there is no need for investment in new fossil-fuel supply if the world is to reach a 1.5-degree future. The report has sent shockwaves to petrostates on the likely erosion of value in their oil and gas reserves.

Disentangling public budgets from fossil-fuel revenue is a key challenge. Will the message trigger a race to the bottom of wells, with countries fast-tracking production to export commodities before value dwindles in an oversupplied, shrinking market? Or, will there be cooperation for an international supply-side agreement to facilitate an orderly phasing-down in alignment with Paris goals? The likely path is unclear, but the issue can be expected to come to the fore in international negotiations and supply-side policies. Even if robust measures aligned with the Paris Agreement are not put in place, the issue will increase the visibility of unserious pledges and government greenwash.

2. Uncertain global trade relations
China, the EU, and the US are now more aligned on decarbonization ambitions. As major economic blocs and trade areas, they are likely to pull other regions along on decarbonization, or else will inhibit market access through carbon-border adjustment mechanisms. Prohibitive trade measures, and disputes that have long played out in wind and solar, are climbing the agenda amid surging investment in clean energy, together with awareness of risks in international supply chains.

The era of recalculating industrial strategies is here. It is focusing on energy-transition value accrual in terms of domestic economic benefits, manufacturing capability, and green jobs, and with import restrictions lurking.

Connectivity helps the spread of technologies and can also unlock synergies as the energy landscape is transforming. Global supply chains helped reduce the cost of renewable energy and related technologies, and the cost of the transition will clearly be lower for all if supply chains remain global. Establishing predictable trade rules will be critical to level the playing field for global exchange and investments, but with emissions reduction uppermost in minds.

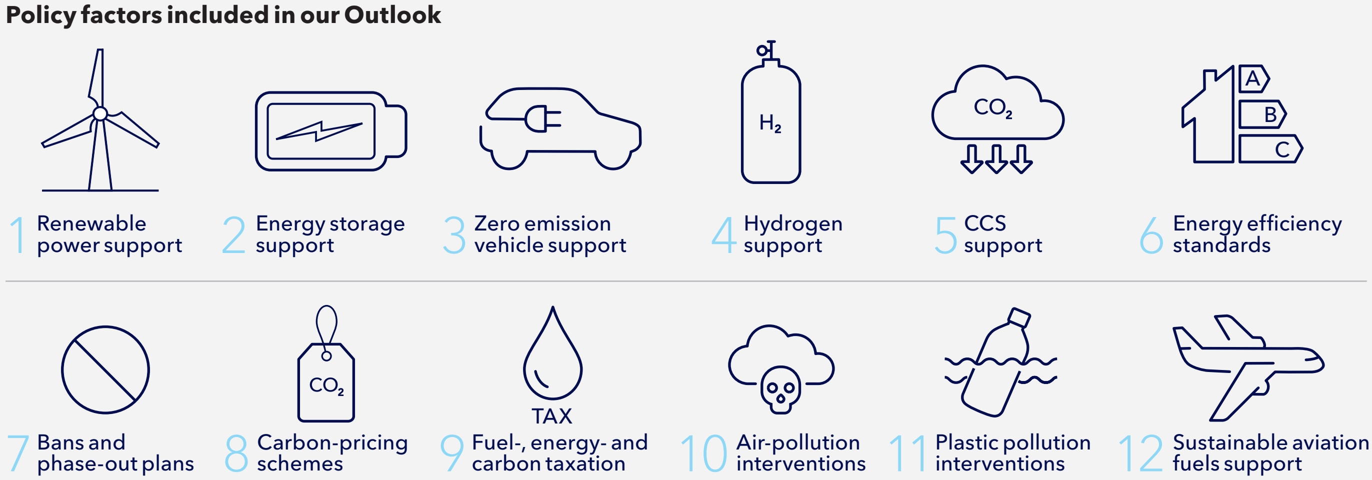
3. Legal risk and government accountability
The potency of courts and boardrooms in holding companies and governments accountable is giving teeth to the Paris Agreement and sending a strong signal to governments to get serious. In April (2021), Germany's highest court found the country's climate law unconstitutional because it inadequately regulates greenhouse gas emissions (GHG) reductions from 2030 onwards and places too great a burden on future generations. The government reacted by increasing its 2030 emissions targets to 65% below 1990 levels, up from 55%.

In May (2021), a Dutch court found that Shell is required to reduce its total emissions – including those from its operations and from the use of the products it sells – by 45% of 2019 levels by the year 2030, to decarbonize in line with the 1.5°C warming objective. In the same month, two ExxonMobil board members lost their seats as shareholders voted for candidates they deemed better suited to fight climate change and guide the company's energy transition.

The digital transformation supports transparency and traceability on GHG emissions in real time, and will push government accountability in the future. This is seen in initiatives such as the EU's Earth Observation programme, which includes using Copernicus environmental monitoring satellites (ESA, 2021), and the Climate TRACE coalition (TIME, 2020). On the flipside, enhanced oversight will enable effective interventions and more targeted policy and boardroom decisions.

FIGURE 6.1

Policy factors included in our Outlook



6.2 GLOBAL AGREEMENTS FRAMING THE TRANSITION

The Paris Agreement

The Intergovernmental Panel on Climate Change (IPCC) – the UN body dedicated to provide objective scientific information on human-induced climate change, impact risk, and response options – provided the scientific input into the Paris Agreement. The IPCC will complete its Sixth Assessment Report (AR6) in 2022. At the signing of the Agreement in 2015, the sum of what the individual countries promised to do in their pledges (Nationally Determined Contributions, NDCs) was far from sufficient to meet the specified target of "holding the increase in the global average temperature to well-below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C".

The Agreement established an ongoing, regular process to increase action by all countries – labelled the "ratchet" or "ambition mechanism". Updated NDCs are to be submitted every five years to ensure that commitments increase over time. However, the process was delayed with the postponement of COP26 from 2020 to 2021 as COVID-19 dominated attention. Many nations with mid-century net zero pledges have NDCs that do not match up in ambition. As of July 5, 2021, 60 countries had submitted new NDC targets (59 countries plus EU27), out of which only 14 jurisdictions submitted stronger targets, including the EU and US (CAT, 2021).

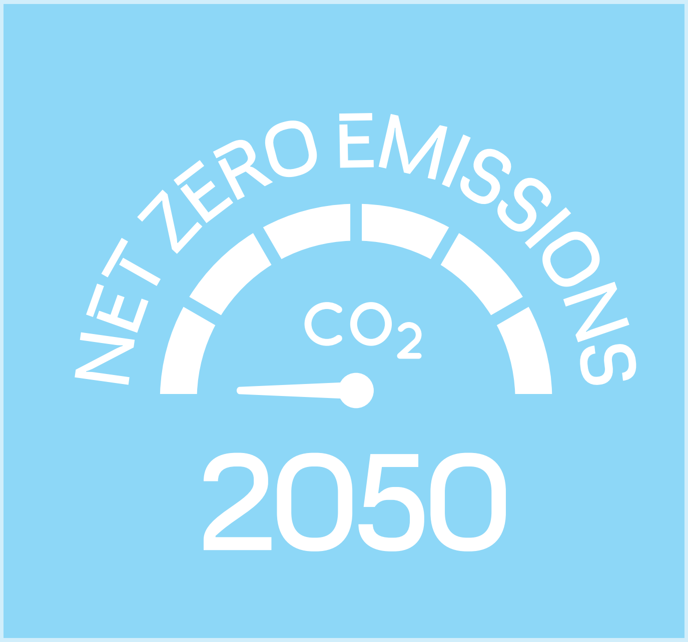
In this forecast, we have given weight to the NDCs since they represent the stated intentions – conditional and unconditional commitments (the latter without outside support) – of sovereign nations. As such, NDC ambitions guide the policy factors incorporated in the analysis, but without assuming that all countries will deliver exactly on their pledges – some will exceed them, others will fall short. How the regions perform in delivering aggregate pledges is discussed in Chapter 7 on regional transitions.

Convention on Biological Diversity

The Parties to the Convention on Biological Diversity (CBD, 2021) are expected to agree on the post-2020 global biodiversity framework in Kunming, China in October (2021). The Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) provides the scientific basis for this Convention. The Taskforce on Nature-related Financial Disclosures (TNFD) will be the framework for organizations to report and act on nature-related risks, aiming to make corporates and financial institutions focus on the financial risks posed by ecological degradation. It is similar and complementary to the framework developed by the Task Force on Climate-related Financial Disclosures (TCFD). The promotion of nature-based solutions will not lessen the momentum for higher reductions in GHG emissions. Climate action, preserving biodiversity, and the energy transition are intertwined, and will thus need tackling in a coordinated way. Examples include zoning of renewables, and decisions over the expansion of forestry or land use for bioenergy production. Some climate measures have negative consequences for other environmental issues, and this can limit e.g., the use of bioenergy with CCS (BECCS).

The UN Sustainable Development Goals (SDGs)

The 17 SDGs for 2030 represent the UN's all-encompassing global development agenda. The world was not on track before the pandemic to achieve these goals; and, COVID-19 has disrupted efforts across the SDGs, in some cases, such as in poverty reduction, also undoing progress to date (UN DESA, 2020). This Outlook does not specifically address the SDGs. However, interactions between objectives – especially SDG #3 (health), SDG #7 (affordable/clean energy), SDG #13 (climate action), SDG #14 and SDG #15 (biodiversity in aquatic and terrestrial environments) – highlight a delicate planning act on energy activities and policy choices. While SDG interactions are location-specific, reducing energy demand and boosting energy efficiency have the fewest trade-offs everywhere. Transition strategies will have to holistically assess lifecycle- and SDG-related impacts. Integrated policy approaches will grow in importance – such as seen in the EU's Green Deal and EU action plans linking pollution, biodiversity, and circular resource use with decarbonization efforts.



To achieve the 1.5˚C goal, several major economies need to go beyond net zero, and faster.

Net zero pledges

UN Secretary-General António Guterres stated in late 2020 that building a global coalition for carbon neutrality is a top UN priority in 2021. Emissions need to be halved by 2030 and reach net zero by 2050 to achieve the 1.5˚C goal. The world is not currently on track to deliver a net zero future.

An abundance of 2050 net zero pledges have moved centre stage, topping the news agenda. Net zero is now a defining lens through which governments and business alike view decarbonization. According to the online platform Climate Watch (climatewatchdata.org), 59 countries have communicated a net zero target: five with a law-based target, 26 in a policy document, and 17 with a pledge. Collectively, these targets cover 54% of global GHG emissions.

Another recent stocktake from the European Consortium of Innovative Universities (ECIU) and Oxford Net Zero (Black et al., 2021) surveying over 4,000 significant entities (nations, states, cities, and companies in the Forbes Global 2000 list) indicates 769 entities, responsible for 61% of global emissions and 68% of global GDP, to be under a net zero pledge.

The world's two largest emitters, China and the US, have communicated net zero emission targets. The closer alignment between Europe, North America, and East Asia (China, Japan, South Korea) on emission reductions lays the ground for renewed global momentum and transition acceleration.

The recent rash of carbon-neutrality pledges signals a shifting into gear to respond to climate change. However, implementation plans and policies on 'how to deliver' are largely missing, as are actions towards 2030. Hazy definitions, and different sector inclusions and baselines make comparison difficult. DNV has argued elsewhere that it is given that some countries and sectors have much better opportunities for reducing emissions than others, both from economic and technical perspectives. Consequently, to achieve the 1.5˚C goal, several major economies need to go beyond net zero, and faster (Forbes, 2021).

DNV supports urgent fast-tracking of meaningful action, including interim targets, a clear timeline, and regular progress reporting so that pledges are not mirages. There is no time for empty words and just appearing to act on distant targets. A net zero future requires massive deployment of technical solutions at scale (cf. DNV Technology Progress Report, 2021a). To support decision makers in planning their pathways and getting set for implementation, we will release our *Pathway to net zero emissions* report (DNV, 2021d) to provide guidance in terms of sector pathways, technologies, and targeted policies.

6.3 DRIVERS AND BARRIERS

The energy transition is unlikely to follow a straight path. Momentous opposing forces influence and create uncertainty about the speed of change, some of which are summarized in the table below. Overall, however, the convergence between the challenge-oriented nature of the transition and the economic inflection points for key technologies suggest to us that the direction of travel is unstoppable, and that barriers will be bypassed.

DRIVERS	BARRIERS
1. A planet pushed beyond its limits Overwhelming scientific evidence paints an alarming picture of global warming, air pollution, degradation of ecosystems, and the potential for pandemics. These problems are closely interconnected manifestations of a planetary crisis. Ongoing crises, with climate and biodiversity threats pulling the global agenda in the same direction, add urgency to change.	**The invisible value of nature** Nature and its services are not appropriately valued in monetary terms. WEF (2020b) estimates USD 44trn of world GDP is dependent on nature. Nature protection compromises fail to reflect the economic impact of ecosystem degradation. Nature rights and associated financial risks are missing, albeit receiving renewed focus from initiatives such as Terra Carta (2021) and the Taskforce on Nature-related Financial Disclosures (TNFD, 2021).
2. Net zero pledges go global A number of countries and businesses are adopting net zero pledges ahead of COP26, muting discussions on the reality of climate change. According to the ECIU/Oxford stocktake, net zero targets encompass 61% of global emissions, 68% of GDP, and 56% of the population. Despite varying definitions, the race to net zero adds momentum to the energy transition, and increases pressure on relevant actors to develop concrete roadmaps to achieve interim and net zero goals.	**Policy weaknesses** Despite long-term targets, voter priorities and political cycles are short term. Lack of long-term political responsibility weakens the incentive for concrete and timely implementation – with vision and mission valued more than progress. Clean-energy technologies are becoming less dependent on government support; but, across all sectors, scaling up relies on conducive public policy. Lengthy authorization processes for renewable generation and infrastructure buildout are also a hindrance.
3. Diverging costs of energy carriers The cost curves of extractive hydrocarbons and renewables/clean technologies are diverging. While wind and solar PV are becoming the most cost-competitive options against both new and existing fossil generation in most markets, 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.	**Increased upfront costs** Transitioning energy systems away from hydrocarbons entails substantial costs to be borne during the transition. The scope for decarbonization in many countries is being weakened by high capital expenditure costs for renewables; spending on electric grids; sunk costs in fossil-fuel infrastructure, and the undesirability of early retirements. There is also pressure from incumbent industries to maintain the status quo.
4. Technology solutions exist Deep cross-sectoral decarbonization is dependent on a plethora of technologies, and solutions already exist. Direct electrification of some transport, industry, and heating for buildings is possible. For hard-to-abate sectors, many options	**Innovation gaps and system complexity** The energy system is highly complex, and cross-cutting deep decarbonization and mass electrification are unbroken ground. There is considerable reluctance to invest in scaling up relatively untested low- and zero GHG solutions

DRIVERS		BARRIERS
	are being considered: green and blue hydrogen, carbon capture and storage (CCS), and hydrogen-based products such as synthetic fuels (aviation) and ammonia (shipping). Supply chains and production infrastructures are evolving.	and the required long-term infrastructure to enable these. R&D investment and deployment are still needed to reduce costs and close critical competence and technology development gaps.
5.	**Influential sub-national players** States, regions, and cities are pivotal in accelerating the energy transition, and have considerable power over decisions. State and city policymakers are moving to improve urban-air quality, deploy clean energy solutions, and build climate resilience. The UN-Habitat's Cities and Climate Change Initiative, and global networks such as the C40 Knowledge Hub, support urban planning and the spreading of best practices.	**Vested interests and societal pushback** Societal and local government opposition to decarbonization policy often escalate when transition policies fail to distribute benefits, protect jobs and address vested interests. The EU's Just Transition focus reflects the importance of supporting communities on the wrong side of the energy transition. Clean energy projects also face delays from public opposition due to landscape impacts or NIMBY-ism (not-in-my-backyard).
6.	**A new normal for corporate sustainability** As the energy transition accelerates, businesses are vying to drive change and avoid being blindsided. This is being driven by the vast opportunities presented, and the greater scrutiny of environmental, social and governance issues (ESG) by stakeholders and investors, which influences the cost of capital and market capitalization. Mandatory disclosure requirements, Scope 3 emissions reporting, and a stronger focus on biodiversity and circularity are forcing companies to show tangible contributions to global goals.	**The gulf between talk and action** Some companies highlight their concern for the environment merely as a promotional ploy: building perceptions that they are aligned with the energy transition. Instead, the focus is on doing the bare minimum to avoid regulatory penalties and negative market sentiment. Rather than adapting business models to make the transition, many prefer to greenwash high-emitting activities, highlight one-off green investments, and possibly relocate to regions with less stringent climate policy (carbon leakage).
7.	**Investors are ESG aware** The finance sector increasingly factors in sustainability risk. Disclosures on biodiversity- and climate-related risks and impacts will enable the pricing of risk and widen divergence in cost of capital. The EU Taxonomy pushes financial actors to reallocate capital towards sustainability-aligned activities. There is also growing action from regulators such as central banks to align with the legally binding targets governments have committed to.	**Pollution still pays** Absence of 'polluter pays' implementation means society bears the costs of pollution or climate impacts, making free-riding possible for polluters. Despite pledges to tackle climate change, public subsidies for fossil-fuel consumption and production distort the price signals of energy resources. Government funding for new fossil-fuel supply and unabated use of these fuels, causes uncertainty about the sincerity of climate ambitions, and delays shifting investment flows.
8.	**Promising cross-sectoral synergies** Energy systems and sector models are transforming, with more physical links between energy carriers. Renewable electricity conversion pathways, and routes to (for example) hydrogen-based 'green steel', will be enabled by coupling between sectors that have traditionally operated within their own siloes. Power-to-X flagship projects, such as Denmark's energy island projects (see Section 6.6), build synergies between sector expertise and competence building for conversion technologies.	**Unfit regulatory frameworks** Regulators are set up to support legacy energy system, overseeing electric and fossil energy-based systems independently. Sector coupling requires better regulatory frameworks, interlinking energy carriers, infrastructures, and price signals. Coordinated planning is needed, particularly between electricity and natural gas systems. Fuel switching in buildings and industrial-heat production will require tax/levy harmonization to create a level playing field across energy carriers and sectors.

6.4 THE ENERGY TRANSITION TRILEMMA FOR POLICYMAKERS

Governments are not in control of the 'drivers and barriers' trends listed in Section 6.3, but they have to find a way to manage the inherent tensions to arrive at progressive policy choices. Here we extend the well-known energy trilemma (energy security/equity/sustainability) to focus on the energy transition. The intention is to guide policymakers and inform a managed balance between the three dimensions. The trilemma and related fundamental issues require a proactive and cohesive policy approach to transition energy systems.

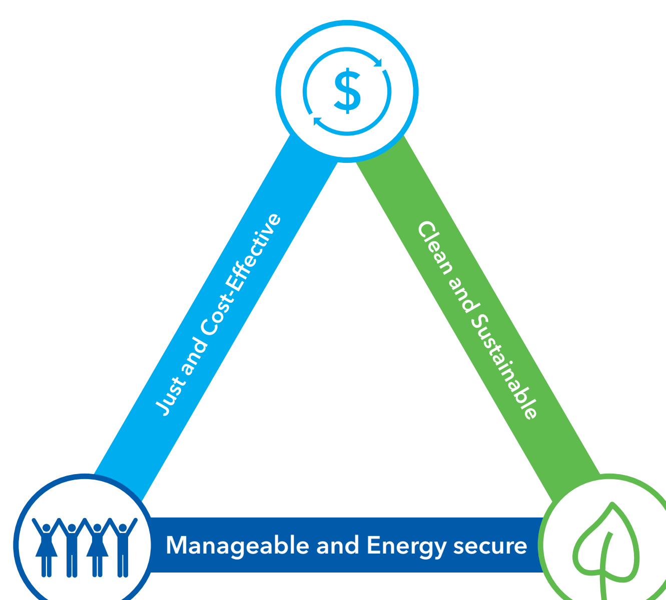
A just and cost-effective transition

A reduction in humanity's carbon footprint requires policies that incentivize behavioural change and uptake of green technologies. Such policies create systemwide impacts on entire fossil-based supply chains and the associated socioeconomic implications need to be addressed. Some jobs are jeopardized while others are created, affecting entire communities. The upskilling and reskilling of labour forces is at the core of energy shifts and require transition planning for both workers and communities. Enabling a 'just transition', with proper handling of distributional effects, is a prerequisite for achieving policy targets, otherwise opposition against transition policies will escalate. Transition initiatives are likely to fail in the absence of sustained broad public support.

At the core of a just transition is continued economic prosperity with a reduced carbon footprint. This should not be achieved through carbon leakage – i.e., the relocation of economic activity with high emissions to regions with weaker carbon regulations. That is likely to excite public opposition to policies that lead to a relocation of jobs and otherwise-profitable industries.

In any given socioeconomic context, it will be important to advance the transition at lowest possible cost. The prime issue is how to achieve stated objectives associated with the Paris Agreement and global Sustainable Development Goals (SDGs), cost-effectively. Here, a priority ranking that weighs costs against technologies and solutions that offer the same or similar desired outcomes is useful. In such an assessment, the long technical lifetimes of energy assets must be considered in the light of the cost learning curves of technologies. Policymakers should avoid the risk of investing in assets that are likely to be stranded by the transition and risk burdening consumers with unnecessary additional energy costs.

The energy transition trilemma



A clean and sustainable transition

The climate and biodiversity crises are fundamentally connected. Nature-based solutions, such as forest preservation or restoration of degraded ecosystems, will enable nature to contribute to tackling climate change. But expansion in renewable energy and related technologies are often area-intensive or lead to impacts on natural habitats and wildlife. The extractive industry, of which fossil fuels are a part, has long been a source of negative impacts on nature, but shifting to a renewables-based energy system may yet deepen the biodiversity crisis, if carefully considered impact mitigation actions are not undertaken (UN DESA, 2020).

Fossil energy, and not renewables, are deeply implicated in health problems associated with poor air quality. 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 (ESA, 2021) and ground-based air quality monitoring technology developing rapidly, such as Google's Project Air View (Google, 2021), emission sources can be comprehensively observed in real time. This, in turn, will enable accountability in clean-air policies to control public-health hazards from point sources and traffic-related pollutants.

Global warming, degrading ecosystems, air pollution, and the potential for pandemics 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.

A manageable and energy-secure transition

Access to energy is crucial for human and economic development. Fossil fuels, with their high energy density at ambient temperature and pressure that simplifies transportation and storage, have supplied most of the increases in demand since the Industrial Revolution. But fossil fuels cause local air pollution, GHG emissions and, in many producing regions, are incurring ever-higher extraction costs. By contrast, renewable energy technologies are not only cleaner, but are becoming increasingly cheaper and more affordable.

Moving from fossil fuels to weather-based renewable energy resources represents a fundamental shift in energy system planning and security of supply. What measures are required to secure a reliable energy supply when the energy mix depends mainly on the weather?

During the transition phase there is a risk that regulatory interventions and market drivers strand or phase out 'old assets' that may not have reached the end of their technical lifetimes. Managed discontinuation practices are emerging as an integral part of energy policies. Examples include the 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, like green hydrogen.

A secure, decarbonized energy supply does not require unknown technological advancements. Instead, it requires a coordinated approach to decommissioning or ending unabated fossil-based energy while targeting investments in and use of renewables, storage technologies and infrastructure for energy transport, as showcased by Germany and the UK.

6.5 THE POLICY TOOLBOX

The energy sector is prone to a lock-in of current technologies due, among other reasons, to practices of incumbent companies, capital intensity, scale and long-lived assets. To break the logjam, decision makers need a policy toolbox to foster the full spread and potential of technology and to transition faster.

Countries and regions will undergo unique energy transitions given their different starting points regarding available resources, existing energy sector infrastructures, political preferences, and national circumstances. However, all policymakers have a shared technology-opportunity space at hand. Affordable and proven clean-energy options are available especially for electricity provision. Cost-parity with fossil energy has been reached for renewables in power generation which are readily available for implementation and market-driven global uptake.

However, where direct electrification is not possible – like in hard-to-abate sectors such as cement, steel, aviation, long-haul trucking, and shipping — alternatives to replace fossil-fuelled technologies are less mature or have yet to reach commercial readiness and cost competitiveness. Acceleration through policy measures will be needed to put solutions on a development track that results in decarbonization alignment for these sectors with the Paris Agreement.

The OECD estimates that, globally, USD 6.9trn a year is required up to 2030 to meet climate and development objectives (OECD et al. 2018). Although governments are lead investors, public resources are not adequate. Both institutional and private capital will be necessary and to accelerate investment policymakers need to send the right signals to prompt changes. There is no silver bullet. Rather, a mix of policy measures will be in play, tailored to sectors and specific problems at hand.

Learning curves are the foundation of 'push' and 'pull' policies, where policy interventions encourage the economic evolution of technologies with uptake triggering technology and cost-learning rates. Some interventions stimulate technology development, others activate the market and accelerate deployment, while a third category aims to level the playing field and fix market distortions.

6.5.1 Three main policy categories

The three main policy categories — technology support, market activation, and economic signals to fix market distortions – are described separately here for clarity; in reality, a mix of policies will always be at play.

An important transition enabler is to design and adjust policy measures to fit the maturity of clean-energy technologies. For immature technologies, R&D support could be the correct instrument. In the next stage, market activation through standards, subsidy schemes or auctions are potential solutions. Finally, when technologies have matured, they should all be exposed to market prices supported by general policies, such as carbon prices.

At the level of sectors or supply chains, comprising several technologies at varying levels of readiness, a blend of policies is needed. The urgency of the transition also suggests overlapping these phases with synchronous acceleration of both technology development and uptake.

A. Policy measures to support technology development

Technology-push policies foster energy innovation by stimulating the interaction between R&D, production, and learning-by-doing. Public funding helps overcome the financial barriers to demonstration and early-stage commercialization, and stimulates technological progress and technology alternatives, in particular within immature technologies with high unit costs.

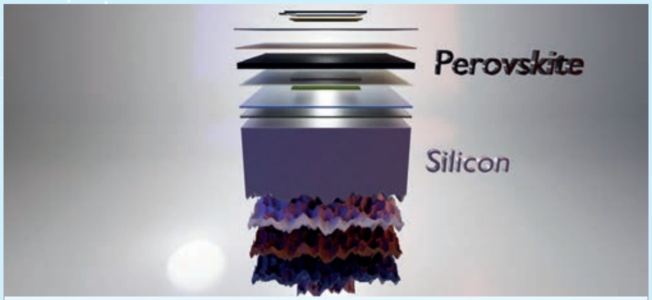
Funding for initial projects, nascent industries, and industrial-scale demonstration helps to prove performance, trigger cost-learning rates, and generate stakeholder alignment. Systems-design thinking with cross-sectoral problem solving and a more flexible approach will be required to support trial-and-error experimentation and ensure that regulated entities recover some of their spending.

1. **Energy technology and transition roadmaps** – covering long-term energy system development with milestones matching infrastructure and technology priorities across sectors. Real-world examples are: the EU's all-encompassing Green Deal strategy and 'Fit for 55' package; Germany's Energiewende; China's five-year plans, as well as the policy blueprints guiding economic development and climate policies (see Chapter 7 for further details).

2. **R&D funding** – aligned with net zero targets and SDG objectives, including the associated sector- and infrastructure challenges. Includes investment support and corporate tax provisions to private company research, novel projects, and capital costs in line with objectives. Examples, with government support of between EUR 300m – 900m annually to 2030 are Germany, South Korea and hydrogen in Japan. International cooperation in "Mission Innovation" strengthens R&D efforts on action areas for Paris Agreement implementation. The members, consisting of 22 countries plus the EU, align clean energy R&D spending (USD 5.8bn annually). Mission 2.0 was launched in May 2021 and will focus on public-private innovation alliances in green-powered future, clean hydrogen, and zero-emission shipping. The EU Innovation Fund (funded via the EU emissions trading scheme, ETS) will provide around EUR 10bn this decade to the commercial demonstration of low-carbon technologies focusing on CCS in energy-intensive industries, reductions in industrial process emissions, direct air capture and bioenergy.

3. **Technology requirements** – such as building codes and product or technology standards setting minimum requirements for energy efficiency, fuel economy, emission limits and carbon intensity. Examples are China's 'Winning the Blue-Sky War' plan to cap coal use and 5-year plans setting energy-efficiency requirements for buildings, transport, and industry sectors. South Korea's Clean Air Conservation Act setting permissible emission levels from stationary sources, buildings, vehicles, and ships.

4. **Taxonomy development** – a classification system for sustainable finance with the aim to reshape financial flows by setting eligibility criteria for funding to underpin private sector and investor-driven change. Examples are seen in many countries like China, Canada, Bangladesh, Mongolia. The EU Taxonomy Regulation creates an EU-wide classification system on environmentally sustainable economic activities. It is accompanied by Delegated Acts on technical screening criteria across sectors, for example, standards for the manufacturing of 'taxonomy eligible' hydrogen. The People's Bank of China and the EU will work together to align their green investment taxonomies across the two markets (FT, 2021).



Schematic structure of the tandem solar cell stack in 3D courtesy of Eike Koehnen/HZB. In January 2020, a group at the Helmholtz Zentrum Berlin (HZB) set the world record for tandem cell efficiency at 29.15%

B. Policy measures to support market activation

Market-pull policies stimulate the demand side by promoting market deployment of solutions. Accelerating uptake helps existing solutions and 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 (i.e., market and technology cost-learning dynamics).

1. **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, that stimulate market uptake. Examples are the high EV adoption in Norway spurred by purchase incentives, the US federal investment tax credit to solar systems and storage systems, and California's Self-Generation Incentive Program (SGIP) with incentives to homeowners pairing batteries with solar panel systems.

2. **Renewable energy auctions** – to develop power-generation capacity with developers bidding for contracts in auctions following government capacity quotas, and with developers' revenues guaranteed from commencement of operation by giving predictable prices by means of contracts for difference or feed-in premiums. Examples include Latin American countries that have built around 80% of the renewable-energy capacity with public tenders and auction schemes. Across our Outlook regions, governments continue to support renewables in power systems with schemes trending clearly towards competitive biddings and contracts for difference (premiums on top of wholesale prices).

3. **Market requirements** – promote the deployment of technology alternatives over others, such as setting binding targets on a certain share of renewables in power mixes and renewable energy use in transport by a certain year; or setting biofuel blending mandates in road transport and aviation. 'Green' public procurement and public institutions spending can be required to prioritize lower energy/carbon content, and bans can be introduced on polluting technologies such as diesel or petrol (ICE) cars. Most nations (145 in total) have renewable energy targets for their power sectors, but few nations (65) have transport targets, and even fewer (22) target heating/cooling in buildings and manufacturing (REN21, 2021). The Biden-administration will use the Federal government procurement system, spending USD 500bn every year, to aim for 100% clean energy and zero-emission vehicles. 26 nations have announced phase-out plans and/or bans on ICEs, and the EU Commission's proposed Euro 7 emission rules for road transport vehicles which is criticized as "an ICE ban through the back door" due to stringency. The G7 has committed to ending direct government support for new thermal coal power generation without co-located CCS by end of 2021 (G7-UK, 2021).

ENERGY STAR

4. **Mandatory disclosures** – such as climate change-related risks disclosure, that is consistent among market participants, or consumer information, such as guarantees of origin on energy products (hydrogen, electricity), or energy labels. Examples include the Energy Star programme that ranks appliances and products on energy consumption. The EU-wide guarantees of origin scheme, CertifHy, provides proof of green hydrogen to end-users, documenting hydrogen originating from renewable or low-carbon energy sources. The UK, Hong Kong, South Korea, and New Zealand have adopted mandatory climate risk disclosures, and G7 finance ministers are also backing the move to mandate climate-related financial disclosures from banks and companies, based on the TCFD (G7-UK, 2021).

C. Policy measures to fix market distortions

Fiscal policies can tilt markets towards Paris Agreement achievement by fixing market distortions that affect competition between low-emission alternatives and carbon-intensive behaviours and practice. Review and reform of tax systems and budgetary expenditures form part of a holistic policy approach to transitioning energy systems.

Inadequate carbon pricing and persistent fossil-fuel subsidies as well as the lack of internalization of negative externalities, are market distortions delaying the transition.

1. Pricing carbon and other externalities – A carbon-pricing scheme can impose a tax on emissions or set an emissions cap while allowing trading to achieve the most cost-effective reduction. Experts conclude that an explicit price of USD 40-80/tCO_2e is needed by 2020 and USD 50-100/tCO_2 by 2030, to meet the 2°C goal (HCCP, 2017). On top of this may come pricing principles for other negative externalities (e.g. air pollution, biodiversity loss etc.). As of mid-2021, 64 carbon pricing initiatives are implemented, 45 national and 35 subnational jurisdictions had introduced, or planned to introduce, a price on carbon. Initiatives cover 11.65 GtCO_2e, representing 21.5% of global GHG emissions (World Bank, 2021). The OECD (2021a) finds that less than 4% of emissions in carbon pricing schemes are covered by a price above USD 40/tCO_2e, with the majority priced below USD 10/tCO_2e. There are notable exceptions with Sweden and Switzerland at the fore with USD 137 and 101/tCO_2e, respectively.

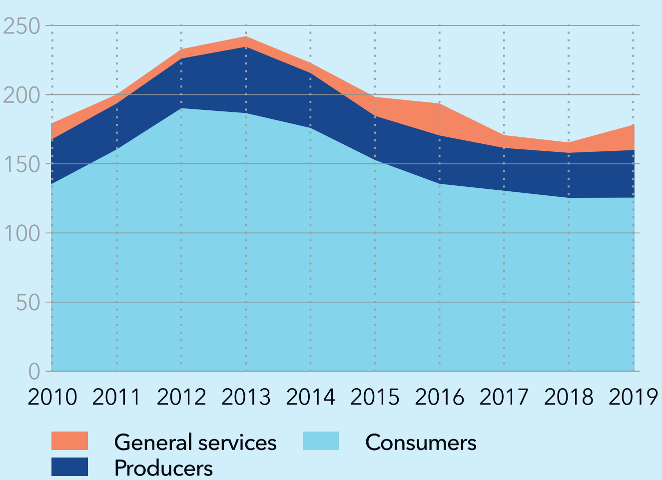
2. Removal of fossil-fuel subsidies – Subsidy savings and carbon-pricing revenues can be channelled to catalyse investments in transition-related technologies as well as to place-based initiatives buffering impacts on communities and vulnerable groups. OECD tracks fossil-fuel support as shown in Figure 6.2 (OECD, 2021b), and the G20 scorecard on fossil-fuel funding (IISD, 2020) estimates that USD 584bn is spent annually supporting fossil fuels. A concrete subsidy reform initiated by the Biden-administration calls for ending special tax breaks for the oil and gas industry, including tax reforms on income made from extracting oil and gas abroad. By eliminating these fossil-fuel tax credits the US government could save USD 121bn over the next ten years (PoliticoPro, 2021). Just transition efforts in the North America region include Canada's Just Transition Taskforce and CO_2 tax revenue recycling on a per capita basis. Colorado, New Mexico, Arizona having initiatives to buffer coal communities affected by mine and power plant closures, and the Biden-administration is placing a just transition at the centre of climate policy to support frontline communities.

3. Revision of government funding – aligning incentives and mandates of all public institutions with SDG and climate objectives, e.g., in export guarantees and development finance. A good example of this is the increase (50% by 2025) in the European Investment Bank's share of finance dedicated to climate action and environmental sustainability, along stopping most fossil-fuel project funding by end-2021. As to the three countries that have been the top global lenders for coal energy infrastructure funding, Japan and South Korea have made moves to limit financial backing for overseas coal projects. However, China has yet to build strict environmental policies for its Belt and Road Initiative, comparable to those applied domestically.

FIGURE 6.2

Fossil fuel support by beneficiary

Units: Billion USD/yr



Historical data source: OECD Inventory of support measures for fossil fuels.

Carbon pricing in our forecast

Carbon pricing is expected to become more robust. Decarbonization pledges are irreconcilable with policies that keep fossil fuels cheap and fail to assign to polluters the costs they impose on society. "By pricing carbon, governments capture the costs that the public pays for in other ways, such as health care costs from heatwaves and droughts, or damage to property from flooding and sea level rise" (UN CC, 2020). Summaries in the Carbon Pricing Dashboard (World Bank, 2021) and from the International Carbon Action Partnership (ICAP, 2021) indicate that the potential of carbon pricing is still largely untapped in terms of low coverage and with prices below the levels needed to drive significant decarbonization. As such, other policy measures from the policy toolbox will be needed to unleash decarbonization efforts, especially in hard-to-abate sectors.

The EU ETS supplementing national taxation among member states makes Europe a front runner in carbon pricing. There are signs that the EU (EC, 2021) will extend its carbon pricing coverage to buildings and road transport, and also for maritime and aviation (see Section 7.3). A sector-by-sector approach to extend carbon pricing is similarly seen in Germany, expanding into transport and home heating, with a more-than-doubling planned from the current USD 30 (euro 25) per tonne of CO_2 to between 55 euros and 65 euros per tonne within five years (CEW, 2021). China's ETS initially targeting approximately 4.5 $BtCO_2$ (GT, 2021) will push the global coverage upwards.

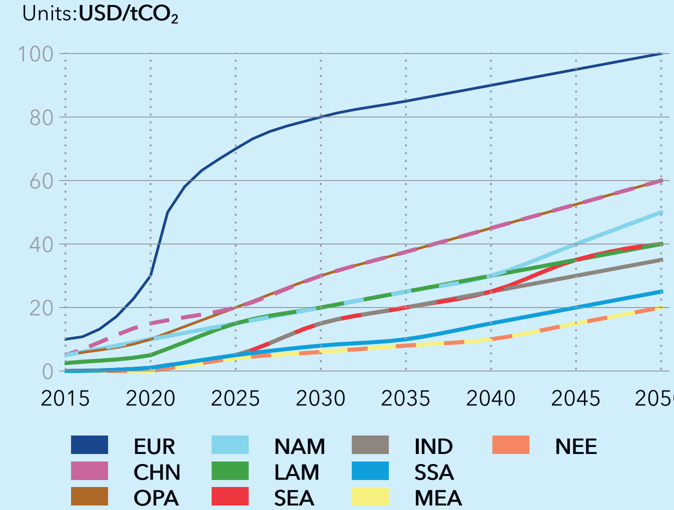
In our forecast, the analysis includes our best estimate of future carbon-price levels, reflected as a cost for fossil fuels. Regional carbon-price trajectories are shown in Figure 6.3. With the increase in net zero commitments and around 60% of global emissions being under net zero targets, the adoption of carbon-pricing schemes is expected to grow, both in prices and coverage. Europe will be the lead pioneer. Greater China is expected to trail Europe with a continuous rise but starting from a lower level. OECD Pacific will be pulled by Greater China, with prospects of linking Asian ETS schemes and with Japan, South Korea and New Zealand taking the lead. Although there will be regional variations, we expect a continued rise, mainly to meet climate targets and avoid carbon-border adjustment mechanisms, as well as to access climate finance and international trade in mitigation (article 6 of the Paris Agreement). The large difference in carbon-price levels accentuates the need for carbon-border adjustment mechanisms to reduce the risk of carbon leakage, and to incentivize higher carbon prices globally. However, as these are still under negotiation, we do not include such mechanisms in this year's forecast.

Regarding fossil-fuel subsidies: These are incorporated in cost projections in the extraction sectors – and reform of subsidies is expected to evolve slowly, given predominant policy focus on job preservation, as reflected in COVID-19 recovery spending (energypolicytracker.org). On consumption subsidies, these are incorporated as part of fuel and energy taxation (Section 6.7). Demand-side subsidies will perpetuate; however, we see tax levels increasing to reflect air-pollution prevention, efforts to limit congestion and emissions.

FIGURE 6.3

Carbon price by region

Units: USD/tCO_2



6.5.2 Key regional policy developments

These are snapshots of key recent policy developments in our forecast regions that capture the policy toolbox at work (cf. Section 6.5) and more generally the role of governments in the transition. The map alongside shows each region's share of global energy-related CO_2 emissions in 2019.

North America

The US re-joined the Paris Agreement and announced a 50-52% GHG reduction by 2030, a carbon pollution-free power sector by 2035 and a net zero emissions economy by 2050.

The Californian coast opened for floating offshore wind, while oil and gas leases in the Alaskan Arctic are suspended and a permit for the Keystone XL Pipeline was revoked, adding to the list of "regulation" of climate policy steering towards renewables and "environmental justice".

Canada announced an emissions reduction target of 40-45% by 2030 compared with 2005-levels, instead of 30% committed to earlier.

Europe

The EU agreed on a binding target of 55% reduction in GHGs by 2030 compared with 1990. The UK followed suit with a 68% reduction target.

High EU ETS prices followed, reaching a record 57 EUR/tonne in May 2021, while UK's new trading scheme provided even higher prices.

A Carbon-Border Adjustment Mechanism proposal was presented in July 2021, charging high carbon intensity imports, facilitating fair competition to protect Europe's heavy industry.

The first set of delegated acts of the EU Taxonomy were approved. Decisions on the role of gas and criteria for the remaining four environmental objectives are expected during 2021.

Sub-Saharan Africa

South Africa is to submit an updated climate plan ahead of the COP26. The draft plan, currently under consultation, proposes GHG emissions 28% lower than current pledge for 2030.

South Africa presented a long-term goal to reduce GHG emissions to net zero by 2050 but a large gap exists between commitments and concrete climate action plans to reach these targets, given the country's reliance on coal-fired electricity generation.

Chinese lenders have been criticized for backing several coal-fired power plants in across Sub-Saharan Africa, which has considerable and largely untapped solar energy potential.

Middle East and North Africa

Turkey launched measures to curb the impact of climate change, with increased targets for solar and wind energy by 2030, stating Turkey "will implement a system that supports climate-friendly investments and rewards facilities investing in clean production technologies" (February 2021).

The International Renewable Energy Agency (IRENA) and Morocco entered a strategic partnership to advance knowledge in renewable energy, working closely together to advance the national green hydrogen economy. Morocco aims to become a major green hydrogen producer and exporter (June 2021).

North East Eurasia

Russia adopted a new target of 30% reduction in GHGs by 2030 compared with 1990. This effectively means an increase in GHG emissions from today's levels (WRI, 2020).

Russia's draft 2050 strategy showed similar ambition, with carbon neutrality far later than Europe. Europe's anticipated Carbon-Border Adjustment Mechanism is therefore likely to impact the competitiveness of Russian exporters.

On the contrary, Ukraine aims to align climate policy with the EU, announcing a strong increase in short term climate action, with GHG emissions reduction of 58%-64% below 1990-levels, instead of 40%.

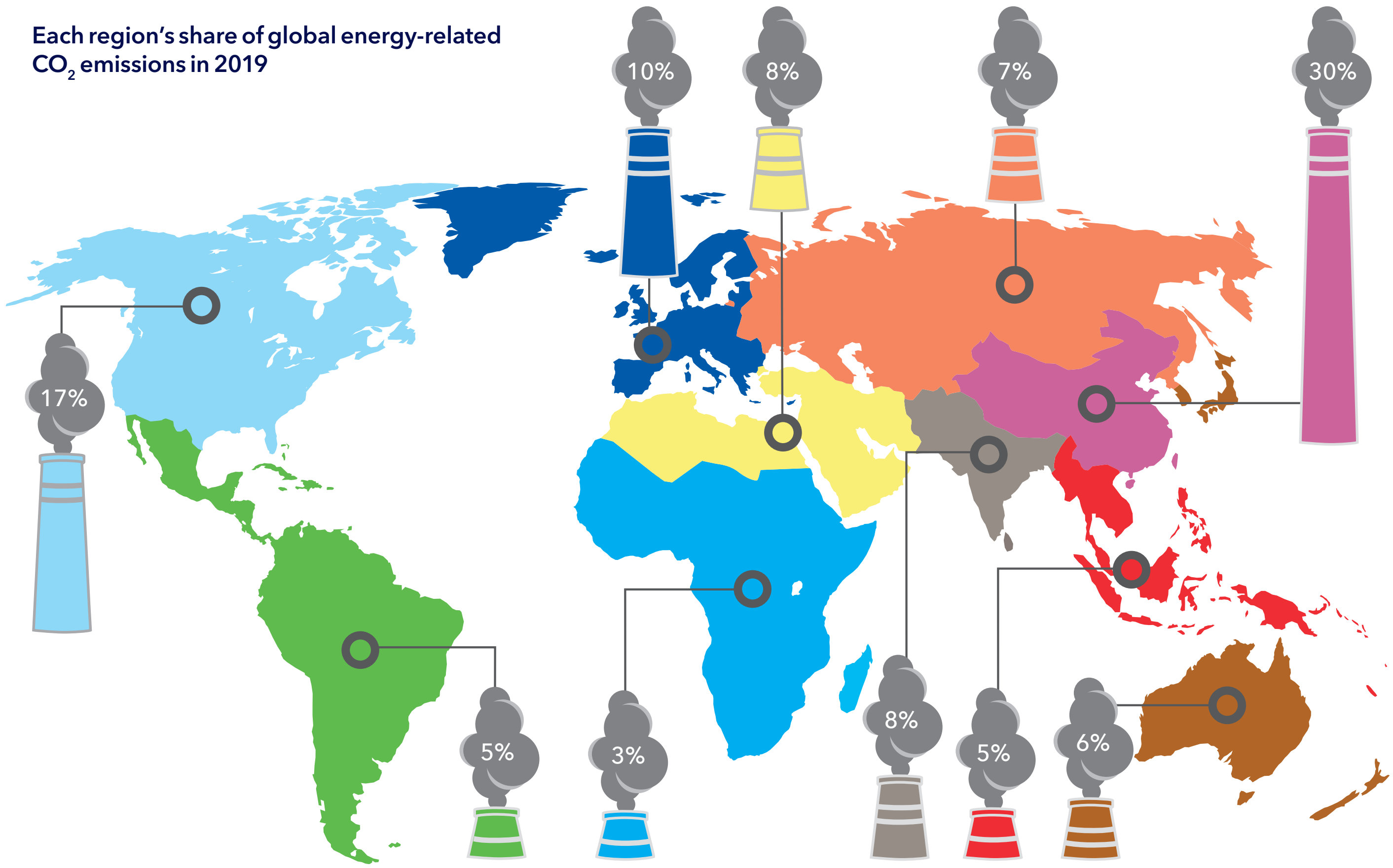
South East Asia

The ASEAN Plan of Action for Energy for 2021-2025 was endorsed, providing 2025 targets of 23% renewable energy in total primary energy supply and 35% in installed power capacity for countries including Vietnam, Thailand, the Philippines, Malaysia and Indonesia.

The Philippines announced an end to its "energy neutrality" policy to favour renewable energy and will no longer accept new coal power plants.

Vietnam passed a revised environmental law in November 2020, with provisions for setting up a domestic emissions trading system.

Each region's share of global energy-related CO_2 emissions in 2019



Greater China (CHN)	30%	North East Eurasia (NEE)	7%
North America (NAM)	17%	OECD Pacific (OPA)	6%
Europe (EUR)	10%	South East Asia (SEA)	5%
Indian Subcontinent (IND)	8%	Latin America (LAM)	5%
Middle East and North Africa (MEA)	8%	Sub-Saharan Africa (SSA)	3%

Latin America

Brazil's President Bolsonaro vowed to end illegal deforestation in Brazil by 2030 and achieve carbon neutrality by 2050, thereby bringing carbon neutrality 10 years forward.

The pledges come in response to U.S. President Biden's demands for stronger climate action, before providing any aid to support plans to end illegal deforestation.

Argentina announced more ambitious 2030 targets and reiterated its goal to be carbon neutral by 2050. Announcements on concrete policy action and implementation is expected during COP26.

Greater China

China approved the 14th Five-Year Plan covering 2021 to 2025. The energy sector specific plan, with concrete targets and actions, is expected later in the year.

President Xi Jinping announced a unilateral target of peaking China's CO_2 emissions before 2030 and reaching carbon neutrality by 2060, at the UN General Assembly (September 2020).

China's national ETS started trade in July, 2021 and is seen as an important policy tool to fulfil the 2060 target.

OECD Pacific

Japan and South Korea announced carbon neutrality pledges by 2050 (October 2020).

Japan's commitment is conditional on disruptive innovations. South Korea's NDC notes that various scenarios will be analysed to reach the 2050 target, also assessing further emissions reduction potential for 2030.

New Zealand announced a revision of its 2030 target after an independent commission advised that current plans fall short of meeting the Paris Agreement.

Indian subcontinent

India announced a National Hydrogen Mission, which will add hydrogen to its national decarbonization strategy, adding to the country's renewable energy plans.

Despite rumours, no new net zero target was announced by Prime Minister Modi during the April 2021 Leaders' Summit on Climate. India reconfirmed the target to install 450 GW in renewables by 2030 and announced an India-U.S. Climate and Clean Energy Agenda Partnership for 2030.

6.6 ENERGY SYSTEM CHALLENGES AND THE POLICY RESPONSE

From our analysis of energy system change, key characteristics of the transition are electrification and decarbonization across all sectors. However, as energy systems are recast, new system challenges arise. The penetration of renewables in power systems and technologies advancing decarbonization in hard-to-abate sectors have their own sets of challenges. Sector coupling is expected to play a pivotal role in overcoming these, but sector coupling itself needs shaping by governments. For all challenges, carefully orchestrated policy frameworks can act as enablers. A picture emerges of future energy policies that increasingly focus on, and are supportive of, systemic innovation. The highlighted cases are meant to illustrate challenges and examples of the policy response, in the hard-to-abate case the issue is how to transition in the absence of robust policy.

1. Challenge: Renewable energy penetration in power system

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 be required. Flexibility will have to come from both physical assets (e.g., 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 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 risks in areas with unstable regulatory frameworks, especially in developing economies.

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.

Case: Renewable expansion in Vietnam

Coal, natural gas, and hydropower are the dominant electricity generation sources in Vietnam. Electricity generation has more than doubled since 2010, with growth in coal and hydropower generation as the main drivers. Vietnamese ambitions to reduce electricity-related GHG emissions have, in parallel, led to a boom in solar PV instalments. Annual solar PV electricity generation was close to zero in 2018, 6 TWh in 2019 and 13 TWh in 2020 (ourworldindata.org, 2021). The wind power market in Vietnam is now also expanding rapidly, with 600 MW of installed capacity in 2020. Vietnam's National Power Development Plan VIII states an ambition of 11 and 19-20 GW wind and solar power, respectively in 2030.

Renewable energy policies in Vietnam have played an important role in the uptake of solar and developing the industry. A feed-in tariff (FIT) at 93.5 USD/MWh for 20 years was introduced in 2017, with all projects in operation before June 30th, 2019 being eligible. The levelized cost of energy (LCOE) for solar PV projects in 2018 was estimated to 87.5 USD/MWh, indicating that the FIT scheme was favourable towards investors. Key drivers behind the introduction of solar-friendly policies in Vietnam are the government's commitment to energy security, public demand for environmental protection, government effort to develop solar power as a new economic sector and a response to climate policies.

The boom in solar investments has led to network congestion when solar generation is peaking. According to the National Power Dispatching Centre of Vietnam, peak hours of PV generation are overloading the 500 kV power transmission channel in the north and south of Vietnam. Consequently, planned solar curtailment in 2021 is 500 GWh (Seetao, 2021).

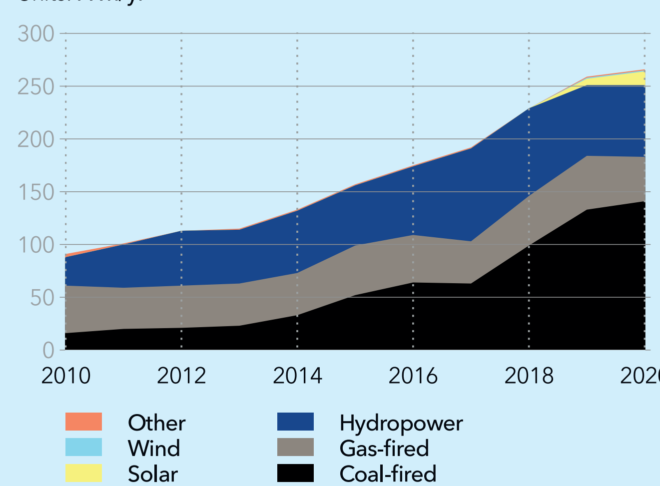
The dilemma policy makers in Vietnam are now facing is how to reduce subsidies while still attracting solar and wind power investments. They must also ensure efficient resource use by limiting curtailment of solar generation during peak hours. Replacing the feed-in tariffs with auction-based schemes are being discussed as a measure to reduce subsidy expenditures. Potential solutions to decrease electricity curtailment are reforming regulations on transmission grid planning, providing more accurate price signals, and incentivising the use of energy storage (ISEAS Perspective, 2021).

Renewable energy policies in Vietnam have played an important role in the uptake of solar and developing the industry.

FIGURE 6.4

Electricity generation in Vietnam

Units: TWh/yr



Historical data source: BP Statistical Review of World Energy (2020)

2. Challenge: Hard-to-abate sectors

All sectors will face continued pressure to reduce carbon emissions, but in certain demand sectors like heavy industry (cement, chemicals) and heavy transport (long-haul trucking, shipping and aviation), the alternatives to fossil fuels are less readily available and need further development and scale up. These sectors are harder to decarbonize than others, and existing solutions to drive down emissions are more costly than conventional carbon-intense technologies.

In maritime, alternative fuels and electrification prospects vary greatly for different ship segments, as do their technical applicability, availability, and commercial viability. In aviation, the picture is similar where longer-term emission cuts will increasingly require sustainable aviation fuels (SAFs). 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. However, few, if any, of these options for decarbonized industrial high-heat processes/production are well developed or available at scale. CCS is also part of the solution for process-related emissions such as emissions from limestone calcination in cement or process emissions from reductant materials. Common to the decarbonization challenge in the hard-to-abate sectors, is that strong policy incentives will be required and accelerated capital deployment through coordinated efforts by governments, companies, and investors is necessary, as highlighted in the following case.

Case: The silicon carbide industry

When Tesla launched its Model 3, it was the first company to use silicon carbide (SiC) in its EVs to enable lighter, more efficient vehicles. Other car manufacturers have followed suit. Due to its unique combination of hardness, high thermal conductivity and chemical inertness, SiC is used in a wide variety of applications ranging traditionally from components in electronics, aerospace, energy and automotive, to its more recent use in semiconductors used in wind or solar power modules and EV drive converters.

SiC is produced from quartz, petroleum coke, which is used as a carbon source, and large quantities of heat. Around 35% of the carbon is contained in the product, and the rest is converted to CO_2. The petroleum coke might also contain volatile compounds, which forms methane, a potent GHG. This leaves the SiC industry with very high GHG emissions from its chemical process in addition to energy consumption for heat production – a situation facing many industry sectors.

Key decarbonization options for process emissions are renewable reductant alternatives to petroleum coke, or to apply CCS to exhaust gases. Neither are readily available options. Replacing solid carbon with gases like hydrogen offers a renewable solution (Aarnæs et. al, 2020), but such hydrogen-based SiC processes are immature. Other solutions with higher technological readiness exist. One route is replacing petroleum coke with biocarbon (CO_2 neutral charcoal) as a reductant, but to become a viable route, R&D funding is required to investigate whether climate benefits do not accrue at the expense of harmful biodiversity impacts. Pilot and full-scale projects are also needed to test the increasing percentage of biocarbon used as reductant. For SiC production in Brazil, there may be transferable learnings from the Plantar Group/World Bank Partnership on making the expansion of eucalyptus plantations and production of biocarbon eligible as certified emission reductions under the Clean Development Mechanism (World Bank, 2018). Securing funding through global policy schemes, such as the Paris Agreement Article 6 and Internationally Transferred Mitigation Outcomes (ITMOs) will be an option. But the price level of credits under Article 6 in these future markets is too uncertain for private sector actors to make pilot plant investment decisions.

Another route is CCS, however the size of most SiC manufacturing sites globally would not be sufficient to develop CCS on a stand-alone basis, in contrast to large global emitters like cement, where CCS is the main and most effective decarbonization option. An established CCS value chain for transport and permanent storage would be required. Yet support to establish CCS infra-structures globally is inadequate. Notable exceptions are the UK with funding to CCS clusters, CarbonSAFE CO_2 storage hubs supported by the US Department of Energy, and the Norwegian government's USD 1.8bn funding to the Longship project, which are examples enabling CCS value chain development. That such infrastructure is available and accessible to smaller scale industrial facilities would be a necessary step for CCS to be a solution for the SiC industry.

The Paris Agreement puts pressure on SiC producers to be carbon neutral in 2050. But current policy schemes like CO_2 prices are either not globally consistent or (far) too low to justify the costs of CCS for such relatively small-scale manufacturers. Stronger policy measures are required to move SiC and other industry players onto a transition path. However, in the absence of robust policy, a driver of change comes from multinationals' focus on supply-chain footprint reduction. Another promising stimulus comes from the financial sector. By providing sustainability-linked finance structures to SiC producers, environmental sustainability performance is directly linked to finance costs, where transition in line with Paris objectives is rewarded, and with slower transition punished.

In the absence of robust policy, a driver of change comes from multinationals' focus on supply-chainfootprint reduction. Another promising stimulus comes from the financial sector.

3. Challenge: Sector coupling

Sector coupling is an important enabler of the energy transition. It involves the coupling of energy vectors (i.e., energy carriers or energy value chains) between different end-users of energy (i.e., transport, buildings, and industry). Fully decarbonizing hard-to-abate sectors implies decarbonizing energy supply and energy carriers, which will lead to increased sector coupling or sector integration. Electrification is a main aspect of sector coupling. End-users of energy that previously used mainly fossil-based energy carriers, will now compete for the same source: electricity, taking advantage of renewable electricity being available at competitive market prices.

Access to cheap renewable electricity creates opportunities for electrification, both direct and indirect. Indirect use occurs through power-to-X (PtX) technologies that process electricity into other products/energy carriers, that are more versatile in their use and can be better stored. Examples are power-to-fuel, power-to-gas, or power-to-liquid, each determined by the downstream application or use case. But sector coupling will not happen by itself. PtX conversion technologies need development, technical demonstration and maturing to be integrated in energy systems. Sector coupling requires integrated planning, harmonization of taxation per energy unit, and also has the arduous challenge of connecting the electricity sector to gas, fuel, and heat sectors, in terms of markets, infrastructures and regulatory frameworks.

Case: The Danish energy islands

In December 2019, eight out of the ten parties in the Danish Parliament agreed on the Climate Act with a legally binding target to reduce Denmark's GHG emissions by 70% compared with 1990 levels by 2030. The Act also stipulates a long-term target of climate neutrality by 2050, at the latest. Every year, the Danish government will present Climate Action Programmes with concrete political initiatives to decarbonize every sector. The legislation also establishes an ambition mechanism designed to ensure early action.

To achieve the emissions reduction target, the Climate Action Plan outlines six main tracks for concrete action, one of which is: "A new era for energy islands". Funding has been granted to initiate the realization of two energy islands, or so-called energy hubs, by 2030 with a total initial capacity of 5 GW by 2030, tripling Denmark's current installed offshore wind capacity. The plan is to expand capacity to 12 GW (DEA, 2021).

One artificial island will be created in the North Sea (80 km off the west coast of the Jutland Peninsula) and is projected as the largest construction project in Danish history. It will serve as an offshore power hub collecting, storing, converting, and distributing green electricity from offshore wind turbines to countries bordering the North Sea. It must initially be able to handle power production from 3 GW offshore wind turbines connected no later than 2030. The total cost of constructing the North Sea island is estimated at DKK 210bn (EUR 28bn, USD 34bn). The second (non-artificial) energy island in the Baltic Sea will use the Danish island of Bornholm to serve as a physical hub for 2 GW offshore wind capacity (133 turbines) and with interconnections to other European countries in the Baltic Sea.

The energy islands are flagship PtX projects that build on legacy offshore wind competence, dating back to the first offshore windfarm in 1991. The Government will be the majority owner, providing 51% of funding and will invite private partners through tenders. The initial investment is intended to lay the foundation for development of cost competitive PtX technologies and production facilities for sustainable energy on the islands. Facilities envisioned are energy storage, electrolysis plants, or plants using other technologies for energy conversion. Suggestions for downstream use are aviation and heavy transport. The

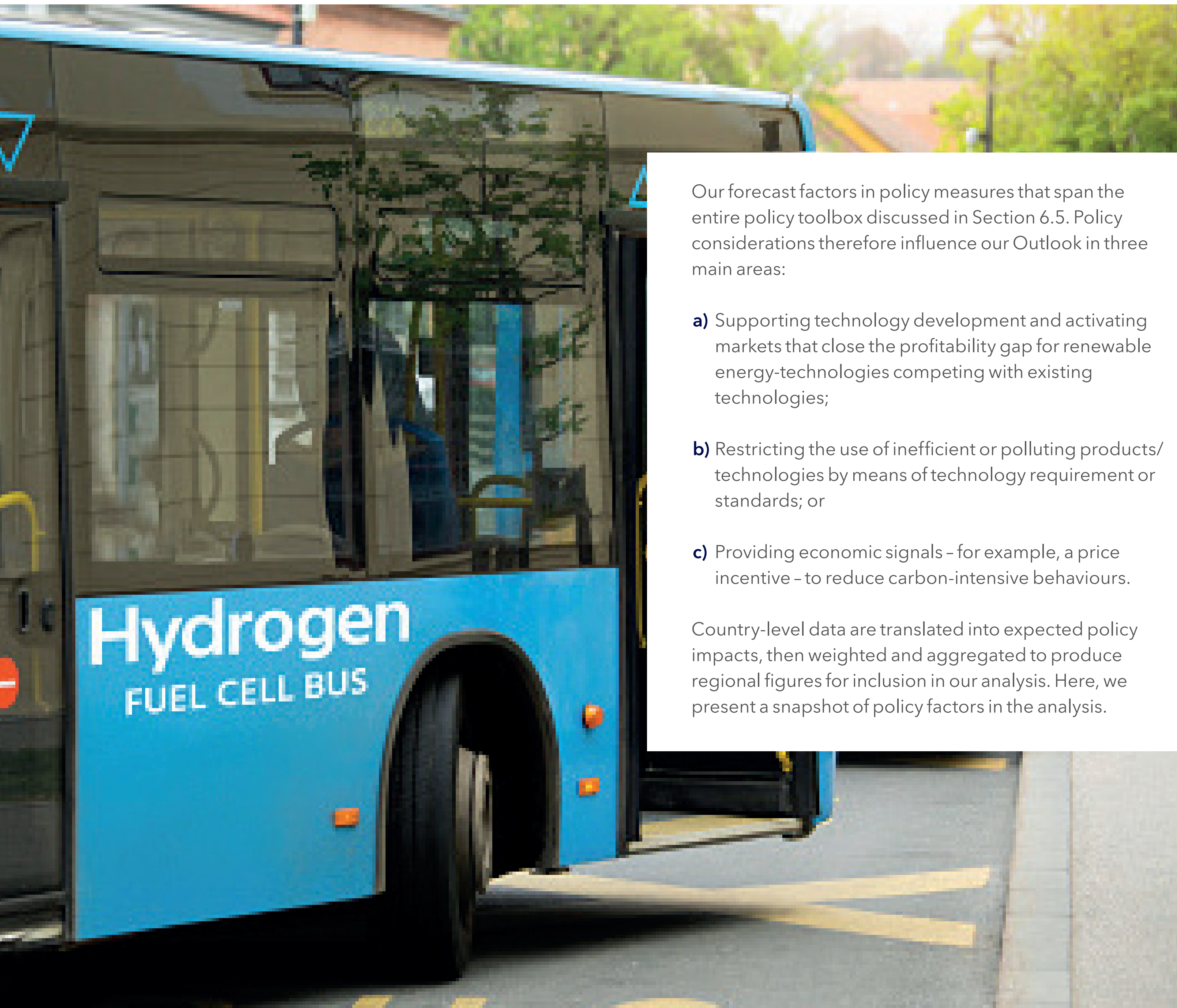
Bornholm Bunker Hub consortium is already investigating how local PtX energy can supply sustainable fuels for the ships passing the island every year (TradeWinds, 2021).

A central pillar in the Danish policy response is broad political agreement creating continuity and predictability for investors and companies. For the green transition to accelerate to achieve the 70% reduction target by 2030, business and technology development priorities, in fields of particular Danish expertise, provide the focus for publicly-funded research and cluster organizations, the latter to bridge companies and research institutions and receiving support from the Board of Business Development. Thanks to this focus, the energy island concept is no longer hypothetical. Denmark is leading the way with large scale, concrete action on sector coupling, showcasing PtX technologies for transition pathways globally.

Every year, the Danish government will present Climate Action Programmes with concrete political initiatives to decarbonize every sector.

Image courtesy Danish Energy Agency

6.7 POLICY FACTORS IN OUR OUTLOOK



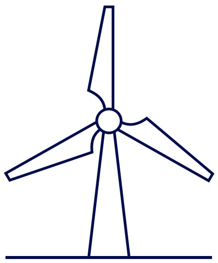
Our forecast factors in policy measures that span the entire policy toolbox discussed in Section 6.5. Policy considerations therefore influence our Outlook in three main areas:

a) Supporting technology development 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

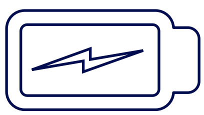
c) Providing economic signals – for example, a price incentive – to reduce carbon-intensive behaviours.

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.



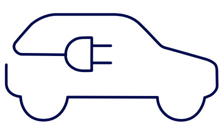
1. Renewable power support

– 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 capture 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.
– The subsidy stays at zero even if profitability of renewables become negative, as long as the profitability of conventional generation is lower.



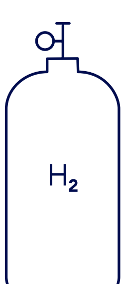
2. Energy-storage support (batteries)

– Existing and planned policy support is translated to an average support as a percentage of battery unit costs for battery-storage technologies.
– Support levels increase with the share of variable renewables in regional electricity generation, incentivizing investment in flexibility while reflecting regional differences in willingness/ability to implement support.



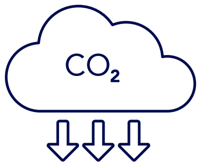
3. Zero-emission vehicle support

– 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 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.
– Higher depreciation through loss of value for fossil-fuel powered vehicles will increase operating costs for ICEs.



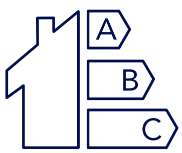
4. Hydrogen support

– Support for the build-up of hydrogen infrastructure and the supply-side in terms of hydrogen production 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 road vehicles, 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.
– For manufacturing and buildings sectors, a hydrogen price subsidy is included, which varies by region through the same hydrogen-policy factor used for road vehicles.



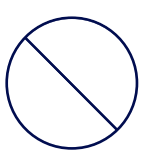
5. Carbon capture and storage support

- The historical CCS implementations, as reported by the Global CCS Institute (2020), are fully incorporated, as well as their future project pipeline of plants and storage to 2030. These projects receive investment and operational government support.
- Regional carbon prices determine the uptake of CCS in power, manufacturing, and industrial processing.
- Regional policy support for CCS, beyond the carbon price, is integrated based on the gap between regular CCS costs and carbon pricing to account for this gap and enable initial CCS uptake. Policy support is reduced when the gap between carbon price and CCS costs closes.
- CCS of hydrogen production is assumed to be fully supported as needed.



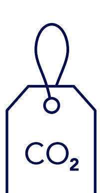
6. Standards for energy efficiency

- 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).



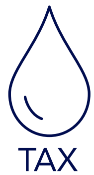
7. Bans and phase-out plans

- 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 are incorporated. For coal-fired power generation, our forecast references the phase-out plans. However, due to market economics and reduced cost-competitiveness, shutdowns might happen earlier than phase-out plans suggest.



8. Carbon-pricing schemes

- Our carbon-price trajectories to 2050 consider hybrid pricing (cap-and-trade schemes and carbon taxation).
- Our carbon-price trajectories (Figure 6.3) are reflected as costs for fossil fuels in the power, industrial processing and manufacturing sectors, as they generally participate in the same regional and/or sectoral carbon-pricing schemes.



9. Fuel-, energy- and carbon taxation

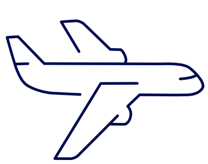
- Fossil fuels used in road transport are taxed at the consumer level, labelled as fuel or carbon taxes.
- Effective fossil-carbon rates per country are incorporated for road transport with Europe seeing the highest taxation, doubling the price of diesel and gasoline for consumers.
- We assume that these 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 is 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, taxes on unrecycled plastic, trade restrictions, and extended producer responsibilities, are incorporated in the form of future year-on-year increasing recycling rates.



12. Sustainable aviation fuels support

- We consider regional biofuel-blend mandates currently in place and we foresee further strengthening of these in frontrunner regions such as Europe and North America. Mandates will likely be enhanced in the future to include other sustainable aviation fuels (SAFs).
- Region-specific consumer push both from business and from individuals that are willing to pay for sustainable aviation, will enable gradual increased uptake of non-cost competitive aviation fuels such as hydrogen and SAFs.

Highlights

The energy transition unfolds differently in each of the 10 world regions included in our forecast. Its speed and scale are influenced by a number of factors, such as: geographical and resource issues; legacy technology- and energy systems; stages of economic development; and government policy.

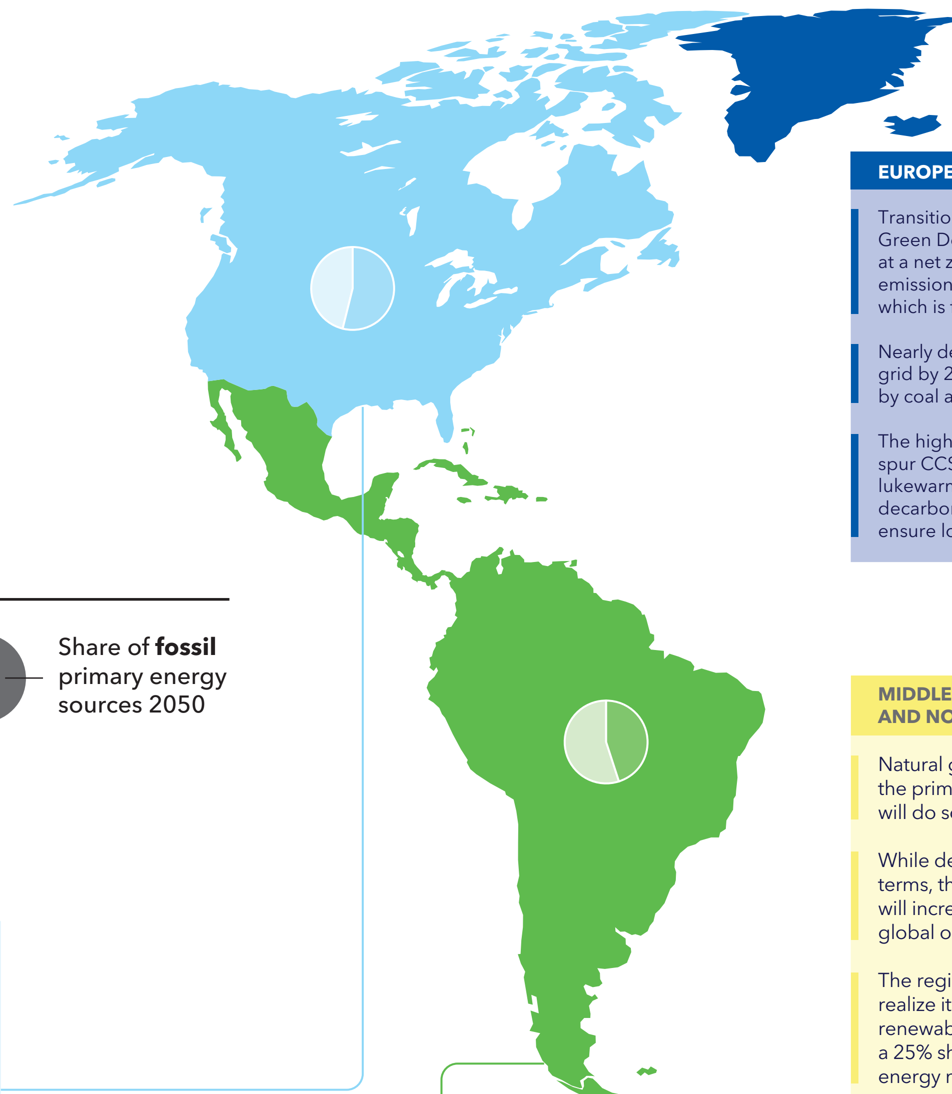
Thus, **every region has a unique starting point and a different transition trajectory** – from OECD countries targeting post-industrial prosperity, to emerging and fast-growing economies, to regions entering an era of development.

Our ETO model generates insights and captures this granularity, and, in the following sections, **the transition story for each of the 10 Outlook 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 highlighting a prominent feature of the regional transition

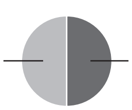
7 REGIONAL TRANSITIONS

WE ANALYSE 10 GLOBAL REGIONS



KEY

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



Share of **fossil** primary energy sources 2050

EUROPE

- Transition policies, European Green Deal and 'Fit for 55' aim at a net zero greenhouse gas emission economy by 2050, which is forecast not to be met
- Nearly decarbonized electricity grid by 2050; < 5% generation by coal and natural gas
- The high carbon price could spur CCS uptake, but lukewarm support and a decarbonized power system ensure low implementation

MIDDLE EAST AND NORTH AFRICA

- Natural gas and oil dominate the primary energy mix and will do so until 2050
- While declining in absolute terms, this region's cheap oil will increasingly dominate global oil production.
- The region will start to realize its vast potential for renewable energy, reaching a 25% share in primary energy mix in 2050

NORTH AMERICA

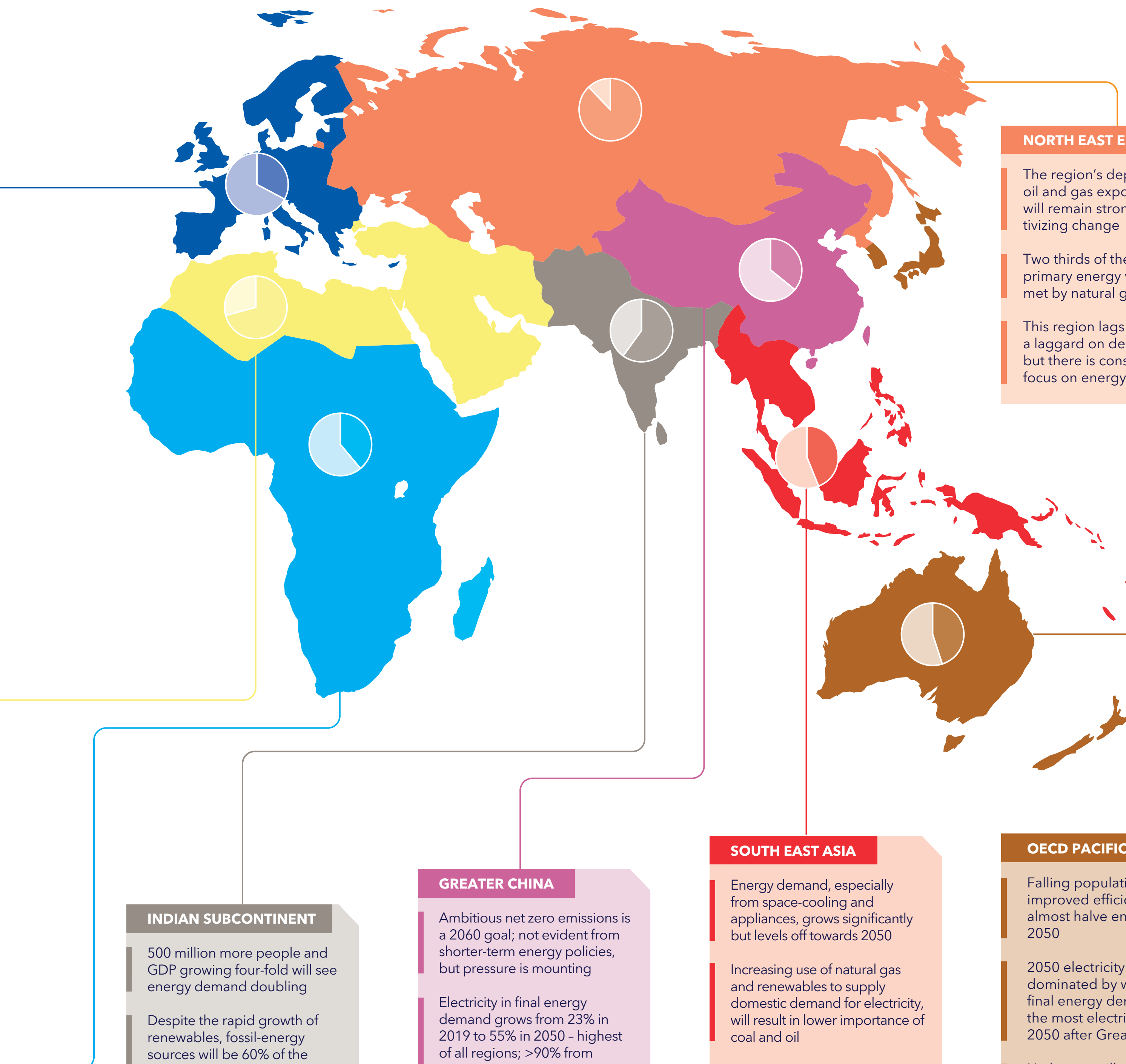
- Decarbonizing electricity by 2035, part of the 'Build Back Better' plan, is ambitious but unlikely to be met
- A massive buildout of grids is forecast to bring aboard renewables; 55% of generation in 2030 and 75% by 2050
- The switch to passenger EVs is slow but gaining momentum, and contributes to declining oil use

LATIN AMERICA

- Hydrogen from dedicated, low LCOE solar PV may change the region's energy landscape
- Power generation mix will switch from hydropower/ natural gas/fuel oil to hydropower/solar/wind
- Renewables > 50% of 2050 primary energy mix; bioenergy above 20%

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 replacement 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, disincentivizing change

Two thirds of the region's primary energy will still be met by natural gas in 2050

This region lags and remains a laggard on decarbonization, but there is considerable focus on energy efficiencies

INDIAN SUBCONTINENT

500 million more people and GDP growing four-fold will see energy demand doubling

Despite the rapid growth of renewables, fossil-energy sources will be 60% of the energy mix in 2050

Electricity's share in building energy demand will triple by 2050, enabling universal access to electricity

GREATER CHINA

Ambitious net zero emissions is a 2060 goal; not evident from shorter-term energy policies, but pressure is mounting

Electricity in final energy demand grows from 23% in 2019 to 55% in 2050 – highest of all regions; >90% from renewable sources

Peak coal already achieved. Share of coal in power mix (currently 60%) reduces to 5% over the forecast period

SOUTH EAST ASIA

Energy demand, especially from space-cooling and appliances, grows significantly but levels off towards 2050

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

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

OECD PACIFIC

Falling population and improved efficiencies will almost halve energy use by 2050

2050 electricity mix dominated by wind; at 45% of final energy demand, this is the most electrified region in 2050 after Greater China

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

7.1 NORTH AMERICA (NAM)

This region consists of Canada and the United States (US)

Characteristics and current position

The current US administration has prioritized tackling climate change at home and abroad and has also re-joined the Paris Agreement. It now targets an emissions-free power sector by 2035, a 50-52% reduction below 2005 levels by 2030 and reaching net zero emissions economy-wide by no later than 2050. Policy is focusing on setting renewable energy goals at federal and state levels and also holding companies and federal agencies to account. The private sector is making commitments to new EVs and renewable energy. Partisanship intensified in the wake of the 2020 US presidential election, creating uncertainty about the long-term stability of climate policy.

2020 was a record year for installation of wind and solar, adding 16.9 GW (ACP, 2020) and 19.2 GW (SEIA, 2021), respectively. Despite COVID-19 significantly reducing the demand for electricity and energy in 2020, wind, solar, and storage markets boomed. The renewables industry is bullish with motivated investors, corporates continuing to push towards green/ESG goals, and increasing activity on leading-edge clean tech.

Volatility/increases in commodity pricing that impact solar LCOE is one point of concern. Another is the fallout following severe winter weather in Texas, where projects with fixed shape hedge contracts or similar offtake structures lost tens or even hundreds of millions of dollars within a week.

Canada's Supreme Court confirmed the federal government's right to implement its economy-wide carbon pricing requirement, set to increase to CAD 50 by 2022. A 2030 target of 40-45% reduction in emissions (versus 2005) has been announced, up from the previous 30%. There is a commitment to reach net zero emissions by 2050, establishing a legally binding ambition mechanism with five-year milestones.

A just transition is high on NAM's policy agenda, to deal with the impacts of the energy transition on communities and workers. Canada and US cooperation on climate change is a key priority.

(NAM)

	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2019	366	298 109	61 600 22.6
2050	437	160 70	76 800 33.6

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

Pointers to the future ›››

- The Biden administration's ambitious agenda to 'Build Back Better' achieved a major victory in March 2021, passing the USD 1.9trn American Rescue Plan. The American Jobs Plan then proposed investing USD 2.25trn in infrastructure over ten years, significantly advance US climate goals. A compromise bipartisan infrastructure bill, investing a still-significant USD 1trn, passed in the Senate in mid-August. Original elements of the proposed plan are likely to feature in the budget reconciliation process later this year (see discussion overleaf). US/China trade and security policy will continue to insert uncertainty into renewable-energy supply chains.
- Public and private funding sources will be used to fill knowledge gaps surrounding the distribution and transmission of hydrogen/hydrogen-blended gas to utilities and consumers.
- An end-of-2020 tax extender pushed the US investment-tax credit qualification for offshore wind out considerably, with projects having until 2025 to start construction. The Biden administration is fast-tracking approvals for the first-mover Vineyard Wind project and backing other tangible moves advancing fixed and floating offshore wind on all coasts. We forecast 26.1 GW by 2030, falling short of the 30 GW target. The tax extender also pushed start-of-construction deadlines for onshore wind and solar technologies.
- Canada's climate plan, A Healthy Environment and A Healthy Economy (Government of Canada, 2020), outlines sector initiatives and increase in carbon pricing to CAD 170 (USD 140) by 2030. Whereas existing gas plants are protected, new natural gas facilities will be fully exposed to carbon pricing forcing a rethink of the role of gas.
- Canadian CCS leadership is expected, with major projects scoped to reduce CO_2 emissions by a total of 6.4 million tonnes per year by 2030. The Budget 2021 supports technology development and investment tax credits effective from 2022. The proposed Clean Fuel Regulations will require liquid fossil-fuel primary suppliers to reduce the carbon intensity of liquid fossil fuels, produced in, or imported into Canada.

Building Back Better: The American Jobs Plan

The Biden administration is pursuing a three-part agenda to rescue, recover, and rebuild the country: The American Rescue Plan, The American Jobs Plan, and The American Families Plan.

The American Jobs Plan (White House, 2021a) details efforts to strengthen digital and physical infrastructures and restore competitiveness and jobs through investments in roads, bridges, water systems, and the electric grid, citing that the US ranks 13th on the overall quality of infrastructure after decades of underinvestment. The plan also addresses long-standing injustices by targeting a 40% share of investments to disadvantaged communities, such as rural populations and those impacted by the market-based transition to clean energy.

The plan will escalate modernization and clean energy in transportation, power, and buildings. It aims to tackle climate change, spur domestic innovation, reduce reliance on foreign manufacturing, and create American jobs in manufacturing and innovation. Focus areas and ambitions include:

– Investing in smart infrastructure to withstand impacts of climate change, including grids, road, rail, and water infrastructure upgrades, and building a national EV-charging infrastructure (500,000 chargers by 2030).
– Promoting jobs, domestic supply chains, and American-made EVs, including uptake through consumer point-of-sale incentives, and an announced target for EVs to make up half of new vehicle sales by 2030.
– Investing in climate R&D priorities for breakthroughs in clean-energy technologies, including USD 2.5bn a year through 2026 for CCUS developments, and with funding to hydrogen fuel research and clean hydrogen commercialization hubs.
– Advancing clean-power generation and storage uptake by extending investment and production tax credits, and by retrofitting buildings to meet the highest standards for energy efficiency.
– Using federal purchasing power – spending USD 500bn every year – to ensure that all US-government buildings and facilities are more efficient and climate-ready, e.g., to drive towards 100% clean-energy purchasing and zero emissions vehicles.

After months of bipartisan negotiation, the US Senate finally passed a USD 1trn infrastructure bill on 10 August, of which USD 550bn is in effect new federal spending. This is a considerable scale-back from the USD 2.25trn plan first proposed by President Biden in March. The exclusion of R&D support, clean energy tax credits and much of the support for EVs is a negative outcome from a transition and climate perspective. It remains to be seen how much of the original plan the Democrats are able to reintroduce through the budget reconciliation process later this year.

Drawing inspiration from the US domestic plan, the G7 partners launched the Build Back Better World (B3W) initiative (June 2021) to narrow the infrastructure development gap in developing regions and to mobilize private capital for climate action, among other areas. Investments are intended to be consistent with achieving Paris Agreement goals (White House, 2021b).

The outcomes, in terms of enforceable regulations and investments, of both the domestic American Jobs Plan and the B3W partnership initiative, remain to be seen. They will be monitored and reflected in future editions of the DNV forecast.

7.1 NORTH AMERICA

Energy Transition

North America's final energy demand (Figure 7.1.1) has been flat for two decades already and will decline in the coming years. The transport sector's lower energy demand is the main reason for this development. Electrification of the road-vehicle fleet will contribute to transport energy consumption being cut by 60%, and in itself will be responsible for the entire fall in the region's energy demand to 70% of the current level. Despite increased energy efficiencies, a North American industrial revival will counteract these effects. With an over 50% lift in manufactured goods, energy demand from manufacturing will increase slightly towards 2050. Energy demand in buildings will decline slightly over the forecast period, with counteracting forces of an increase in residential space by 25% and commercial by 40% and improved energy efficiency afforded in particular by electrification and heat pumps.

The share of electricity in final energy demand will continue to rise, growing from 20% in 2019 to over 40% 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, contributing 27% and 29% to the power mix, respectively.

Electrification of transport will be the strongest driver of the reduction in oil consumption over the forecast period. Natural gas overtook oil as the region's largest primary energy source in 2018 (Figure 7.1.2), and will consolidate that position over the coming decades with a share of 30% in 2050. Coal will continue its rapid decline, already outcompeted in the power sector by cheap natural gas and increasingly by variable renewables. As electricity use expands and renewables become cheaper, wind and solar will see their energy supply grow, ten-fold and sixteen-fold, respectively, to 2050. By then, onshore and offshore wind will generate more electricity than natural gas.

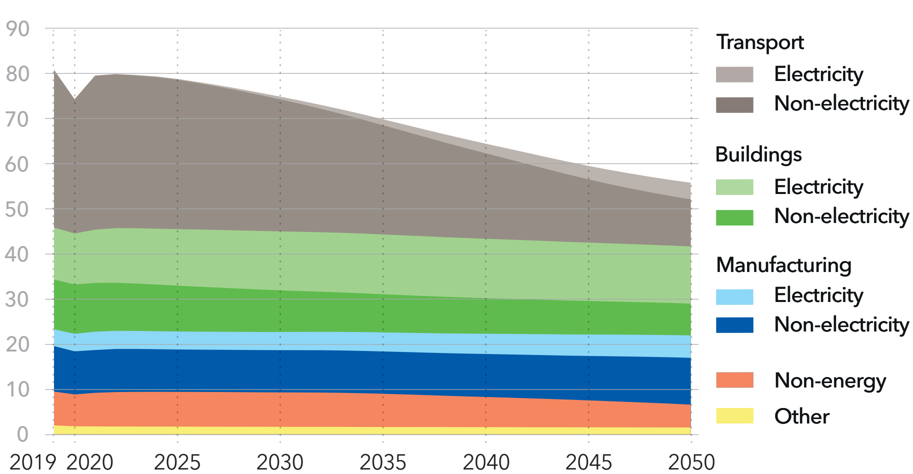
Energy Transition Indicators

Figure 7.1.3 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 7.11.

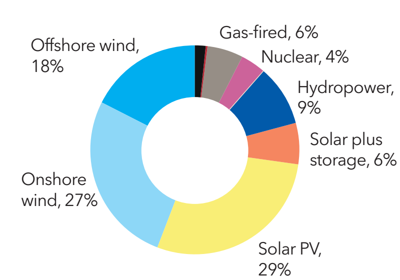
FIGURE 7.1.1

North America final energy demand by sector

Units: EJ/yr



2050 electricity mix

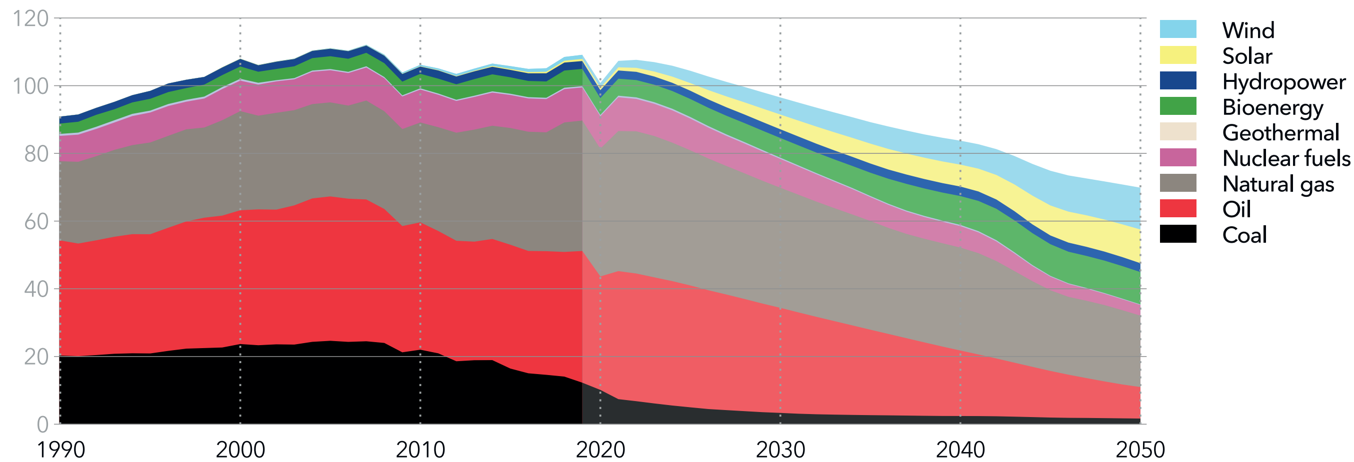


– The share of electricity in the final energy demand mix will double between 2019 and 2050, reaching over 40%, which is similar to developments in Europe and the OECD Pacific.
– There is a significant improvement in energy intensity in North America, more than halving the primary energy consumption per unit of GDP over the forecast period compared with 2019 values. The 2050 value of 2 MJ/USD is around average for this indicator.
– Carbon intensity, measured as tonnes of carbon dioxide per terajoule of primary energy consumption, will decline by more than 55%, becoming the second-lowest value of all regions, after Europe.

FIGURE 7.1.2

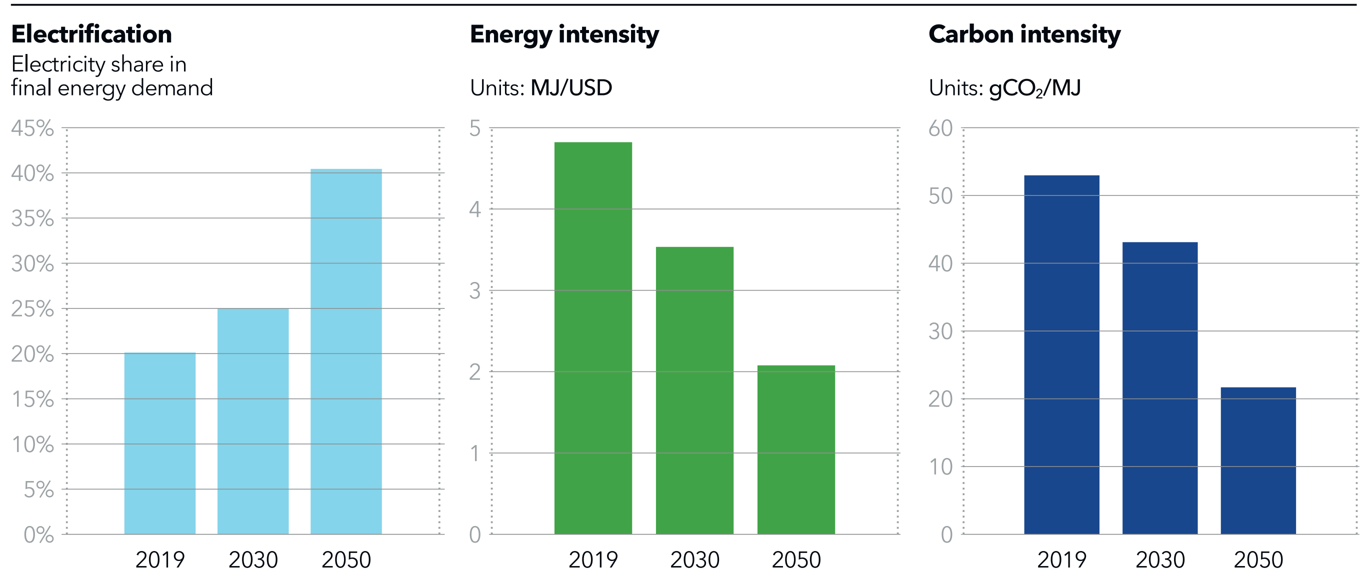
North America primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.1.3



Emissions

We project a quintupling of the average carbon-price level to USD 50/t CO_2 by 2050. Pricing will be dominated by developments in US cap-and-trade schemes. Other factors include possible system linkages to Latin America, and the Pan-Canadian approach of setting an economy-wide carbon price.

Energy-related CO_2 emissions from North America peaked just under 15 years ago. They will continue declining, falling to a level in 2050 of about 73% lower than today (Figure 7.1.4). Transport emissions will decline over three quarters, due to the rapid uptake of EVs in the coming decades.

Emissions from coal continue their decline and will be around 10% of overall emissions in about 5 years' time. With its declining share of the energy mix, emissions from natural gas will surpass those of oil in 2036. CCS uptake rises to 315 $MtCO_2$ in 2050, reflecting a capture rate reaching 66% in natural gas processing and 56% in non-combustion industrial processes. Manufacturing energy use captures less by 34%, and the power sector sees only 1% of its emissions captured. By 2050, renewables will have overtaken such a large share of energy generation that carbon capture in that sector will not be performed at scale.

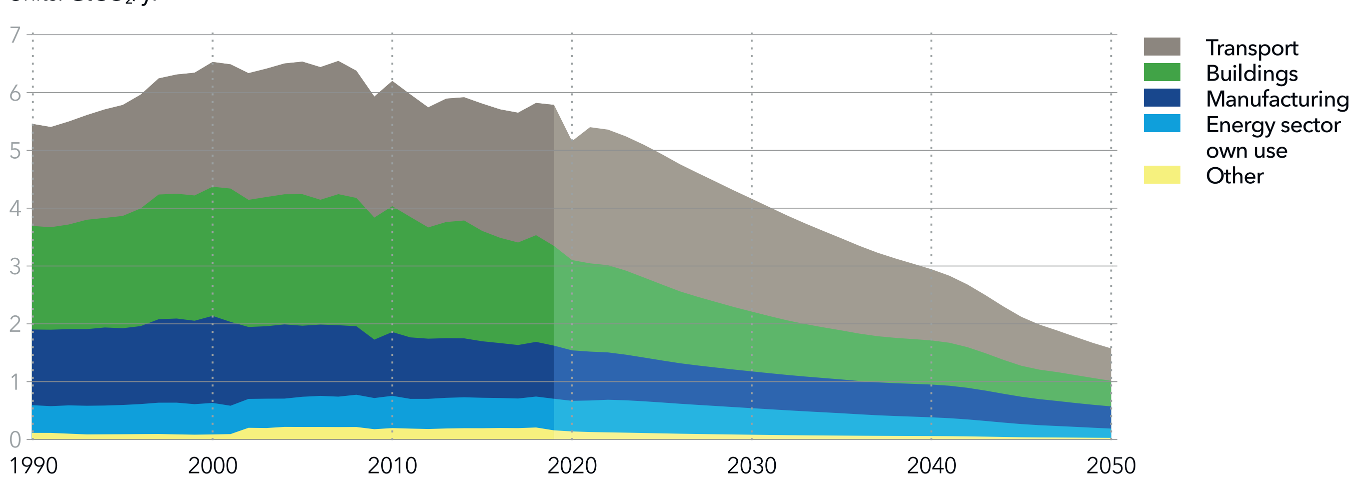
Nationally Determined Contributions (NDCs) under the Paris Agreement indicate that North America – viewed as a region – is targeting reductions in energy-related emissions of 37.5% by 2030. Note that we calculate the NAM target compared to 1990 in order to have a common reference point for all regions. The average target is lower than stated NDC pledges as 1990 emission levels were lower than in 2005. We estimate emissions to fall by about 24% by 2030 compared to 1990, meaning the region target will not be easily achieved. By 2050, our estimates indicate that the region will have reduced its energy-related emissions by 73% compared with 2019, with a remaining 1.58 $GtCO_2$/yr in 2050 in contrast to the region's net-zero pledge.

North America's emission level of 3.9 tCO_2/person in 2050 will be around one quarter of the present level, but will still be the second highest of all the regions, behind North East Eurasia.

FIGURE 7.1.4

North America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Carbon-free electricity

With the 'Build Back Better' Plan (see box on p168), President Biden aims to revamp the ailing energy and power infrastructure of the US. One of the key goals of this plan is for the US to have carbon-free electricity by 2035.

It is not possible to isolate the US in our model. Nevertheless, since Canada already had 80% carbon-free electricity in 2019, analyzing the 2035 forecast for the NAM region will not distort our conclusions, but might rather improve them.

Carbon-free electricity by 2035 is an ambitious goal, and our Outlook forecasts that it will not be achieved. Almost 24% of generation will remain from coal (3.9%) and natural gas (19.1%) in the North American electricity grid in 2035 and this derails the ambition of obtaining carbon-free electricity. Although a minor share of the CO_2 emissions will be captured, approximately 7 $MtCO_2$, this is only 0.9% of the total emissions from the power sector and cannot possibly compensate for the use of coal and natural gas. The CO_2 emissions from electricity generation will be 720 $MtCO_2$ (Figure 7.1.5).

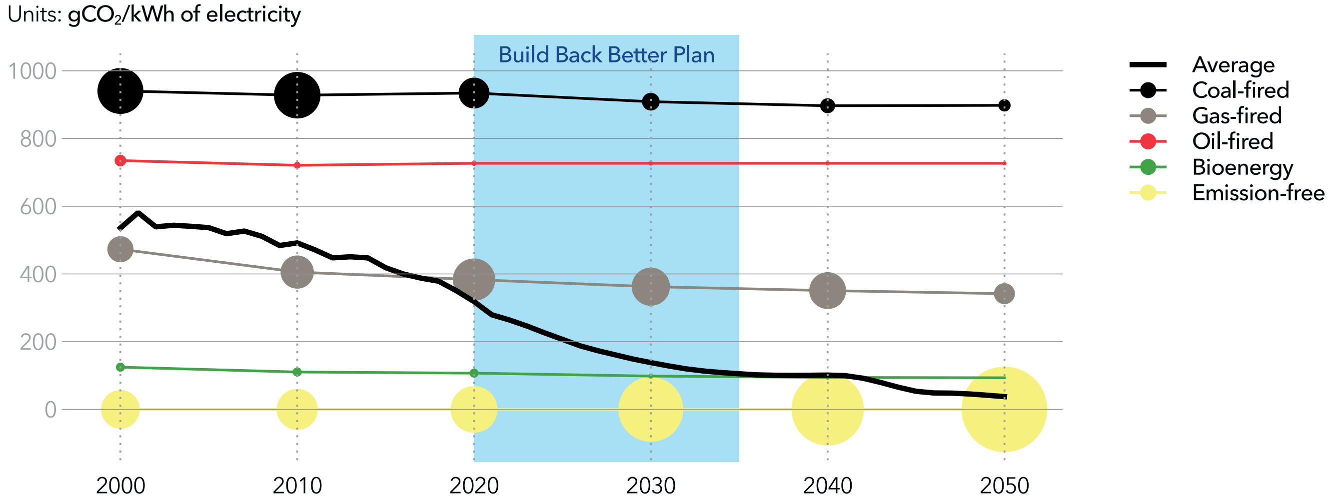
According to our forecast, the North American region will generate more electricity with less and less emissions, leading to the emission intensity of electricity more than halving in 2035 (Figure 7.1.5); nevertheless, clearly it still does not achieve the target.

Our Outlook also forecasts a continuing reduction of emissions from electricity generation in the region after 2035. By 2050, coal and natural gas will account for less than 8% of the generation in North America, and the emissions from electricity generation will be one-sixth of those in 2020. Almost no new power capacity additions from coal and natural gas will occur after 2027. The region will invest heavily in solar PV and wind power technologies, enabling integration of renewables with high grid additions and reinforcements, as discussed in the "Massive Build-out of Grids" Section below.

FIGURE 7.1.5

CO_2 emission intensity of electricity generation in North America

Units: gCO_2/kWh of electricity



Bubble sizes show annual electricity generation. Historical data source: IEA WEB (2020)

Massive build-out of grids

From 2020 to 2050, the North American region will see a massive build-out of grids, in tandem with investments in renewables (Figures 7.1.6 and 7.1.7). This forecast grid build-out is remarkable, particularly if we acknowledge that North America is already a region with universal access to electricity, unlike other regions such as the Indian Subcontinent or Sub-Saharan Africa.

Despite this, the power sector will be restructured in North America, with increased electrification in various sectors, including transport charging infrastructure, electrification in buildings and industry, and a ramp up of hydrogen production via electrolysis. Furthermore, the electricity mix will change with massive installations of solar PV and wind, both of which will require additional connectivity due to variability. All the new solar PV and wind power plants will need connections to the power grid, along with strengthened and reinforced transmission and distribution to reach even the most remote places in the region. In the period from 2020 to 2030, 455 GW of solar and 307 GW of wind will be added to North American power production.

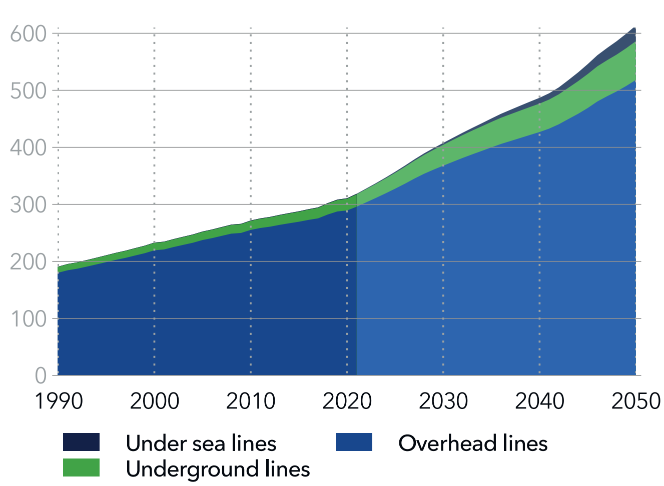
Our Outlook forecasts a 75% increase in overhead grids from 2020 to 2050 and a 250% increase in underground grids. A remarkable 2500% increase in undersea grids, albeit from very low levels, is also foreseen, mainly to connect offshore wind (Figure 7.1.6). Similarly, all categories of voltage levels will also see grid-capacity additions, with ultra-high voltages experiencing a tripling of grid capacity from 2020 to 2050, while low and medium voltages will double grid capacity during the same period (Figure 7.1.7).

As part of President Biden's "Build Back Better" plan, Targeted Investment Tax credits are proposed for high-voltage capacity grids. These tax credits will be given to any entity with high-voltage capacity grids on their property. This too will contribute towards the massive build-out of grids in the NAM region.

FIGURE 7.1.6

North America power line capacity by grid type

Units: TW-km

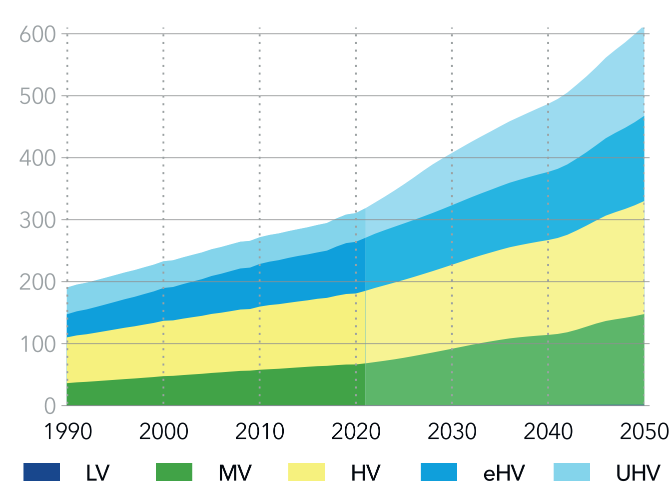


Historical data source: GlobalData (2021)

FIGURE 7.1.7

North America power line capacity by voltage level

Units: TW-km



Historical data source: GlobalData (2021)

Electrification of the passenger vehicle fleet

The North American region will experience a sea change in its passenger-vehicle fleet in the next 30 years. We forecast battery electric vehicle (BEV) sales to overtake internal combustion engine (ICE) sales by 2032, even as sales of passenger vehicles will slowly decline from 2020 (Figure 7.1.8), and the overall number of vehicles will plateau in 2024. This transition will require a massive build-out of charging infrastructure, and this will be aided by the enormous amounts of solar and wind power coming onto the grid, as detailed above.

The North American region has the highest road density of vehicles in the world at 0.78 vehicle/person in 2019. Additionally, it has the highest distance-range requirement for road vehicles, leading to the need for more and larger batteries. This is reflected in our ETO model as well, where the distance range of BEVs in the region is approximately 42% higher than that of the rest of the world. This, in turn, translates to North America having the highest battery-pack cost compared with all the other regions in our ETO. Nevertheless, innovation from US car manufacturers, not least Tesla, is expected to spur market growth.

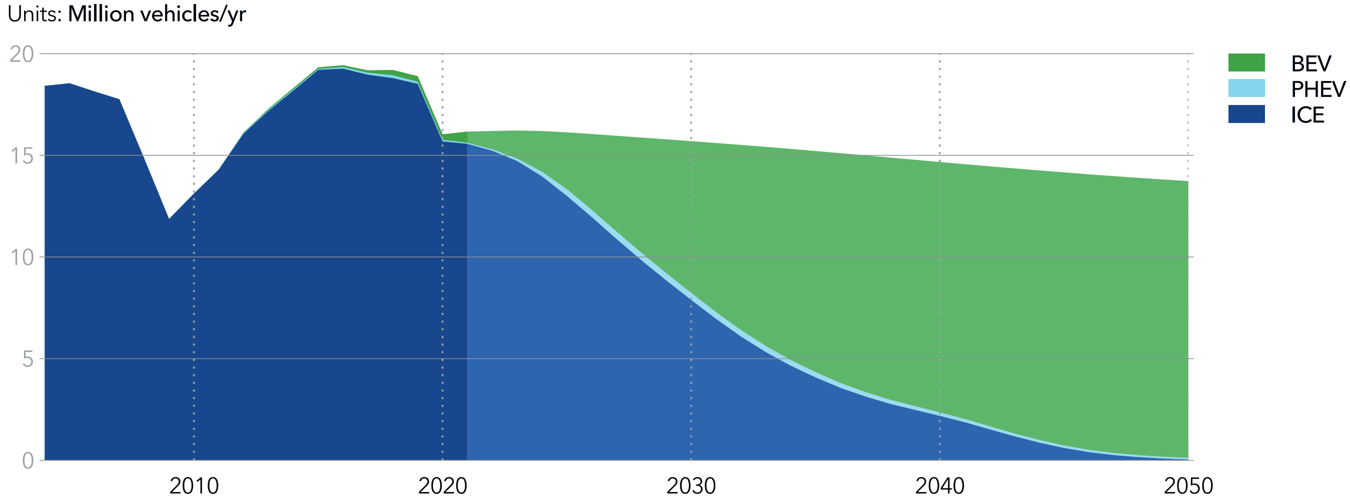
Given the local air pollution and the climate benefits of electric transportation, the US administration is urging US car manufacturers to 'go electric' by trying to reintroduce emission requirements for vehicles. Although law-making in the US is a heavily politicized process, such a positive attitude towards BEVs indicates a reason for cautious optimism.

Although oil demand in the North American road transport sector recovers to pre-pandemic levels in 2021 in our Outlook, from thereon there is a sharp decline, with the oil demand for road transport reducing to a seventh by 2050. The transition to EVs will need to occur simultaneously with mitigations against the ramifications associated with the economic effects and job losses among ordinary people due to the decline of the oil industry. If not, the push towards electrification may become an unpopular, polarizing issue.

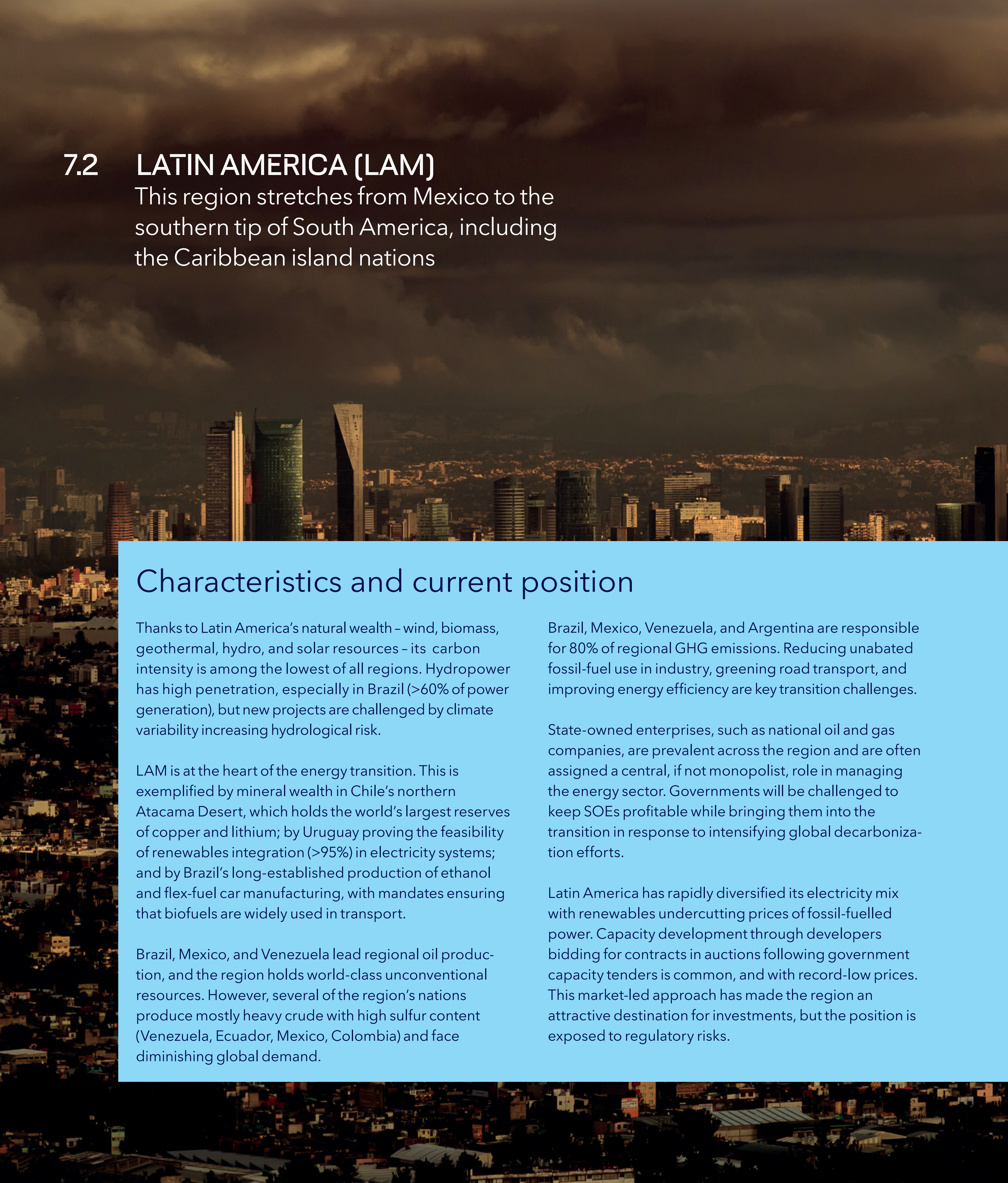
FIGURE 7.1.8

North America passenger vehicle sales

Units: Million vehicles/yr



Historical data source: Marklines (2021), IEA EV Outlook (2021)



7.2 LATIN AMERICA (LAM)

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

Characteristics and current position

Thanks to Latin America's natural wealth – wind, biomass, geothermal, hydro, and solar resources – its carbon intensity is among the lowest of all regions. Hydropower has high penetration, especially in Brazil (>60% of power generation), but new projects are challenged by climate variability increasing hydrological risk.

LAM is at the heart of the energy transition. This is exemplified by mineral wealth in Chile's northern Atacama Desert, which holds the world's largest reserves of copper and lithium; by Uruguay proving the feasibility of renewables integration (>95%) in electricity systems; and by Brazil's long-established production of ethanol and flex-fuel car manufacturing, with mandates ensuring that biofuels are widely used in transport.

Brazil, Mexico, and Venezuela lead regional oil production, and the region holds world-class unconventional resources. However, several of the region's nations produce mostly heavy crude with high sulfur content (Venezuela, Ecuador, Mexico, Colombia) and face diminishing global demand.

Brazil, Mexico, Venezuela, and Argentina are responsible for 80% of regional GHG emissions. Reducing unabated fossil-fuel use in industry, greening road transport, and improving energy efficiency are key transition challenges.

State-owned enterprises, such as national oil and gas companies, are prevalent across the region and are often assigned a central, if not monopolist, role in managing the energy sector. Governments will be challenged to keep SOEs profitable while bringing them into the transition in response to intensifying global decarbonization efforts.

Latin America has rapidly diversified its electricity mix with renewables undercutting prices of fossil-fuelled power. Capacity development through developers bidding for contracts in auctions following government capacity tenders is common, and with record-low prices. This market-led approach has made the region an attractive destination for investments, but the position is exposed to regulatory risks.

(LAM)	**Population** (M)	**Energy use/person** (GJ) **Energy use** (EJ)	**GDP/person** (USD) **GDP*** (USD TRN)
2019	657	55 36	16 100 10.7
2050	763	59 45	29 700 22.7

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

Pointers to the future

- Argentina targets 20% of power from non-hydro renewables in 2025 (up from 9% in 2020) and 35% in 2030, with a dominant role for onshore wind. Natural gas is seen as a transition fuel; plans to develop the Vaca Muerta shale formation were unveiled in 2020. (NGI, 2020).
- Brazil aims to maintain hydropower and boost solar and offshore wind output. Yet it wants oil and gas production to almost double by 2030. Land-intensive production of liquid biofuels challenges the forest-fuel-food balance. Incipient, but lacking a regulatory framework, hydrogen is set to become part of the Brazilian energy strategy (National Energy Plan 2050, December 2020).
- Chile aims for a 70% renewable power mix by 2030, and carbon neutrality by 2050. The Chilean Green Hydrogen Strategy (2020) sets high ambitions: 5 GW of electrolysis capacity under development by 2025 and global leadership (25 GW) by 2030. Mining, Chile's largest industry, sees decarbonization potential through green hydrogen.
- Colombia's updated NDC targets a further 51% reduction in emissions for 2030 and carbon neutrality by 2050. Tackling deforestation and fast-tracking EV uptake will be key focus areas (CHN, 2021; ICCT, 2020). Promotion of renewables through public tenders is expected to continue (first auction in 2019), along with infrastructure development such as the La Guarija HVDC corridor for wind generation.
- Mexico fast-tracked legislation in 2020 to assert public sector responsibility for energy and halt private investments in renewables. It will favour state-owned fossil-fuel generation over renewable-energy plants. Boosting demand for PEMEX heavy-fuel oil through combustion in CFE-owned power plants will contribute a rise in post-pandemic GHG emissions.
- In Venezuela, despite abundant renewable and non-renewable energy-resource potential, turbulent political developments will continue to impede security of supply, hinder domestic energy developments and discourage private investors.

7.2 LATIN AMERICA

Energy Transition

Latin America's final energy demand reflects little improvement in standards of living in the last decade. It is only after 2025 that GDP growth and standards of living are expected to rise, and energy services, like passenger cars, will increase commensurately (Figure 7.2.1). Transport energy demand will reflect both population growth and a higher income per capita, with a greater use of vehicles; however, increasing electrification will counteract growth in vehicles, so energy use will only lift marginally. Energy demand from manufacturing will grow modestly (37% by 2050), also due to efficiency gains. Increasing living standards from a growing population will see heating and cooling services spreading to new segments resulting in a full 67% increase in the buildings sector energy use.

The share of electricity in final energy demand will continue to increase, almost doubling from 17% in 2019 to 34% in 2050, observable in all final demand sectors. By 2050, hydropower will have lost its present status as the largest source of electricity, with a 20% share by mid-century, surpassed by both wind and solar with 32% and 38% respectively. At the end of our forecast period, fossil-fuel-based electricity production in the region will have reduced to 7%.

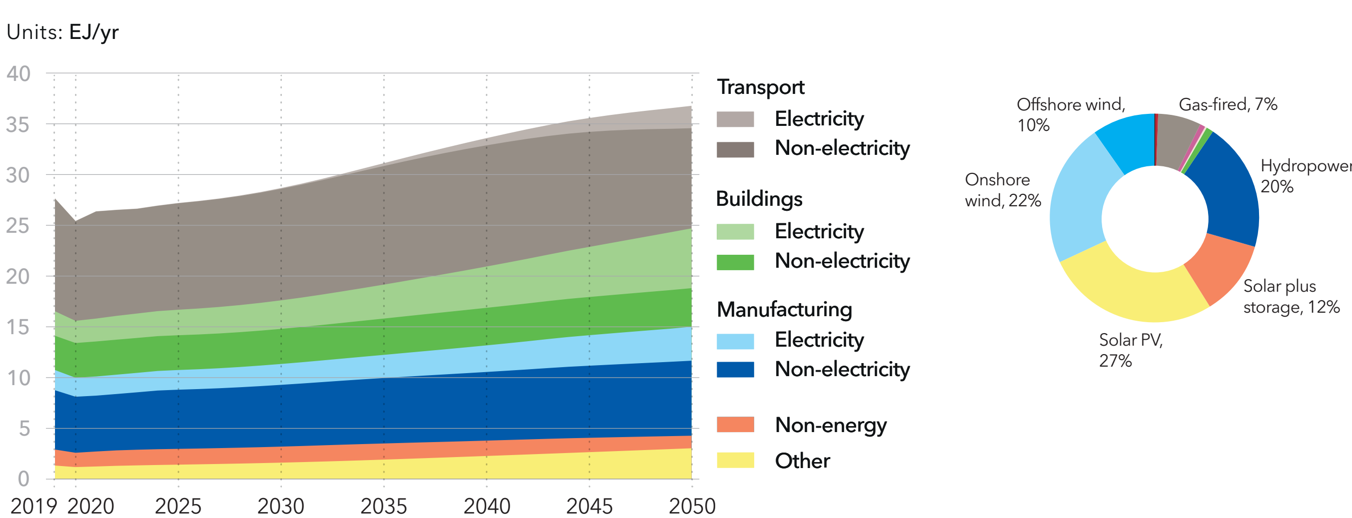
Figure 7.2.2 illustrates that oil, the region's largest energy source, will decline by a quarter, as EVs increase their fleet share and, by 2050, are more plentiful than ICEs. Growth in natural gas use will stall soon, and will not overtake oil as the largest primary energy source within the forecast period. Coal and nuclear fuels will remain insignificant energy sources in the region. Renewables, led by biomass and hydropower, and supported by strong solar PV and wind growth, will supply 53% of primary energy by 2050.

Energy Transition Indicators

Figure 7.2.3 presents Latin America's developments on three main energy-transition indicators: electrification, energy-intensity improvements, and decarbonization (definitions and regional comparisons are given in section 7.11).

FIGURE 7.2.1

Latin America final energy demand by sector **2050 electricity mix**

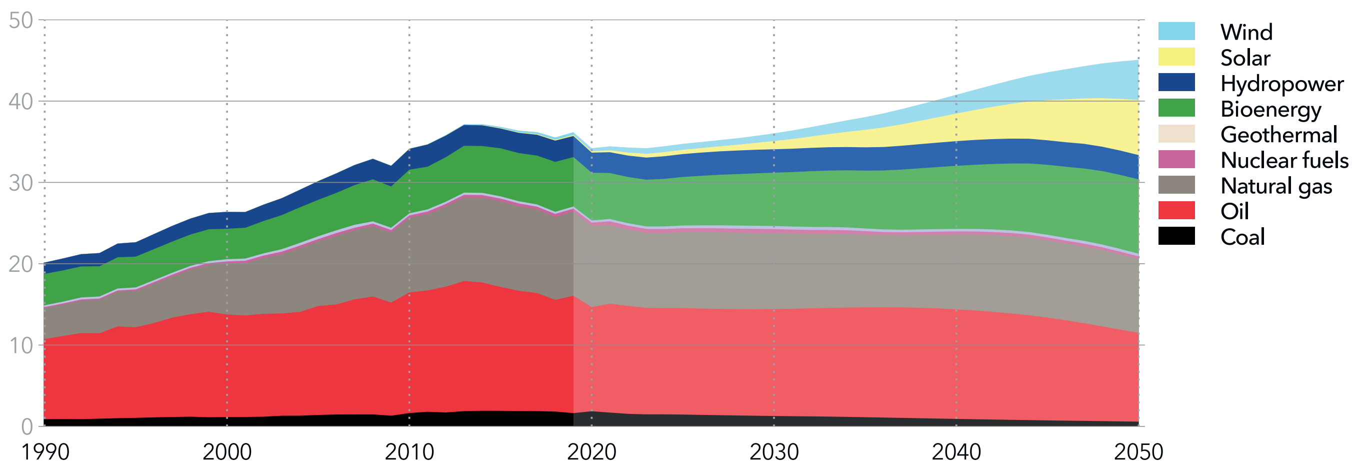


- The region's share of electricity in final energy demand will increase to 34% by 2050, which is only around 6% lower than in Europe and North America.
- Reflecting energy-efficiency gains, Latin America will reduce its energy intensity to about 2 MJ/USD in 2050.
- The region's carbon intensity will decrease by 40% between 2019 and 2050, reaching a 2050 value of 30 tCO_2/TJ, slightly below average for this regional indicator.

FIGURE 7.2.2

Latin America primary energy consumption by source

Units: EJ/yr

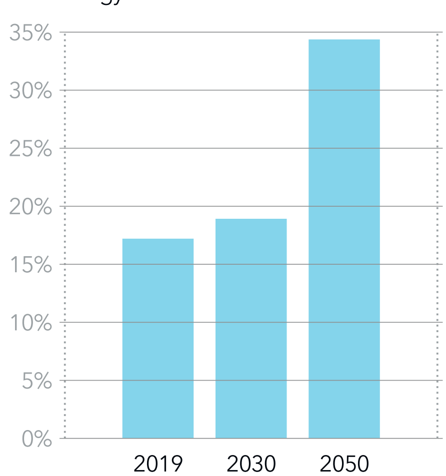


Historical data source: IEA WEB (2020)

FIGURE 7.2.3

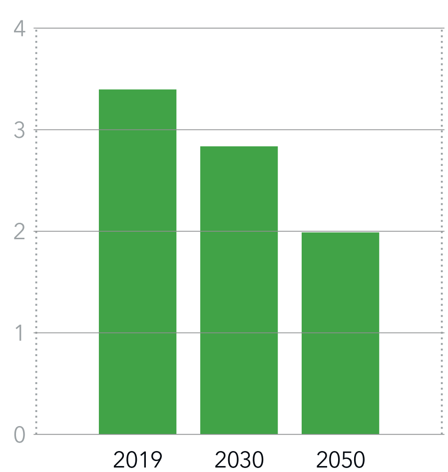
Electrification

Electricity share in final energy demand



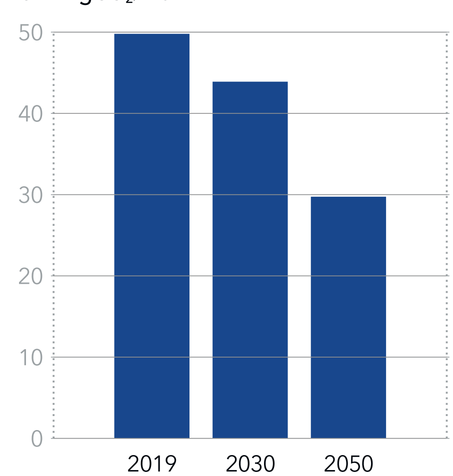
Energy intensity

Units: MJ/USD



Carbon intensity

Units: gCO_2/MJ



Emissions

The region's average carbon-price level is projected to increase almost tenfold, reaching USD 40/t CO_2 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 adjustment mechanisms from large trading partners, e.g., China and Europe, both of which have carbon pricing in place.

Latin America's energy-related CO_2 emissions peaked around 2015. They will decline further through the 2020s, stabilize in the 2030s, then fall to 25% less than today in 2050 (Figure 7.2.4). The decline will occur in all main demand sectors, driven by efficiency gains, a changing energy mix, and to a smaller extent by carbon capture.

Today and in the future, oil contributes most to emissions. In 2050, CCS will reduce CO_2 emissions by 51 Mt, equivalent to around 3% of the region's emissions at that time.

Country NDC pledges indicate an increase in the regional target of limiting emissions to about 91% by 2030, relative to 1990. Our Outlook indicates energy-related emissions rising 68% over the same 40-year period. This suggests that the regional target will be achieved by a good margin, indicating 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. By 2050, the region is expected to reduce energy-related emissions by 25% compared with 2019, with a remaining 1.35 $GtCO_2$/yr in emissions.

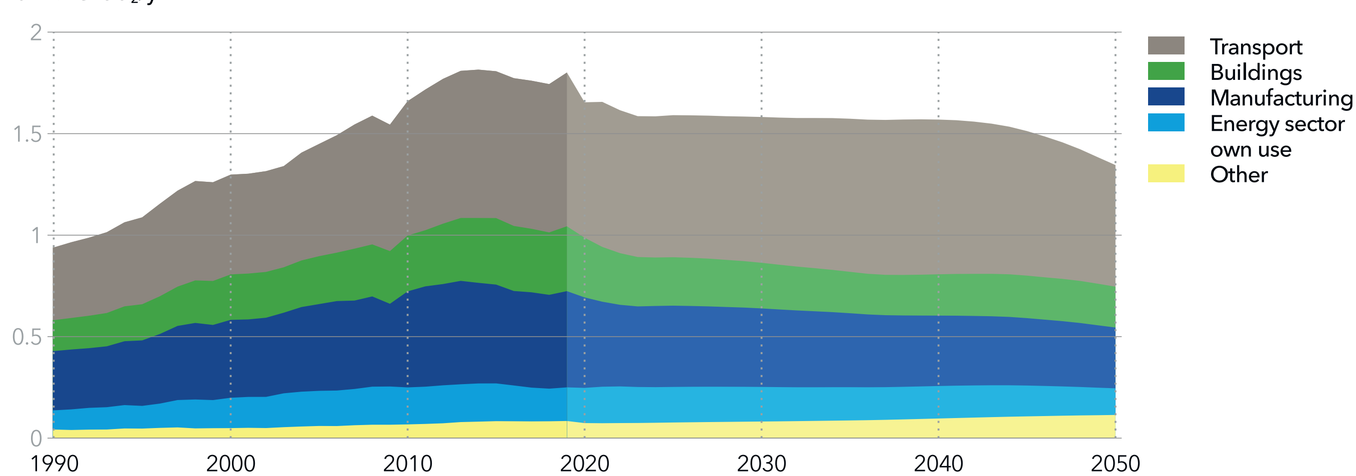
Also note that some Latin American countries, including Brazil, Argentina, Colombia, and Chile, have indicated – or have already adopted – carbon-neutrality targets by 2050 or 2060. However, these targets often take into account the land and forestry sector which means CO_2 uptake from rainforest areas are included.

Latin America's 1.9 tCO_2/person emissions level in 2050 is comparable to those in India and South East Asia, and is 33% lower than the region's current level.

FIGURE 7.2.4

Latin America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Solar-powered green hydrogen?

Latin America will see a rapid growth in renewables, especially in solar power technologies. While in 2019, 56% of electricity generation was through renewables (including 46% by hydropower generation), 42% was through fossil fuels, with a major share from natural gas fired thermal plants. Solar power provided less than 2% of electricity generation. We forecast that solar power will grow significantly in the coming decades and will provide almost 15% of power generation in 2030, then growing further to provide almost 40% of power generation by 2050 (Figure 7.2.5). Given the near-perfect conditions for solar power in the Atacama and Chihuahua deserts in Latin America, countries such as Chile, Argentina, and Brazil are betting on solar power to achieve decarbonization in energy and other sectors.

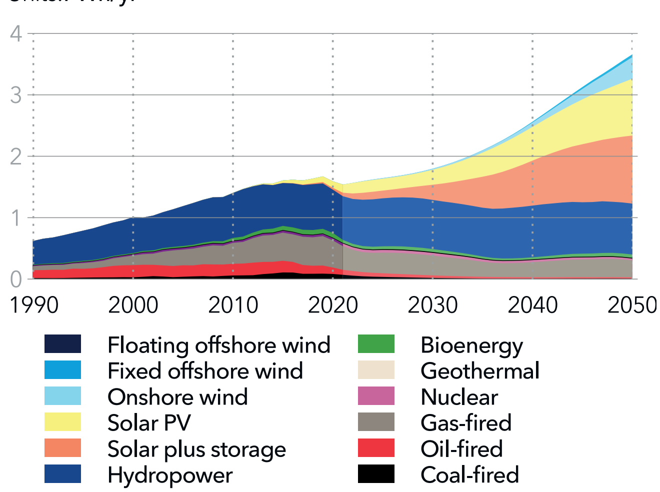
More compellingly, we also predict that solar powered green hydrogen will play a vital role in the region. From the late 2020s, hydrogen produced by electrolysis with dedicated renewables will start dominating hydrogen production. In 2040, almost 31% of the total hydrogen produced will be green hydrogen, and by 2050 this will increase to 46%. Our model also shows that the Latin America region has the lowest levelized cost for solar powered hydrogen production (Figure 7.2.6), thanks to high capacity factors, reaching, on average, 29% in 2050. In fact, LAM's solar-based hydrogen is cheaper than most of its competitors, such as wind-based hydrogen, in almost all regions. Such low levelized costs of hydrogen production through renewable electrolysis could have far-reaching implications, with use of hydrogen for decarbonizing hard-to-abate sectors globally.

Our model does not consider inter-regional hydrogen trade. Thus, we cannot reach a conclusion about the viability of Latin America producing hydrogen through green electrolysis to supply the rest of the world. However, given the low levelized cost of production of hydrogen and the vast potential for solar power exploitation, Latin America might become a major hydrogen exporter if large volumes could reduce storage and transportation costs to those of local production in regions with high demand.

FIGURE 7.2.5

Latin America electricity generation by power station type

Units: PWh/yr

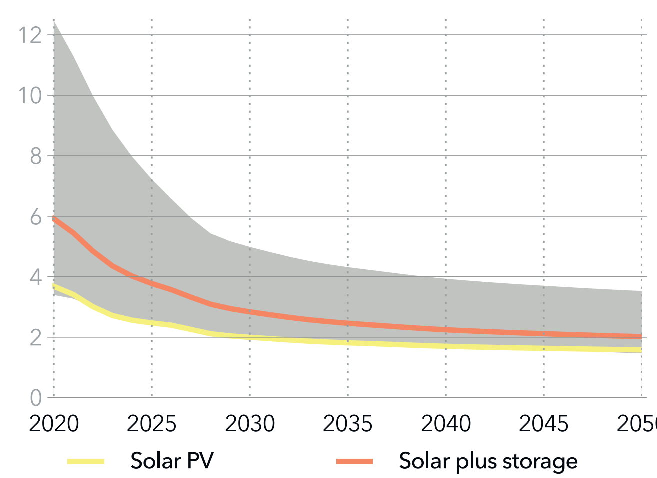


Historical data source: IEA WEB (2020), GlobalData (2021)

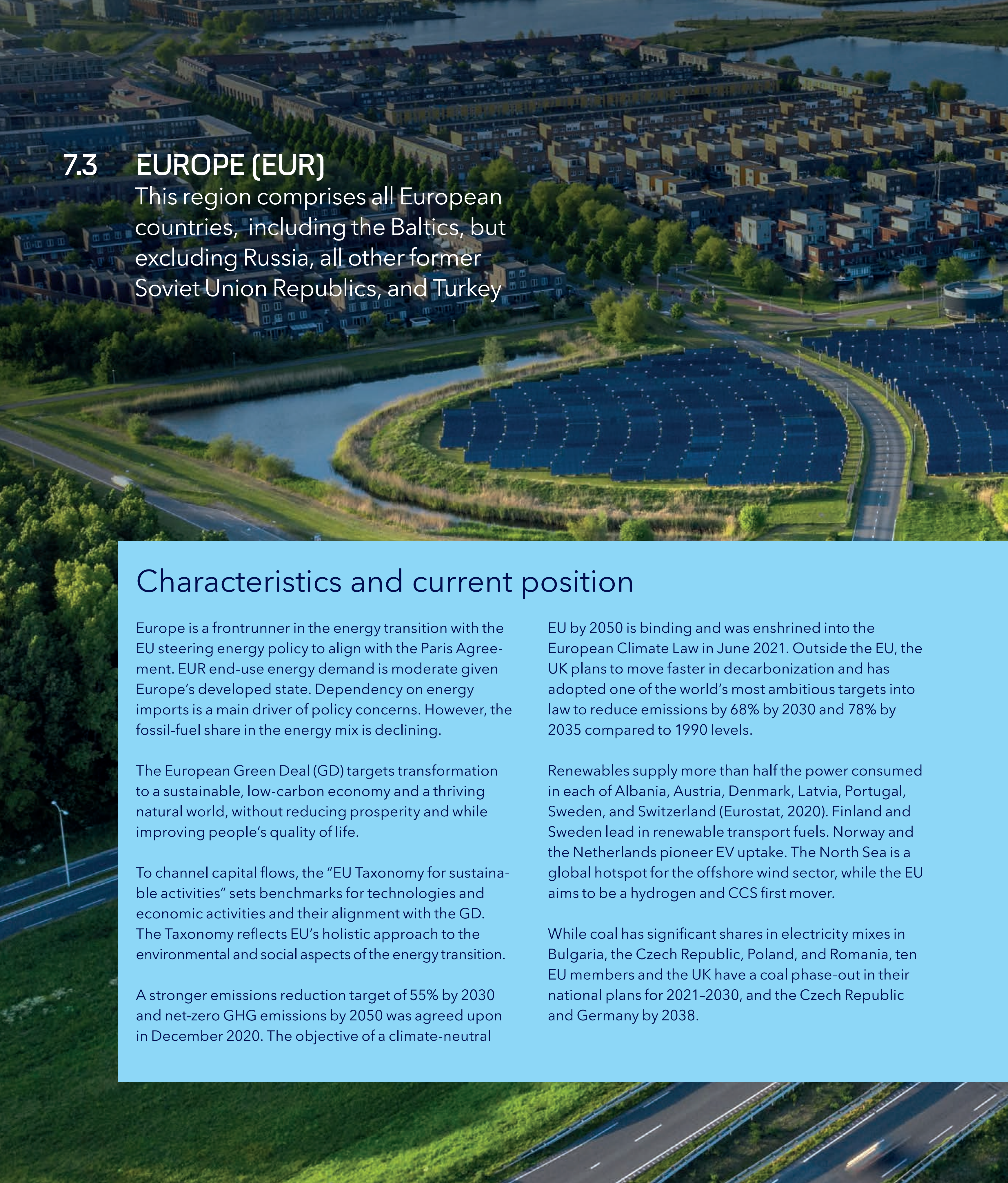
FIGURE 7.2.6

Levelized cost of hydrogen via solar power in Latin America

Units: USD/kgH_2



Grey: cost range for green H_2 in other regions and/or from different sources



7.3 EUROPE (EUR)

This region comprises all European countries, including the Baltics, but excluding Russia, all other former Soviet Union Republics, and Turkey

Characteristics and current position

Europe is a frontrunner in the energy transition with the EU steering energy policy to align with the Paris Agreement. EUR end-use energy demand is moderate given Europe's developed state. Dependency on energy imports is a main driver of policy concerns. However, the fossil-fuel share in the energy mix is declining.

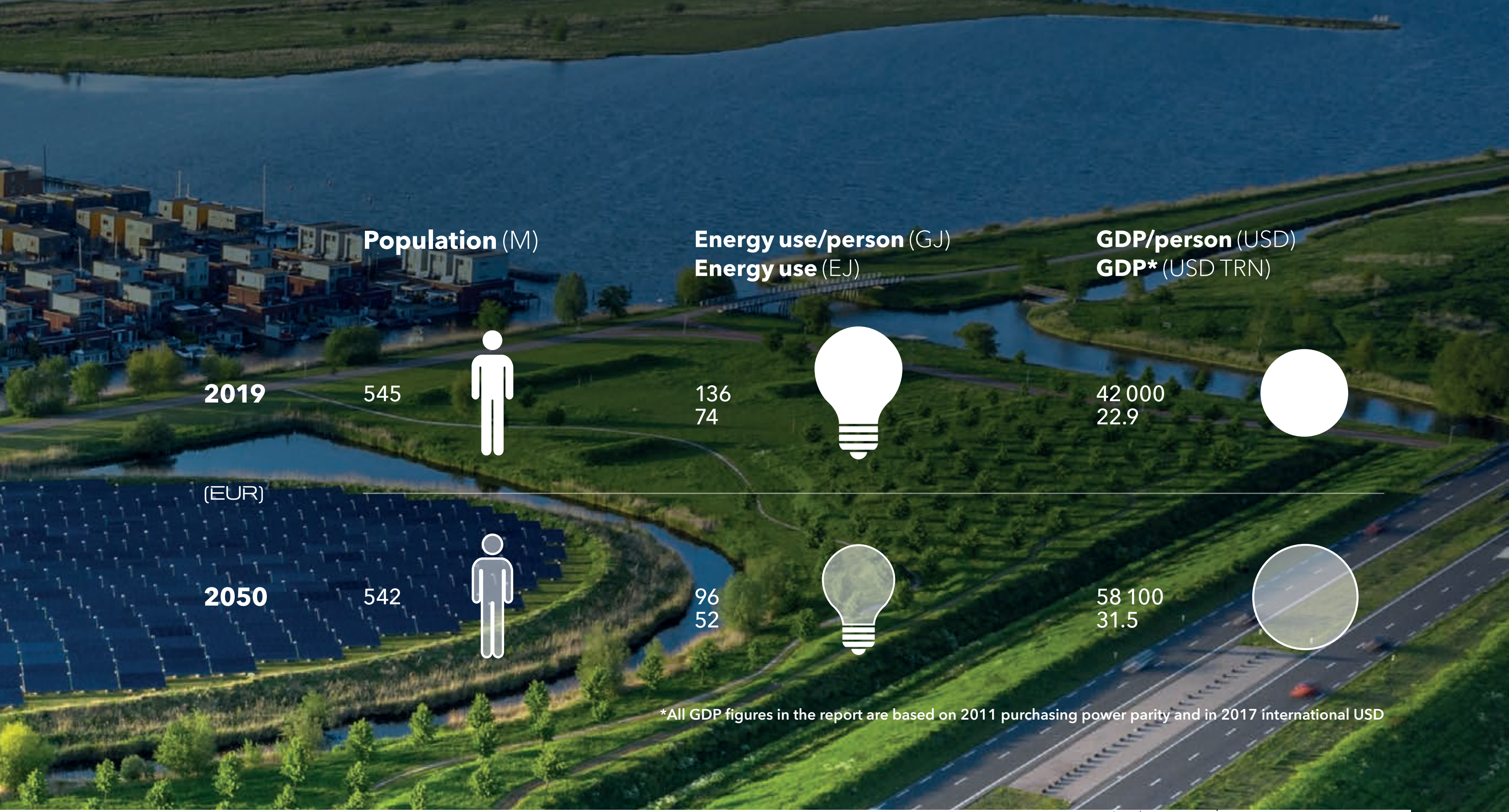
The European Green Deal (GD) targets transformation to a sustainable, low-carbon economy and a thriving natural world, without reducing prosperity and while improving people's quality of life.

To channel capital flows, the "EU Taxonomy for sustainable activities" sets benchmarks for technologies and economic activities and their alignment with the GD. The Taxonomy reflects EU's holistic approach to the environmental and social aspects of the energy transition.

A stronger emissions reduction target of 55% by 2030 and net-zero GHG emissions by 2050 was agreed upon in December 2020. The objective of a climate-neutral EU by 2050 is binding and was enshrined into the European Climate Law in June 2021. Outside the EU, the UK plans to move faster in decarbonization and has adopted one of the world's most ambitious targets into law to reduce emissions by 68% by 2030 and 78% by 2035 compared to 1990 levels.

Renewables supply more than half the power consumed in each of Albania, Austria, Denmark, Latvia, Portugal, Sweden, and Switzerland (Eurostat, 2020). Finland and Sweden lead in renewable transport fuels. Norway and the Netherlands pioneer EV uptake. The North Sea is a global hotspot for the offshore wind sector, while the EU aims to be a hydrogen and CCS first mover.

While coal has significant shares in electricity mixes in Bulgaria, the Czech Republic, Poland, and Romania, ten EU members and the UK have a coal phase-out in their national plans for 2021–2030, and the Czech Republic and Germany by 2038.



(EUR)

	Population (M)	Energy use/person (GJ)	Energy use (EJ)	GDP/person (USD)	GDP* (USD TRN)
2019	545	136	74	42 000	22.9
2050	542	96	52	58 100	31.5

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

Pointers to the future ▸▸▸

- The Green Deal (GD) adoption and upgraded decarbonization commitments will cement the EU's leading position in shaping global climate action.
- Horizon Europe, the key EU funding programme for R&D, will contribute to the GD, with a budget of over €100bn between 2021-27. At least 35% will be earmarked for climate. The EU Innovation Fund supplements national government funding with CCS and energy intensive industries among its key focus areas.
- Revision of the Third Energy Package for gas will support further decarbonization of natural gas by introducing rules for hydrogen markets and infrastructure, including strengthened legislation on methane emissions from natural gas use (including emissions from natural gas imports).
- Reform of the EU Emissions Trading System (ETS) will include a proposed extension of the scheme to shipping and aviation, and a new system for buildings and road transport. Measures to align the cap with the higher emission reduction target, will help to sustain high carbon prices.
- Natural gas overtakes oil as the largest primary energy source in 2034. More LNG import terminals and retrofit of existing gas pipelines for hydrogen transport will sustain long-distance gas pipelines.
- CCS uptake will be promoted, with important early steps reached for Norwegian Northern Lights and the Netherlands' Porthos projects. Both are partly supported by the increasing ETS carbon price. Blue hydrogen (steam methane reforming (SMR) with CCS) will be used to decarbonize natural gas.
- More low-cost renewables will increase the push for storage solutions such as batteries, hydrogen, and power-to-X. Green hydrogen will become competitive in the medium to long term as investment ramps in line with long-term decarbonization ambitions.
- Nuclear energy will still play a key role in several EU countries, and governments such as the UK are investing in a new generation of small modular reactors.

EU's Green Deal and the 'Fit for 55' Package

With the announcement of the European Green Deal (2019), the European Commission (EC) President Ursula von der Leyen pledged to put forward an increased emission reduction target and a comprehensive, responsible plan for its achievement. The EC's reduction target of 55% by 2030, up from previous 40% target, was proposed in September and agreed upon in December 2020.

An extensive impact assessment and a public consultation during spring 2020 concluded that the current policy framework was insufficient to achieve the 55% target as well as net zero GHG emissions by 2050. Without strengthening, the EC Communication (EC, 2019) projected that current policies would lead to a 60% emissions reduction by 2050. Hence to accompany the targets, a legislative train schedule has been set in motion.

The EC's "Fit for 55" Package will set the pathway to a 55% reduction compared to 1990 levels. It includes a range of Directive fitness tests and revisions to align the existing EU climate and energy policy framework with the 2030 ambition, and with the various Green Deal objectives within climate, biodiversity, and resource circularity.

The 'Fit for 55' list of proposals evidence the comprehensive approach to deliver and translate ambitions into concrete policies, and support implementation across sectors. On July 14th, 2021, the EC released (EC, 2021) its first set of revision proposals, among others:

- Revision of the EU Emissions Trading System (ETS), including extension to the maritime sector and removal of free allowances to aviation by 2027, for a 60% emission reduction by 2030 versus 2005 levels (representing an increase from current -43% contribution to EU's climate target) and with a 4.2% annual reduction instead of current 2.2%. A new, separate ETS for road transport and buildings targeting fuel suppliers is to become operational as of 2025.
- Carbon-Border Adjustment Mechanism (CBAM) will be gradually implemented from 2026 and fully operational by 2036, replacing free allocation of emission allowances.
- Amendment to the Renewable Energy Directive (RED) with a proposed increase to a 40% renewables share of European energy use by 2030 (contrasted with today's aim of 32%); and the Energy Efficiency Directive (EED) proposing member states reduce energy use annually by 1.5% from 2024 onwards, and that the public sector renovates 3% of its buildings each year to drive the renovation wave.
- Revision of the Regulation setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles by requiring average emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels to advance zero emission mobility.
- The following initiatives are announced for the fourth quarter of 2021:
  - Revision of the energy performance of Buildings Directive (EPBD)
  - Revision of the Third Energy Package for gas (Directive 2009/73/EU and Regulation 715/2009/EU) to regulate competitive decarbonised gas markets.

The process of negotiations and outcomes (enforceable regulations) of these revision proposals were not concluded at the time of finalizing this year's Outlook and will be reflected in future editions of the DNV forecast.

7.3 EUROPE

Energy Transition

Europe's final energy demand (Figure 7.3.1) peaked in 2006 and will continue to decline towards mid-century. With a transition to more efficient EVs, transport energy demand will fall to half its current level and see the strongest absolute reduction. Manufacturing's energy demand will also reduce, due to 15% less production of base materials and to greater manufacturing efficiency. Commercial space increases by half and residential space by a fifth, but rising electrification and particularly heat pump technology will see a very slight decrease in energy demand in buildings.

Electricity's share in final energy demand rises from 20% in 2019 to 39% in 2050. Buildings has the highest electricity share today (33%) that will grow to 41% of energy use. But the fastest growing share is for transport (1% today to 39% mid-century), as EVs become dominant.

Wind dominates the 2050 electricity mix – onshore 18%, and offshore 30%. Solar PV will account for 21%. Gas-based electricity supply dwindles to 3% in 2050. Hydrogen from electrolysis shows strong growth from the mid-2030s to account for 100% of European hydrogen production by mid-century. Hydrogen's share of final energy demand is 12% in 2050, the highest among all regions.

More than half of Europe's vehicle fleet will be electric by 2037 and a full 92% by 2050. Natural gas therefore overtakes oil as the largest primary energy source in 2036 (Figure 7.3.2), consolidating that position over the following decades. Coal-based electricity reduces by a factor of four to only 4% in 2030 and is marginal thereafter. Coal is harder to replace in other sectors and retains 2% of total primary consumption in 2050 vs. 11% today. The biomass share grows from 11% to almost 16% in 2050, even as it becomes entirely sustainable – from forestry waste and similar sources. Fossil energy share in primary energy consumption falls by more than half to 33% by 2050.

Energy Transition Indicators

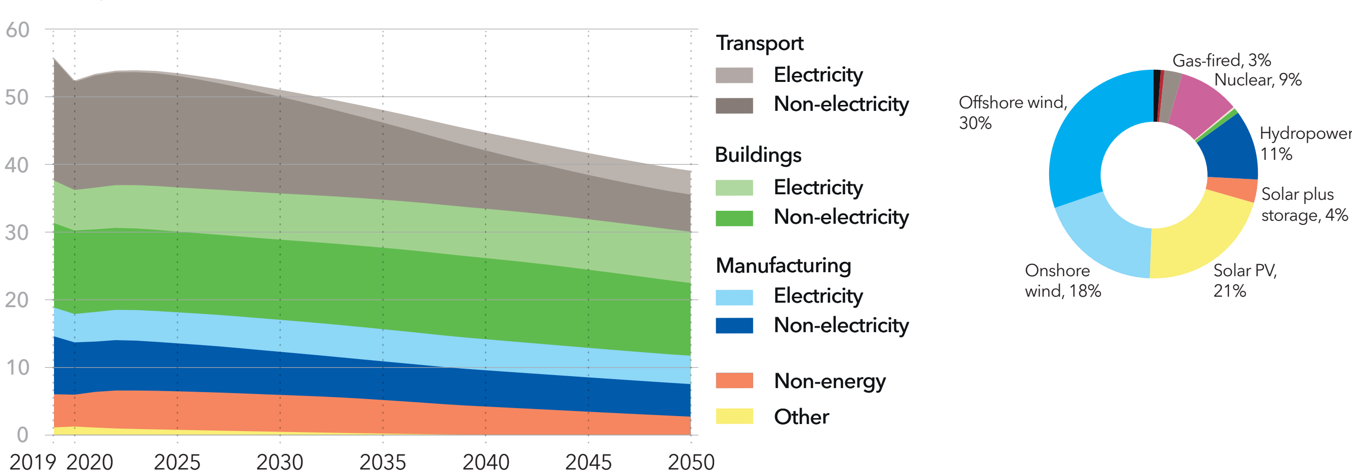
Figure 7.3.3 presents Europe's developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 7.11).

FIGURE 7.3.1

Europe final energy demand by sector

Units: EJ/yr

2050 electricity mix

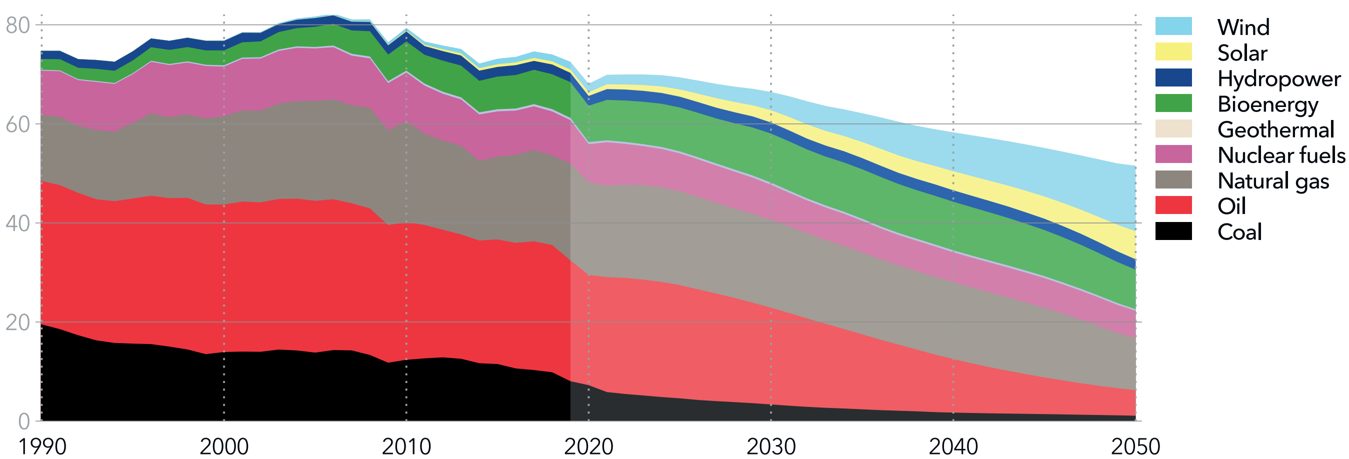


- The region's share of electricity in final energy demand will reach 39% by 2050, a level similar to North America, and explained by fossil fuels becoming more expensive in relative terms as higher carbon prices and renewable cost learning propels electrification in ever new markets.
- Energy intensity in 2050 will be at a low 1.7 MJ/ USD, representing efficiency gains amounting to a reduction of around 45% from 2019 values, and reaching the lowest value of all regions.
- Both of these developments support the 60% decline in Europe's carbon intensity by 2050 – one of the strongest decarbonizations of any region, over 15% lower than North America and Greater China, in second and third place respectively.

FIGURE 7.3.2

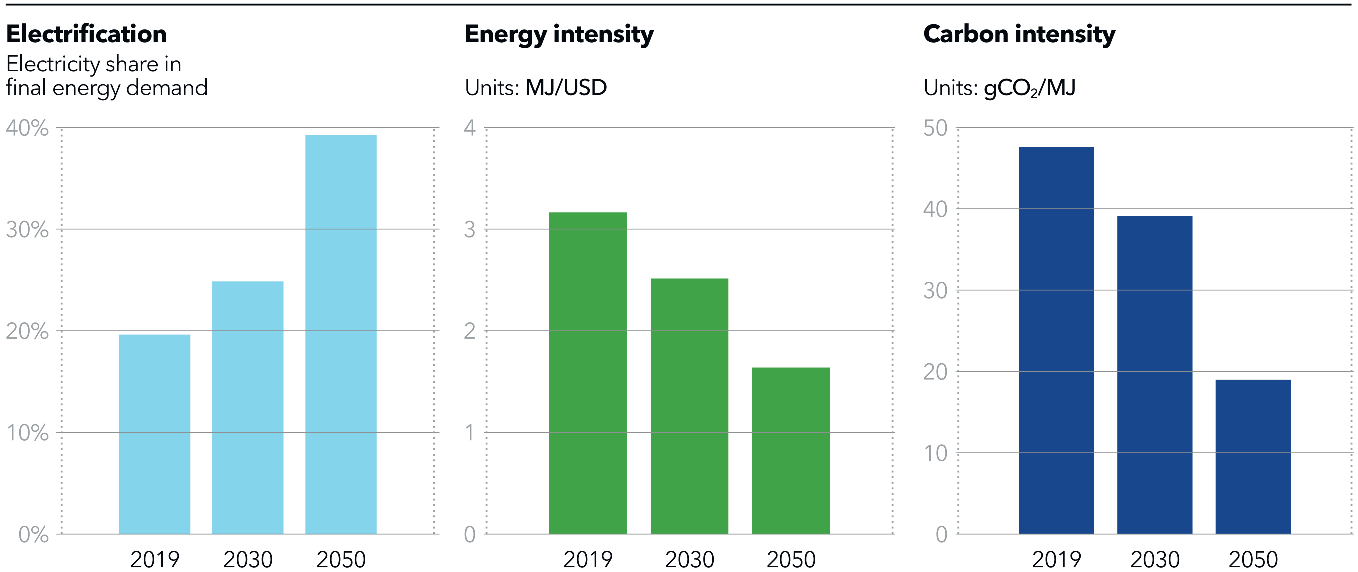
Europe primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.3.3



Emissions

We project the region's carbon price-level to triple to 2030 and quadruple by 2050 to reach USD 100/t CO_2. 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 many countries also having national carbon taxes and price-floor mechanisms on non-EU ETS sectors.

The EU's and Great Britain's new NDC pledges, target a 55% and 68% reduction in CO_2 emissions by 2030 relative to 1990 respectively. 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 44% by 2030, more than the EU's initial Paris Agreement pledge of 40%, but certainly less than 55%. By 2050, Europe is forecasted to reduce its energy-related emissions by 74% compared to 2019, with a remaining 0.90 $GtCO_2$/yr in emissions. This contrasts most of the countries' 2050 net-zero pledges.

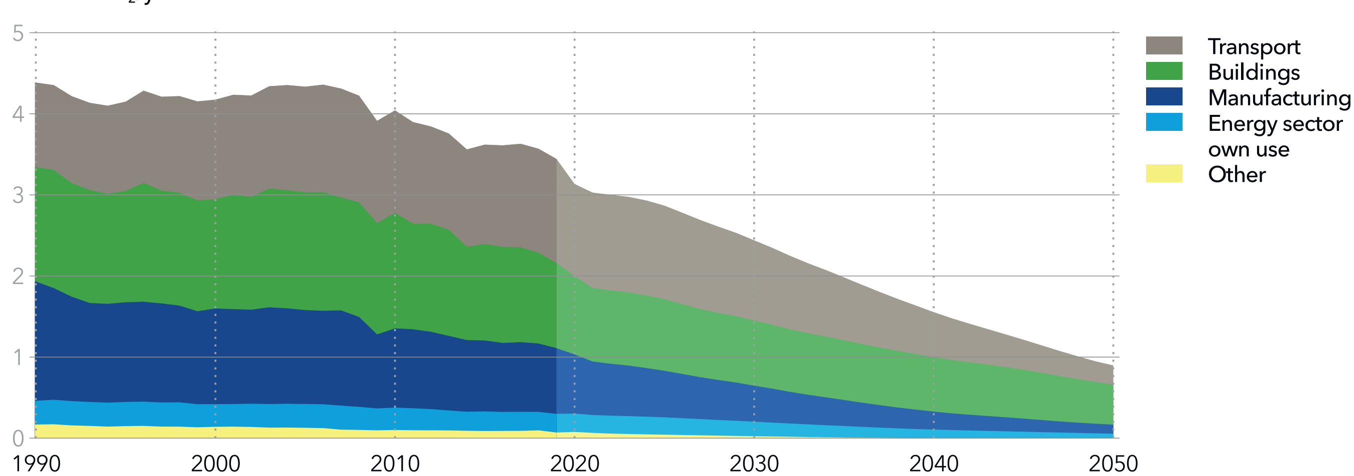
Figure 7.3.4 shows transport and manufacturing reducing emissions the quickest. In manufacturing, this is mainly due to declining use of coal and gas, as the role of cheaper green electricity increases.

Emissions from using gas will surpass oil as largest source of CO_2 emissions in 2036. Emissions from coal use will decline rapidly, almost disappearing as coal use will dwindle: Those from oil will gradually decline by 2050 to less than a fifth of today's level, primarily because of lower oil use. Overall emissions in 2050 are 923 $MtCO_2$ after CCS has captured – and stored 169 $MtCO_2$, which captures 15% of Europe's emissions in 2050. CCS – though limited in Europe – is still capturing the largest such share among all regions. CCS will not be a big enough industry to counter carbon emissions, even with a 100 USD/t carbon price. In relative CO_2 emissions, Europe's 1.7 tCO_2/person is well below world average.

FIGURE 7.3.4

Europe energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Advancing hydrogen-based energy

Europe will lead the transition to hydrogen production and use, alongside China. By 2050, hydrogen will meet 12% (4.5 EJ) of Europe's final energy demand, representing 20% of the world hydrogen energy use.

As with the rest of the world, hydrogen as an energy carrier is virtually non-existent in Europe today, with almost all hydrogen produced for use as a feedstock to industrial processes, mostly via steam methane reforming (SMR) from natural gas. The European share of primary energy sources for these non-energy uses will remain about the same, but with a slow transition to blue hydrogen with uptake of CCS for natural gas-based production. The staying power of gas is mainly explained by no need for new capacity additions and the long lifespan of production equipment, that is often installed in close vicinity to where hydrogen is needed.

As an energy carrier, hydrogen will see much more evolution as shown in Figure 7.3.5, with a shift to hydrogen being produced mostly by electrolysis, initially relying on grid electricity until 2035, and thereafter most of the growth will be supported by dedicated green hydrogen production facilities. The latter will represent 68% of the total capacity in 2050, and given the almost fully decarbonized electricity mix, 98% of hydrogen as an energy carrier will at that point in time be produced from non-fossil energy sources.

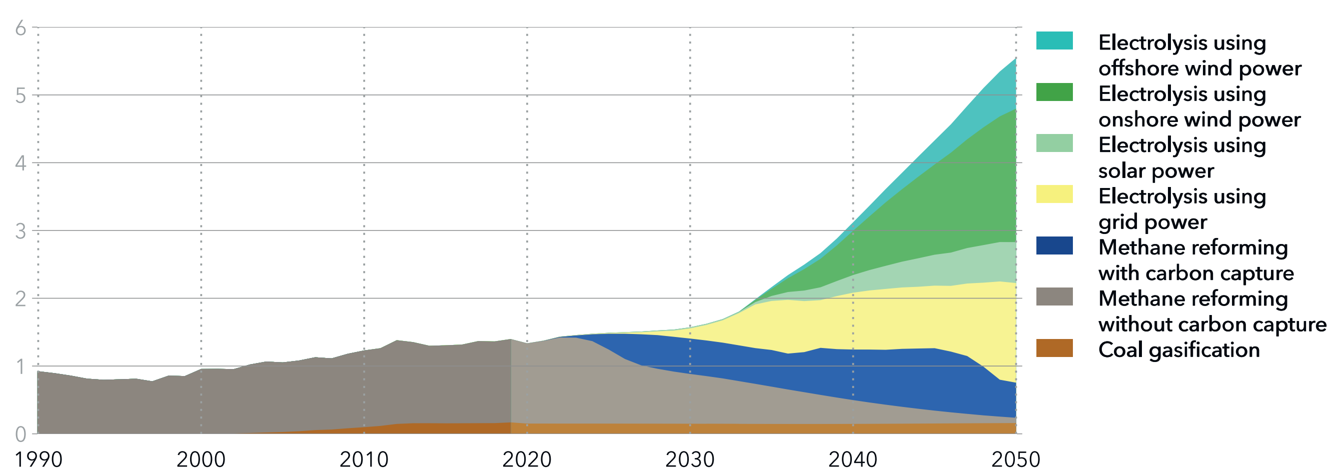
In 2050, green hydrogen (see Section 2.4 for definitions) will be mainly produced with onshore wind (59%), followed by fixed offshore wind (23%) and solar PV (18%).

Europe will lead the transition to hydrogen production and use, alongside China. In 2050 green hydrogen will be mainly produced by dedicated onshore wind, fixed offshore wind and solar PV.

FIGURE 7.3.5

Europe hydrogen production by source

Units: **EJ/yr**



Only includes pure hydrogen supply. Historical data source: IEA Future of Hydrogen (2019)

A high hydrogen share in road transport

Hydrogen uptake in Europe (12% of final energy demand by 2050), will be almost three times faster than in the rest of the world (4%). Usage will be distributed among the three demand sectors: manufacturing (43% of hydrogen demand by 2050) and transport (40%) will represent the majority of it, buildings (17%) taking the remaining share.

Around 1.8 EJ, or 15 Mt of hydrogen will be used for transport purposes by 2050. The maritime transport and aviation subsectors will each represent around 30% of hydrogen demand for transport. In Europe, the hydrogen uptake in these two international industries will be similar to the rest of the world, because the transition is driven by global decarbonization trends in these competitive subsectors.

Road transport will account for the rest of Europe's hydrogen usage in transport (43%) with 0.8 EJ, well above the average in the rest of the world at 13%. While fuel-cell vehicles (FCEV) will not be competitive in the passenger cars segment, sales will ramp up for commercial vehicles from 2030 onwards. Indeed, hydrogen will be competitive for heavy vehicles requiring a lot of energy to be stored, especially for long-haul trucking. Europe will be the world's largest hydrogen consumer in road transport with its 37% share of the global total, also with FCEV representing 28% of European commercial vehicles sales by 2050 as shown in Figure 7.3.7.

Steel industry at the hydrogen transition forefront

Looking closer at manufacturing, the steel industry, one of the hard-to-abate sectors, is expected to decarbonize faster in Europe than elsewhere, as a result of dedicated initiatives and supportive policy measures. ArcelorMittal and Tata Steel, two major steelmakers in Europe, have for example already pledged to be carbon neutral by 2050.

Steel demand will slowly recover from the pandemic-induced downturn but will eventually slowly decrease. Demand for steel was 203 Mt in 2019, 11% of global demand. It will be 157 Mt in 2050, representing 10% of global steel demand, and it is met mostly by Europe's own production, with only 8% being imported from other regions, and this share is expected to stay constant in the coming decades.

Energy demand from steelmaking will decrease, but

FIGURE 7.3.6

Europe hydrogen demand in transport

Units:EJ/yr

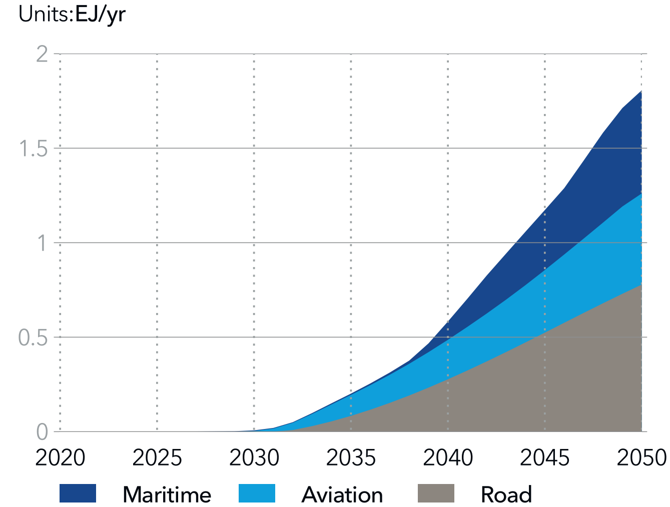
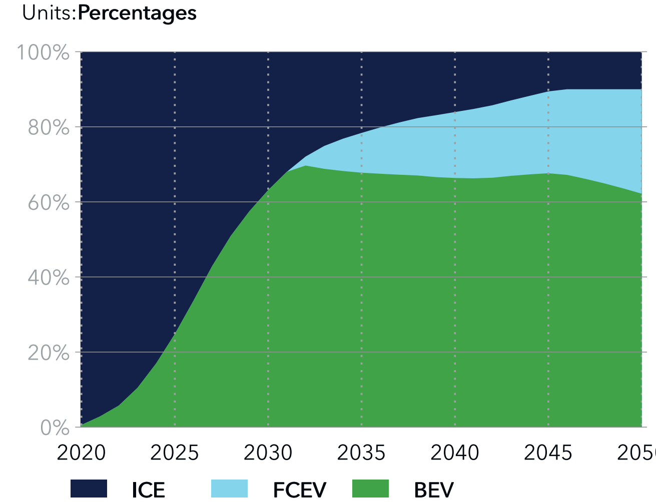


FIGURE 7.3.7

Europe commercial road vehicles sales split

Units:Percentages



more interesting from a transition perspective, the energy required to produce a tonne of steel (15 GJ/t) will be 34% lower in 2050 than for the rest of the world (23 GJ/t). This is partially explained by the increased share of recycled steel, enabling electrification and the shift towards steel production in the less energy-consuming electrical arc furnaces, but direct reduction of virgin iron ore with hydrogen replacing coal, will also play a big part.

As shown in Figure 7.3.9, hydrogen will cover 32% of the Europe's steel industry energy demand by 2050, a six times higher share than in the rest of the world.

A policy-driven hydrogen uptake

Hydrogen is not economical compared to conventional fossil fuels. Uptake in Europe is therefore not driven by more competitive technology- and production costs, levelized costs being in the average compared to other regions, as seen in Figure 7.3.10.

The European hydrogen uptake trigger will mainly be political. The EU hydrogen strategy targets at least 6 GW of electrolyser capacity for renewables-based green hydrogen production by 2024 and 40 GW by 2030. We forecast 3 GW by 2024 and 31 GW by 2030, hence achieving targets will require a further push to ramp-up integrated renewable electricity and electrolyser projects and simultaneous development in end-use sectors to ensure hydrogen offtake. Another policy driver of hydrogen uptake comes from the expectation of Europe having the highest carbon pricing over the next decades, expected to be around 100 USD/t in 2050. Results from sensitivity analysis in Figure 7.3.11 show the influence of carbon price on the demand for hydrogen by 2050. A 50 USD/t price would place Europe around the world average, while higher carbon prices would significantly increase hydrogen demand.

Natural gas prices will have little influence on hydrogen uptake, but will significantly affect hydrogen origin. If they were to be 50% lower, production from renewable sources would be slowed down and two thirds of hydrogen would be produced from natural gas in 2050, while a 50% price increase would mean almost no use of blue hydrogen.

FIGURE 7.3.8

Europe steel demand

Units:Mt/yr

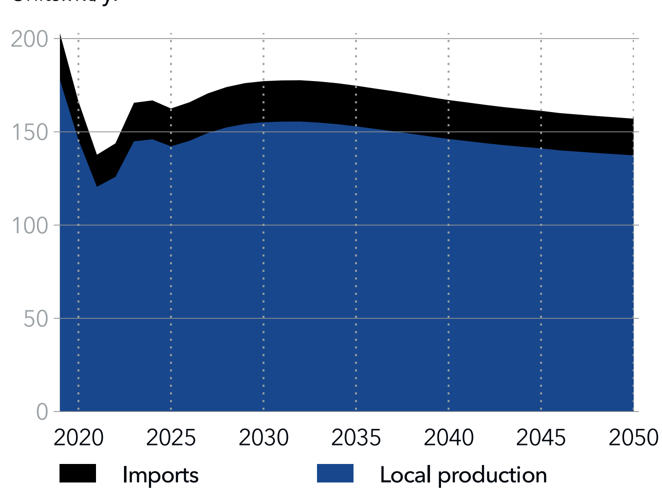


FIGURE 7.3.9

Share of hydrogen in iron and steel energy demand

Units:Percentages

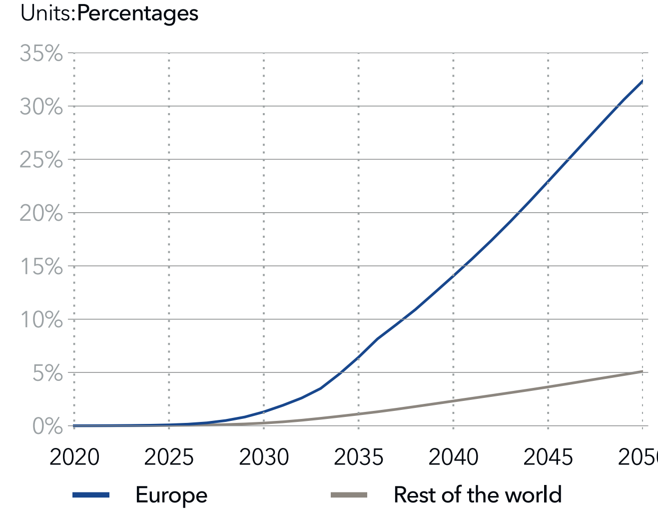
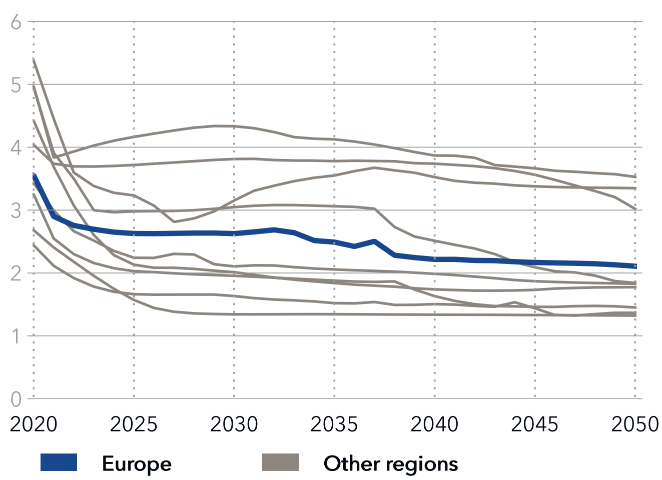


FIGURE 7.3.10

Average levelized cost of low-carbon hydrogen in Europe and in other regions

Units: USD/kg



Low-carbon hydrogen: produced by electrolysis or by SMR with CCS

FIGURE 7.3.11

Sensitivity of Europe's hydrogen demand in 2050 to changes in carbon price

Units: Percentage relative to the base

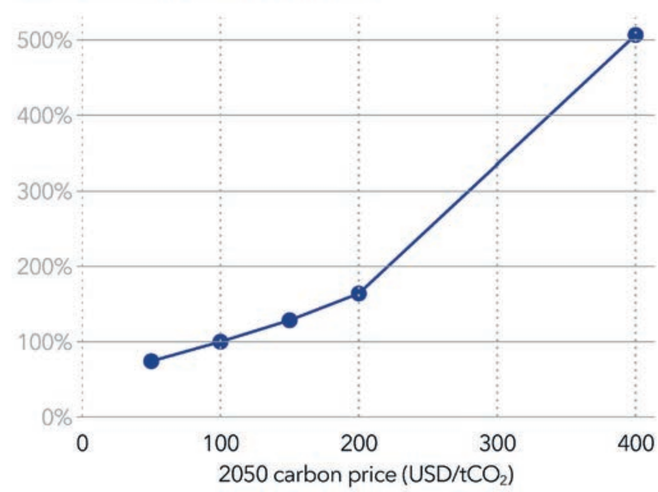
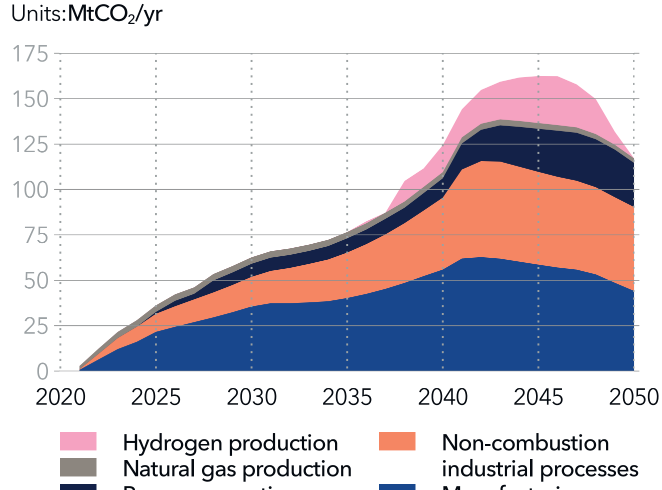


FIGURE 7.3.12

Carbon capture by sector in Europe

Units: $MtCO_2$/yr

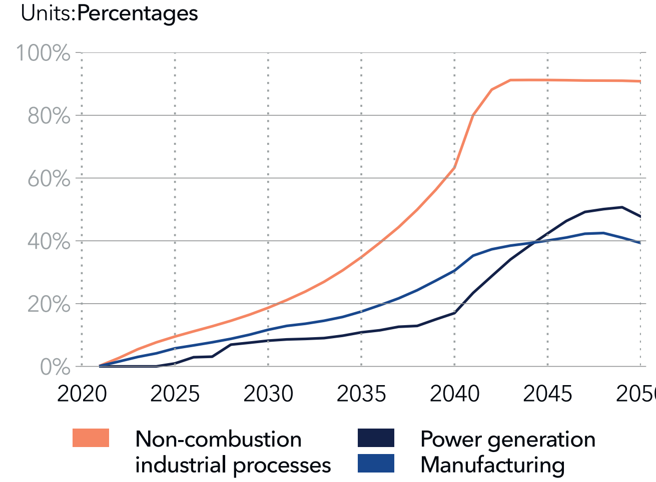


Hydrogen used as for non-energy purposes is included in manufacturing.

FIGURE 7.3.13

Shares of Europe's CO_2 emissions captured by sector

Units: Percentages



Early CCS adoption

Europe will be one of the early adopters of CCS, again due to high carbon prices. In 2030, more than a half of global CO_2 captured with CCS will be in Europe, representing 65 Mt. This share will progressively decline afterwards as other regions are picking up, but the quantity of captured CO_2 will continue to increase to 163 Mt in 2045. CCS will then decline due to the decline of fossil-fuel use.

As shown in Figure 7.3.12, CCS will first be used to capture process emissions, and in the manufacturing sector, especially for hydrogen production in the chemical and petrochemical industries. CCS deployment to produce hydrogen as an energy carrier will not start before the late 2030s and will remain quite low due to the dominant policy focus on green hydrogen.

CCS will not cover emissions or the different sectors evenly. While more than 90% of process emissions will be captured by 2050, less than 50% of emissions from manufacturing and power generation will be captured. Emissions before capture in these two sectors will however be much lower compared to today's levels, decreasing by 82% in the power sector (as a result of renewables uptake) and by 77% for manufacturing (electrification and hydrogen use) between 2019 and 2050.

The world's first hydrogen-powered car ferry, Norled's MF NESVIK, undergoing sea trials in March 2021 (Image, courtesy Westcon/ Økland foto.)

7.4 SUB-SAHARAN AFRICA (SSA)

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

Characteristics and current position

Sub-Saharan Africa has a diversity of natural resources. Nigeria and Angola are the largest oil-producing countries, while 88% of the region's coal production, used in its electricity generation, is from South Africa. Geothermal resources are widely available in East Africa. Congo, Ethiopia, and Zambia have high hydropower potential, and the continent has abundant solar and wind resources.

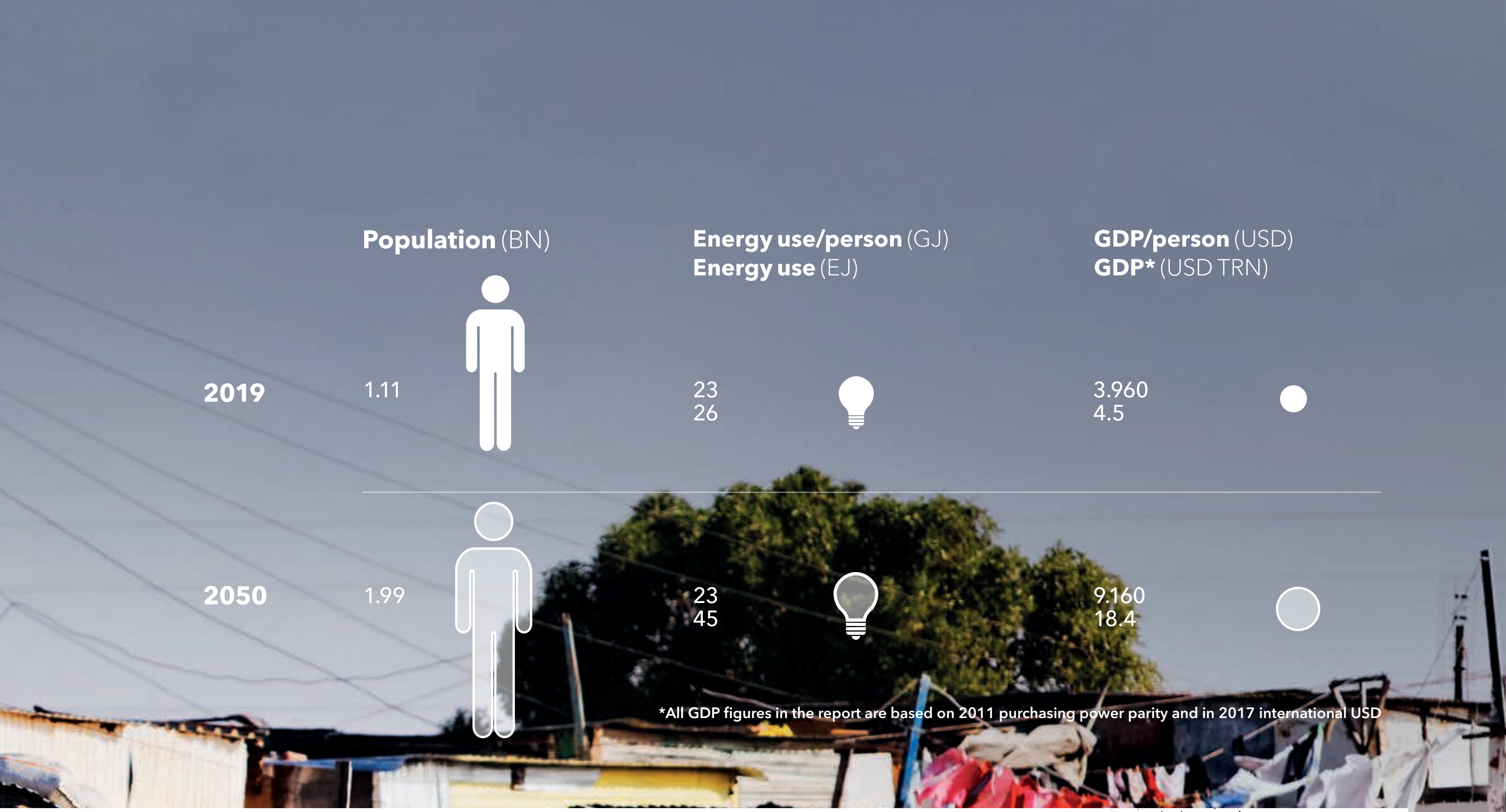
The region urgently requires power infrastructure; hitherto supply has not kept pace with population growth and colossal energy deficiencies hamper economic development and industrialization.

The world's energy access deficit is increasingly concentrated in SSA, despite the rich resource potential. Only 42% of the population have access to electricity, and overall gains in energy access were reversed during the pandemic (IBRD, 2021)

Impact investors, in partnership with the World Bank, UNDP, and other bi-lateral donors, are making positive impacts towards electrification. By leveraging the power of IoT connectivity and asset-financing platforms, the pay-as-you-go model has become increasingly attractive in off-grid electrification across the SSA region, with. online platforms, such as the Energy Access Explorer, supporting better decision making.

State-owned utilities dominate ownership, and, in many parts of the region, run persistent deficits from under-priced electricity. Indecisive power-sector reforms, along with unpredictable policy frameworks, hinder inflow of private capital/investment. Utility-scale developments in renewables (non-hydro) have progressed slowly, a result of finance needs in combination with the absence of creditworthy off-takers. Nevertheless, 2020 marked the year where private sector-led independent power projects (IPPs), accounted for more than 50% of new capacity added (African Energy Live Data, 2021).

With the weak financial positions of state-owned utilities, large energy deficiency and an enormous funding gap, a rise in private-sector involvement appears inevitable in the future.



	Population (BN)	Energy use/person (GJ) / Energy use (EJ)	GDP/person (USD) / GDP* (USD TRN)
2019	1.11	23 / 26	3.960 / 4.5
2050	1.99	23 / 45	9.160 / 18.4

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

Pointers to the future

- Electrification of Sub-Saharan Africa is among the most important global challenges and opportunities to meet SDG #7 on affordable and clean energy, and for SDG #13 on combatting climate change.
- Solar PV and solar-plus-storage solutions, onshore wind, and battery technologies will boom, but starting from a low base. On-site solar projects among commercial and industrial players are expected to proliferate along with off-grid solutions for rural electrification.
- For on-grid, utility-scale renewables, regional infrastructure, interconnections, and regional and continental power pools are key – and are at the centre of the Program for Infrastructure Development in Africa (PIDA), led by the African Union and the African Development Bank.
- The region has the highest number (85%) of submitted NDCs with renewable energy targets (IRENA, 2020). There is a nascent shift to competitive tenders; e.g., Kenya, Ghana, Uganda, Zambia, and South Africa have already run auctions, indicating the growing role of IPPs in bringing renewable power to the region.
- National utilities, generally favouring large, centralized power plants, will perpetuate hydropower expansion and greater use of natural gas. Chinese lenders have been criticized for backing several coal-fired power plants across the region. However, 15.2GW coal-fired capacity is currently shelved (Steckel et al., 2020), and our Outlook does not foresee a coal boom in SSA.
- South Africa is the only country with an announced net-zero emissions goal by 2050. An updated climate plan is to be submitted ahead of COP26; there is a draft proposal for cutting emissions by 28%, from its current pledge for 2030. Given the country's reliance on coal-fired electricity generation, there is a large gap between commitments and concrete actions. In July 2021, the Presidential Climate Commission (PCC, 2021) announced that emission reductions will mostly come from retiring and repurposing coal-fired power stations.

7.4 SUB-SAHARAN AFRICA

Energy Transition

Sub-Saharan Africa's final energy demand (Figure 7.4.1) will keep growing over coming decades as the population almost doubles and the economy quadruples. Greater energy efficiency counteracts this partially, particularly in buildings, where electricity and gas will replace highly inefficient traditional bioenergy for cooking and kerosene for lighting. The largest rise in energy demand, more than doubling, comes from manufacturing, as the region starts to scale-up manufacturing production. Energy demand for transport will double.

Figure 7.4.1 shows electricity's share in final energy demand rising from 7% in 2019 to 19% in 2050. Despite this growth, the 2050 share is the lowest of all regions. Renewables dominate the electricity mix, with hydropower and wind making up 26% and 30% of the mix, respectively. Solar provides another 36% of electricity by 2050. 8% of that is off-grid generation – typically very small installations in rural homes and smaller businesses. Infrastructure challenges are a major obstacle to faster electrification; see story on next page.

Biomass will remain the dominant source of energy, although its share will decrease to 40% in 2050 (Figure 7.4.2). Despite more efficient use, such as closed combustion instead of open, bioenergy brings adverse health effects and inefficiencies; furthermore, traditional bioenergy impoverishes arable land. Oil and gas will increase slightly – also in relative terms.

The largest growth will come in solar PV, and wind generation. However, as electricity's share in the final demand is relatively minor, uptake of these renewables is also lower than in many other regions.

Energy Transition Indicators

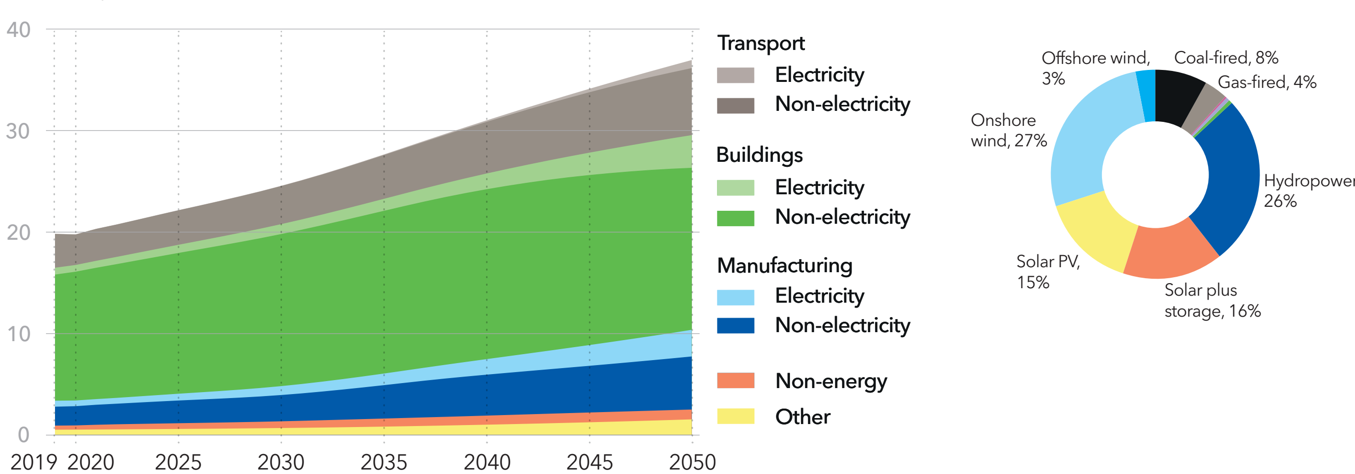
Figure 7.4.3 presents Sub-Saharan Africa developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparisons are given in Section 7.11).

– The pace of electrification is fast, with the electricity share in final energy demand almost tripling between 2019 and 2050. Even so, its final share of 19% is the

FIGURE 7.4.1

Sub-Saharan Africa final energy demand by sector **2050 electricity mix**

Units: EJ/yr



lowest among all regions. Off-grid electrification is only 2% of the electricity share in final energy demand in 2050.

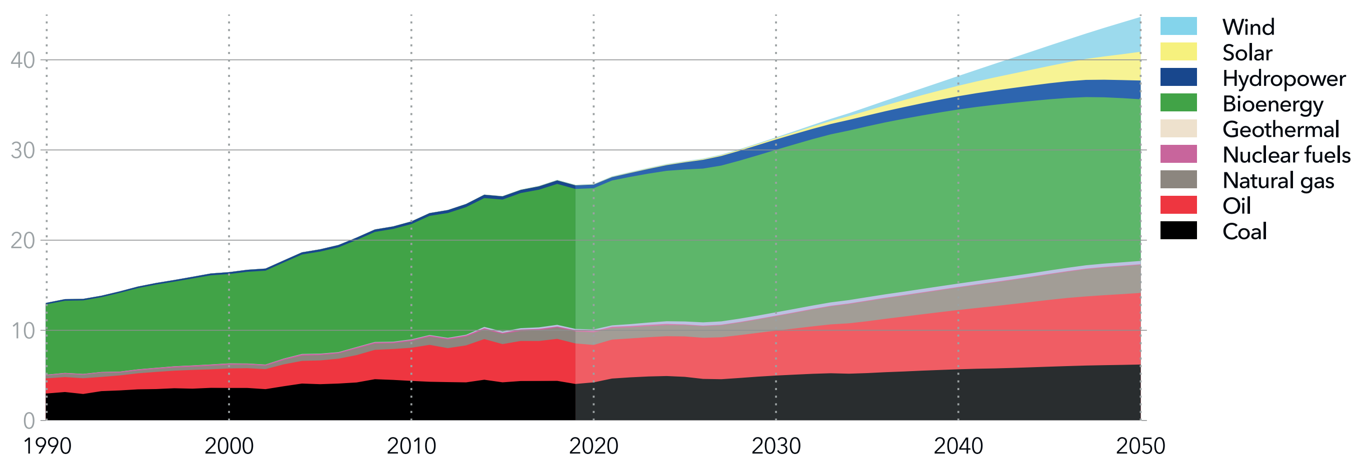
– A strong decrease in energy intensity will occur after 2030, more than halving by 2050. Nevertheless, the level achieved, about 2.2 MJ/USD, is third highest in all regions. This due in part to the extensive, but very inefficient, use of bioenergy and the low share of electricity compared within the other regions.

– While energy intensity halves, there is only a marginal reduction in carbon intensity. Current carbon intensity is the lowest of any region, thus further improvements are difficult. The lack of electrification means that renewables will not displace a significant share of fossil-based energy sources.

FIGURE 7.4.2

Sub-Saharan Africa primary energy consumption by source

Units: EJ/yr

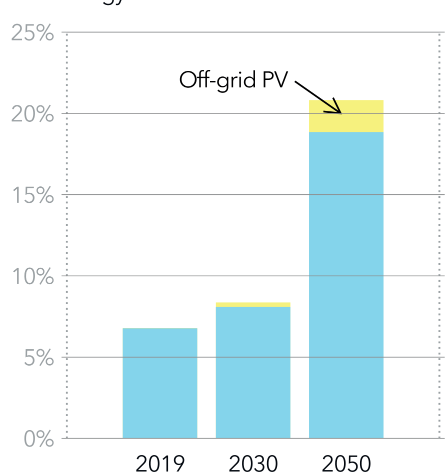


Historical data source: IEA WEB (2020)

FIGURE 7.4.3

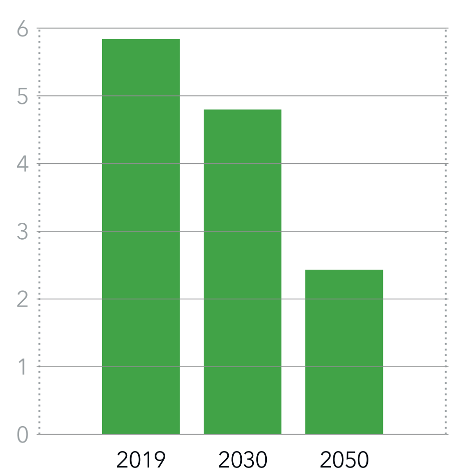
Electrification

Electricity and off-grid PV share in final energy demand



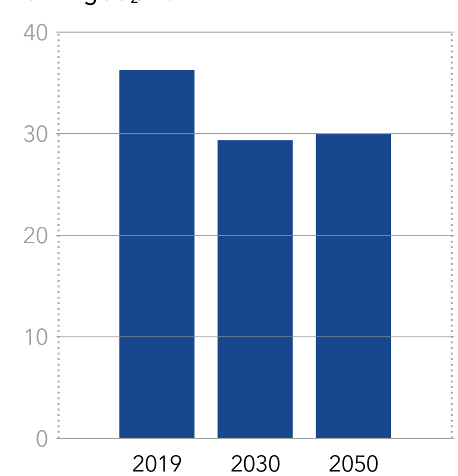
Energy intensity

Units: MJ/USD



Carbon intensity

Units: gCO_2/MJ



Emissions

We project an average carbon price of USD 25/t CO_2 in Sub-Saharan Africa by 2050, and there will be only 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-adjustment mechanisms.

The region's energy-related CO_2 emissions will dip slightly in the coming years of lower growth after COVID-19, but they will then rise, becoming 55% higher in 2050 than today, amidst a quadrupling of the economy. Figure 7.4.4 shows growth coming from all sectors, and even considerable efficiency improvements can only partially counter the mounting final energy demand linked to economic growth in general and to rising living standards in particular.

Emissions from coal are the largest today and will remain so over the forecast period. Oil emissions will grow slightly, as will gas emissions, the latter being increasingly used in buildings, manufacturing and power. CCS uptake is negligible at 5 MtCO2/yr in 2050, less than 1% of total CO_2 emissions.

NDC pledges suggest the regional target is for emissions to grow no more than 174% by 2030 relative to 1990. Our Outlook indicates energy-related emissions rising 113% over the period, suggesting that the 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.

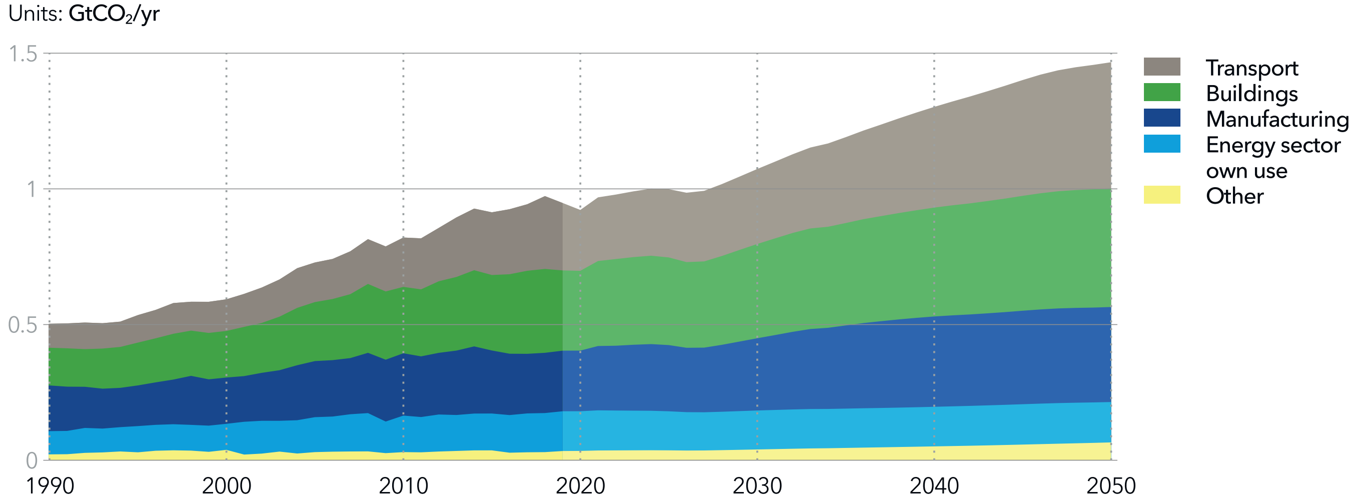
Looking ahead to 2050, very few Sub-Saharan African countries have adopted targets to reduce CO_2 emissions. Our Outlook estimates that emissions in 2050 will have increased by 55% compared with 2019, emitting a little under 1.5 $GtCO_2$/yr.

Despite population growth and rising standards of living, Sub-Saharan Africa's 0.76 tCO_2/person emissions in 2050 are 12% lower than today. It will remain the region with the lowest emissions, primarily due to its population remaining by far the poorest and thus continuing to benefit little from modern energy comforts.

FIGURE 7.4.4

Sub-Saharan Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Rethinking the (urban) grid

Commentary on electrification of Sub-Saharan Africa often focuses on the supply side (power generation), whereas demand-side issues are arguably a far greater barrier to electrification (World Bank, 2019). While off-grid solar will indeed bring basic energy access to hundreds of millions of people across SSA, 77% of solar power will be grid-connected in SSA by 2050. But there is considerable potential for even greater grid-connected access.

On SSA's inadequate grid infrastructure, IRENA (2021) observes that the weighted average transmission and distribution losses in SSA total some 23%, against a world average of 10%. Reducing these losses by just 1% annually would reduce demand by approximately 10 TWh/yr, or the equivalent of some 6,500 MW of solar capacity. (In comparison, total installed solar PV capacity across Africa is around 6,300 MW).

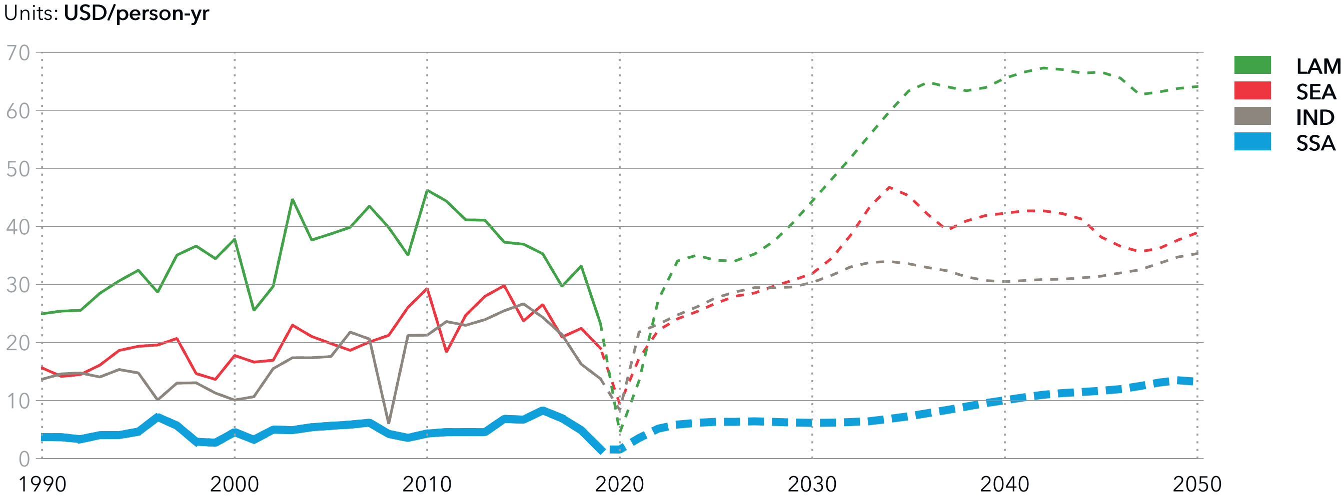
Sub-Saharan Africa is the fastest urbanizing region, and while aid organizations have targeted rural energy access, the reality is that there are already 100 million urban Africans living right under the grid without connections to it (World Bank, 2017). Establishing reliable, cost-effective 'last mile' distribution in urban and peri-urban areas must overcome power and cable theft, corruption, and the difficultly of collecting payment from informal households with a high unwillingness and inability to pay. Paradoxically, unwillingness to pay is related to the frequency of blackouts, such that those connected to the grid end up paying for two sources of power (World Bank, 2017).

In India, an innovative programme by Tata Power Delhi Distribution Limited to provide last-mile access to the urban poor with low-cost connection fees has sparked similar programmes in Kenya (Attia, 2017). There is considerable potential to establish mini-grids in urban areas, with larger paying customer bases than rural areas, and with careful planning and policy frameworks such grids could eventually be integrated into national grids (Deign, 2020 and Greacen, 2020). IPP-financed mini-grids could prove a vital lever to SSA governments in lifting grid expansion and reliability – edging the region closer to the levels of grid investments in other developing regions like Latin America (Figure 7.4.5).

FIGURE 7.4.5

Power grid investments per capita in Sub-Saharan Africa compared to other regions

Units: USD/person-yr



7.5 MIDDLE EAST AND NORTH AFRICA (MEA)

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

Characteristics and current position

This is a diverse region, economically and politically, with vast petroleum resources, the largest being in the Kingdom of Saudi Arabia (KSA), Iran, Iraq, United Arab Emirates (UAE), and Kuwait. There is ample solar radiation year-round, and desert winds and open spaces are available for renewables projects.

MEA is the cornerstone of the geopolitical system of extraction and trade in oil and gas. Economic conditions are affected by volatilities in international oil prices, and the OPEC members in the region are trying to maintain a delicate balance between maximizing production and oversupply weakening prices.

Among producing countries, hydrocarbon wealth and vital government revenue, face pressures from global decarbonization ambitions and unpredictability of returns due to the structural decline in oil demand, linked particularly to the electrification of transport.

The region faces a host of environmental challenges, from water scarcity and food insecurity to climate change adaptation and chronic air pollution.

MEA countries are taking serious steps to realize their vast renewables potential to meet growing domestic electricity demand and to diversify energy sources as an economic growth strategy. Egypt, KSA, the Kingdom of Morocco and UAE have some of the region's largest renewable energy programmes. In UAE, for example, projects are being commissioned at a rate of 1GW+/yr, and Turkey has made solid progress in securing supply through renewables expansion.

The region is pushing ahead with rooftop solar programmes, also with local manufacturing ambitions for renewables and, in KSA, for EVs. EV uptake is minuscule with charging infrastructure buildout and standard development incipient in Morocco, Egypt, UAE and KSA. The COVID-19 pandemic-induced downturn has delayed renewable energy projects and diversification efforts.

(MEA)	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2019	539	91 49	20 600 11.2
2050	728	82 60	35 000 25.6

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

Pointers to the future

- Renewables will expand in power generation directly liberating fossil-fuels for exports among producing countries. Paradoxically, government funding to boost renewable energy mega-projects among the Arab states will come from sustained fossil-fuel revenue.
- Both KSA and UAE target 40-50% of their energy from renewables in 2030. Morocco aims for 52% renewable power by 2030, Egypt 42% by 2035, and Turkey's 50% target by 2023 is likely raised as 66% was already achieved in 2020. More of the region's countries are adopting public tenders/auctions to promote renewables.
- With more variable renewables, interconnections and regional power trade will gain more rationale, as will battery utility-scale storage. Rising electricity demand will place focus in the medium term on energy efficiency and demand-side management measures.
- The region is expected to exploit its lowest per-barrel extraction costs with continued investment in upstream oil and gas production and liquefaction capacity. Refinery capacity in the region will stay almost constant until 2040, then slightly decrease until 2050. Maintaining oil-supply shares will be in focus to maximize government revenue.
- Given the cost advantage in renewable-electricity production, new forms of energy exports will be pursued for staking a position in green hydrogen. Examples include: Morocco entering a strategic partnership agreement with IRENA; and a joint venture (2020) among Air Products, ACWA Power, and Neom for a 4 GW plant in KSA to produce green hydrogen powered by solar and wind, and intended for ammonia exports globally.
- Systemic subsidization of energy will probably reduce slowly due to the stress on state budgets from growing populations and rising consumption. Carbon-border adjustment mechanisms and increased carbon-footprint quantification will play a key role in pushing oil and gas producers to demonstrate and improve carbon intensities from production.

7.5 MIDDLE EAST AND NORTH AFRICA

Energy Transition

Figure 7.5.1 shows Middle East and North Africa final energy demand growing throughout the forecast period. The growth is distributed across all sectors, with the exception of non-energy use. This reflects the decline in manufacturing output in the region as imports will serve its citizens rather than local production. Efficiency improvements will limit growth of final energy demand in all sectors, thereby counteracting the effects from population growth and rising standards of living.

The share of electricity in final energy demand will continue to increase, rising from 17% in 2019 to 32% in 2050. Buildings see early electrification, with transport and manufacturing sectors following later. The 2050 electricity mix will be dominated by renewable sources. Remarkably, for this oil and gas rich region, variable renewables will generate over 80% of power in 2050.

Figure 7.5.2 shows natural gas and oil dominating the primary energy mix through to 2050. Both oil and natural gas will see stable use until 2050, with around 78% of the gas going to the power sector. Solar PV and wind will provide an entire 26% growth in primary energy, affording shares of 15% and 11% respectively, by mid-century. Coal, nuclear, hydropower, and biomass will all remain as minor players.

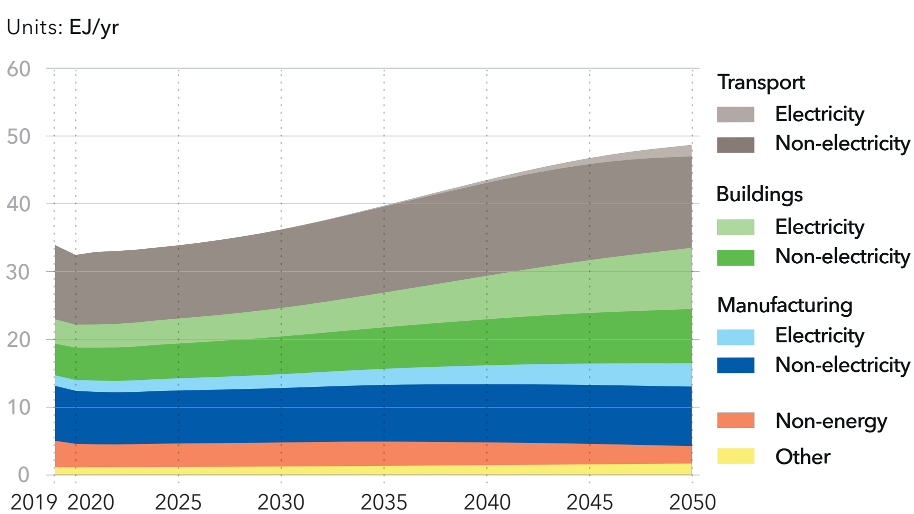
Energy Transition Indicators

Figure 7.5.3 presents Middle East and North Africa developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparisons are given in Section 7.11).

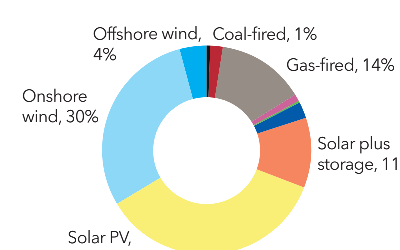
– The region will see a near doubling in the share of electricity in its final energy demand mix after 2030, with a share of 32% in 2050

FIGURE 7.5.1

Middle East and North Africa final energy demand by sector



2050 electricity mix



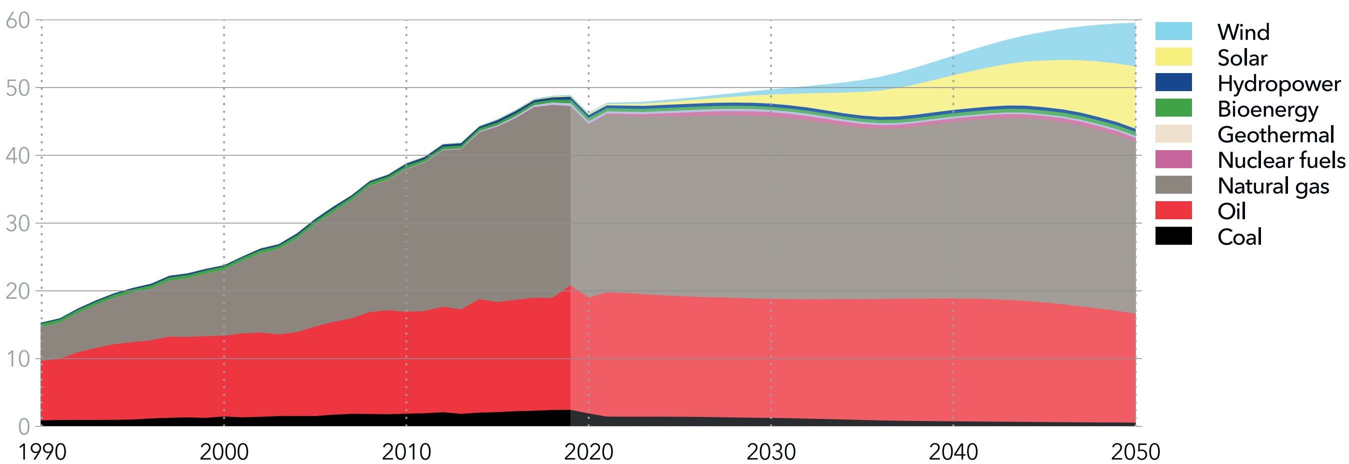
– Energy intensity in this oil and gas rich region will decline by more than 40% between 2019 and 2050. Nevertheless, it will still have the second-highest energy intensity of any region.

– The high share of fossil fuels in the energy mix will counteract further carbon-intensity reductions, declining to about 42 tCO_2/TJ in 2050 and representing the third highest regional carbon intensity.

FIGURE 7.5.2

Middle East and North Africa primary energy consumption by source

Units: EJ/yr



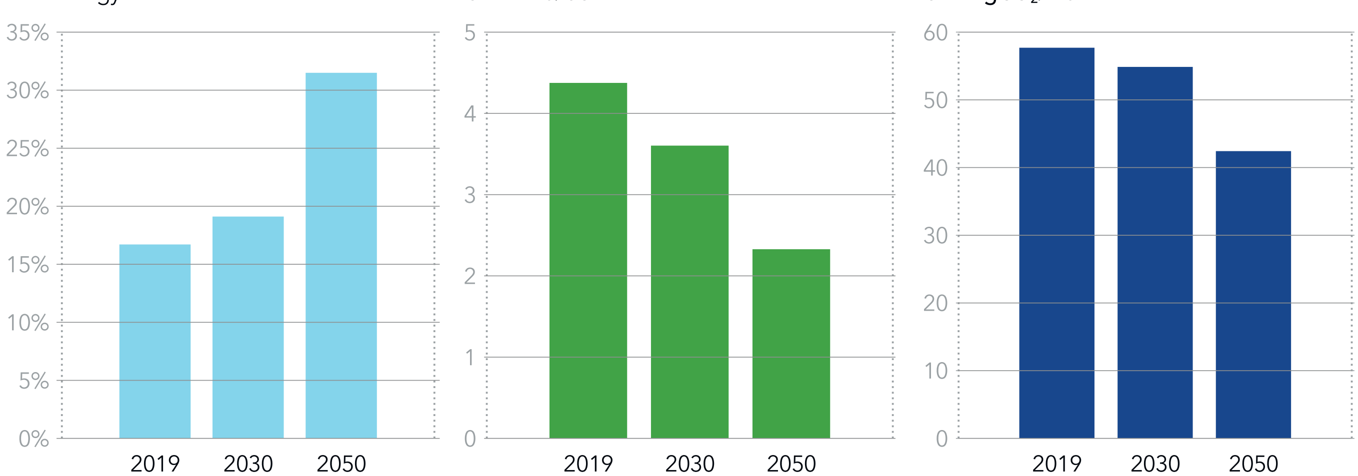
Historical data source: IEA WEB (2020)

FIGURE 7.5.3

Electrification
Electricity share in final energy demand

Energy intensity
Units: MJ/USD

Carbon intensity
Units: gCO_2/MJ



Emissions

We project the region's carbon price to be USD 20/t CO_2 by 2050. There will be limited explicit carbon-pricing instruments, and the likely first step towards carbon pricing will be the elimination of fossil-fuel subsidies.

Reflecting stable gas and oil use over the next decades, energy-related emissions will remain at current levels. Figure 7.5.4 shows a slight decline in manufacturing emissions and a small increase in transport emissions.

As the carbon price will remain low, the expected uptake of CCS is negligible in the region, at 7.8 $MtCO_2$/yr in 2050, which is below 1% of total emissions.

NDC pledges indicate the regional target for emissions to increase by no more than 377% by 2030 relative to 1990. Our Outlook suggests that energy-related emissions will be limited to a 190% increase by then, demonstrating that emission-target ambitions could be considerably higher. There are however 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. Most Middle Eastern emission targets are also given in relation to a "business as usual" trajectory.

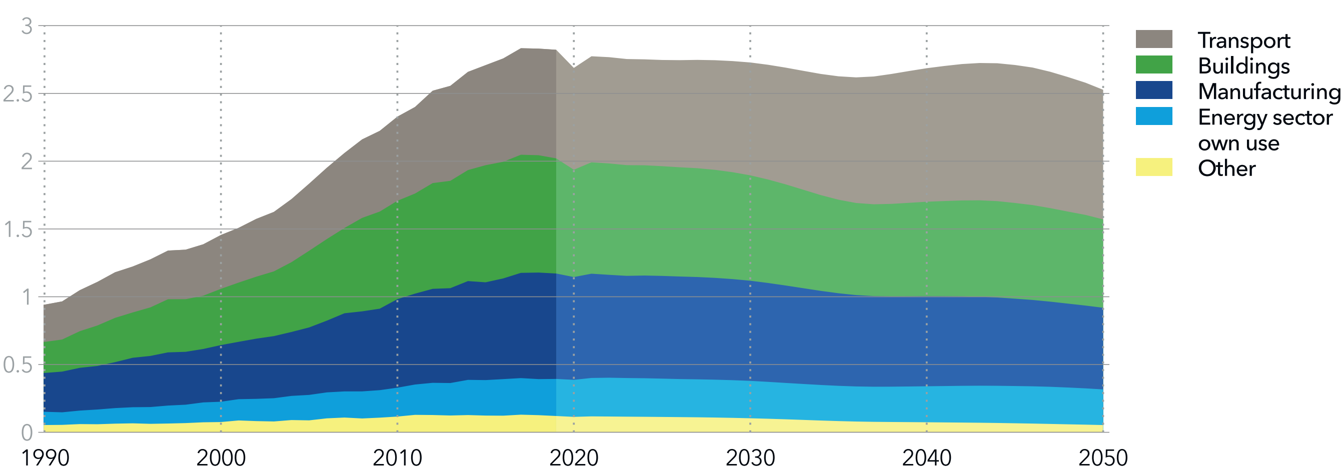
By 2050, emissions in the Middle East and North Africa region are expected to be reduced by 10% compared with 2019. This is equal to energy-related emissions of 2.5 $GtCO_2$/yr. None of the countries in this region have set emission targets for 2050.

The Middle East and North Africa's forecast emissions of 3.6 tCO_2/person in 2050 are 32% below the present level, but the third highest of all regions. This fossil-rich region will have a relatively slow transition, with emissions declining less than in other regions with similar standards of living.

FIGURE 7.5.4

Middle East and North Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Unleashing solar's potential

Middle East and North Africa is one of the most favourable regions for solar-power generation. Abundant regional oil and natural gas supplies mean the solar-power resource has been quite unused, but we expect that to change dramatically during our forecast period. In 2019, the region had one of the world's lowest shares of solar in the power mix (1.1%). In 2050, solar will represent 48% of power generation, sharing the top spot with the Indian Subcontinent (49%). This will correspond to 15% of primary energy in 2050.

To achieve this transition, as shown in Figure 7.5.5, almost every new power-generation installation will be renewable by 2030. Solar will represent up to 80% of new additions in the early 2030s, flattening to around 70% thereafter; the remaining share will be mostly covered by onshore wind. This means that there will be a yearly installation average of 38 GW from 2020 to 2050.

This transition to variable sources and massive electrification will be accompanied by a large adoption of utility-scale storage. From being almost non-existent today, 145 TWh will be stored yearly by 2050. This will correspond to 15% of global storage, a similar share to that of Greater China. Around 100 TWh, or 70% of the needs, will be stored in Li-ion batteries.

In 2019, the region had one of the world's lowest shares in solar in the power mix (1.1%). In 2050, solar will represent 48% of power generation.

FIGURE 7.5.5

Middle East and North Africa grid-connected electricity generation capacity additions by power station type

Units: **GW/yr**

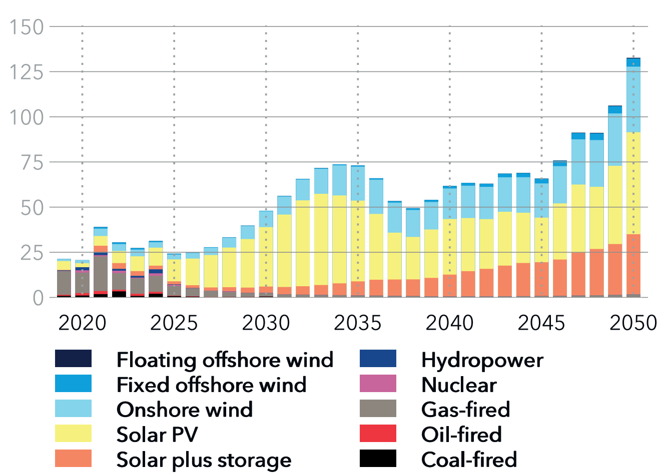
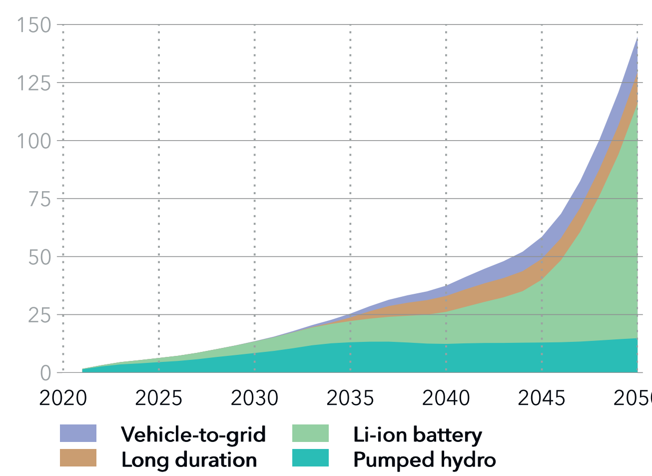
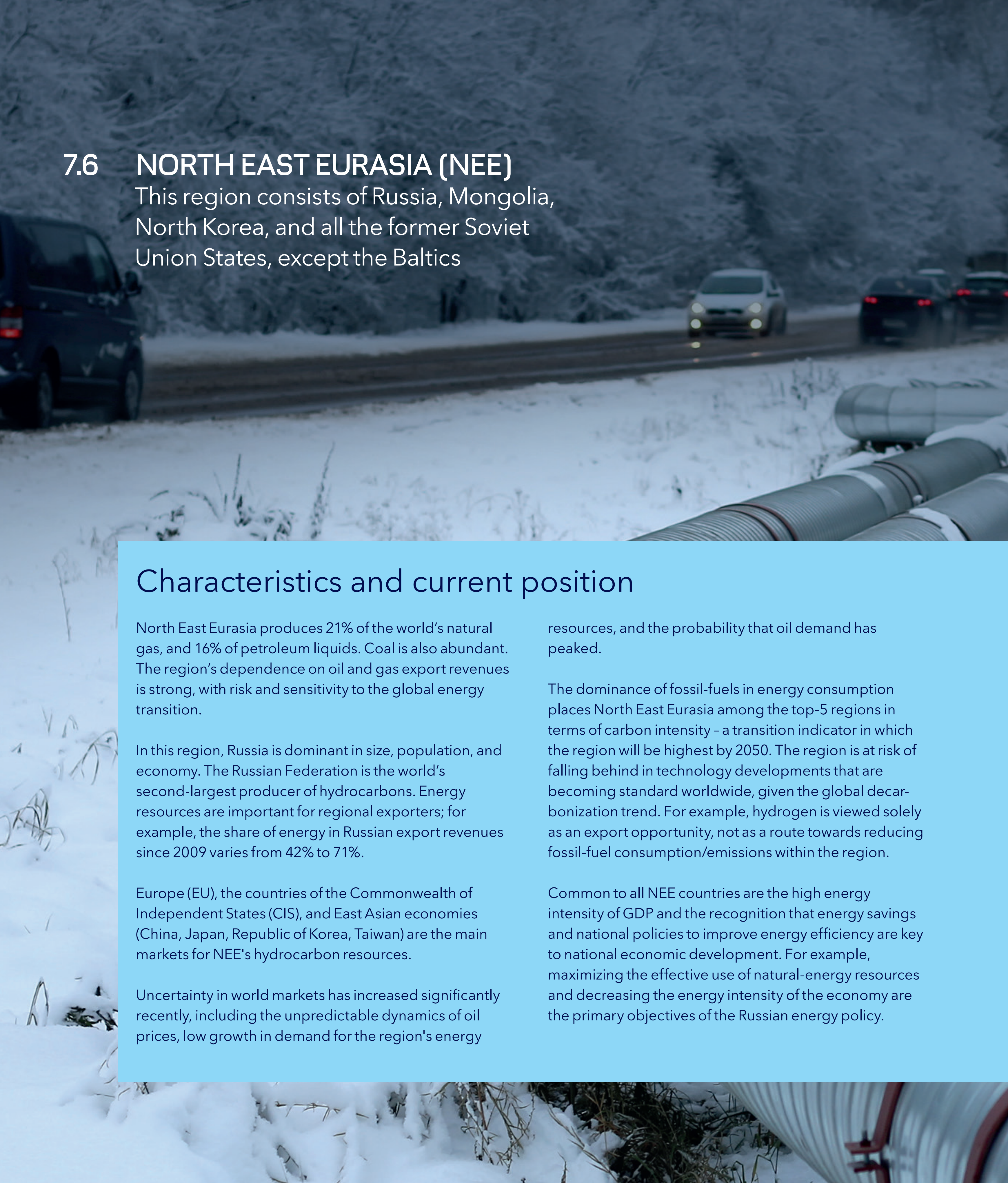


FIGURE 7.5.6

Middle East and North Africa electricity generation from utility-scale storage

Units: **TWh/yr**





7.6 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 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.

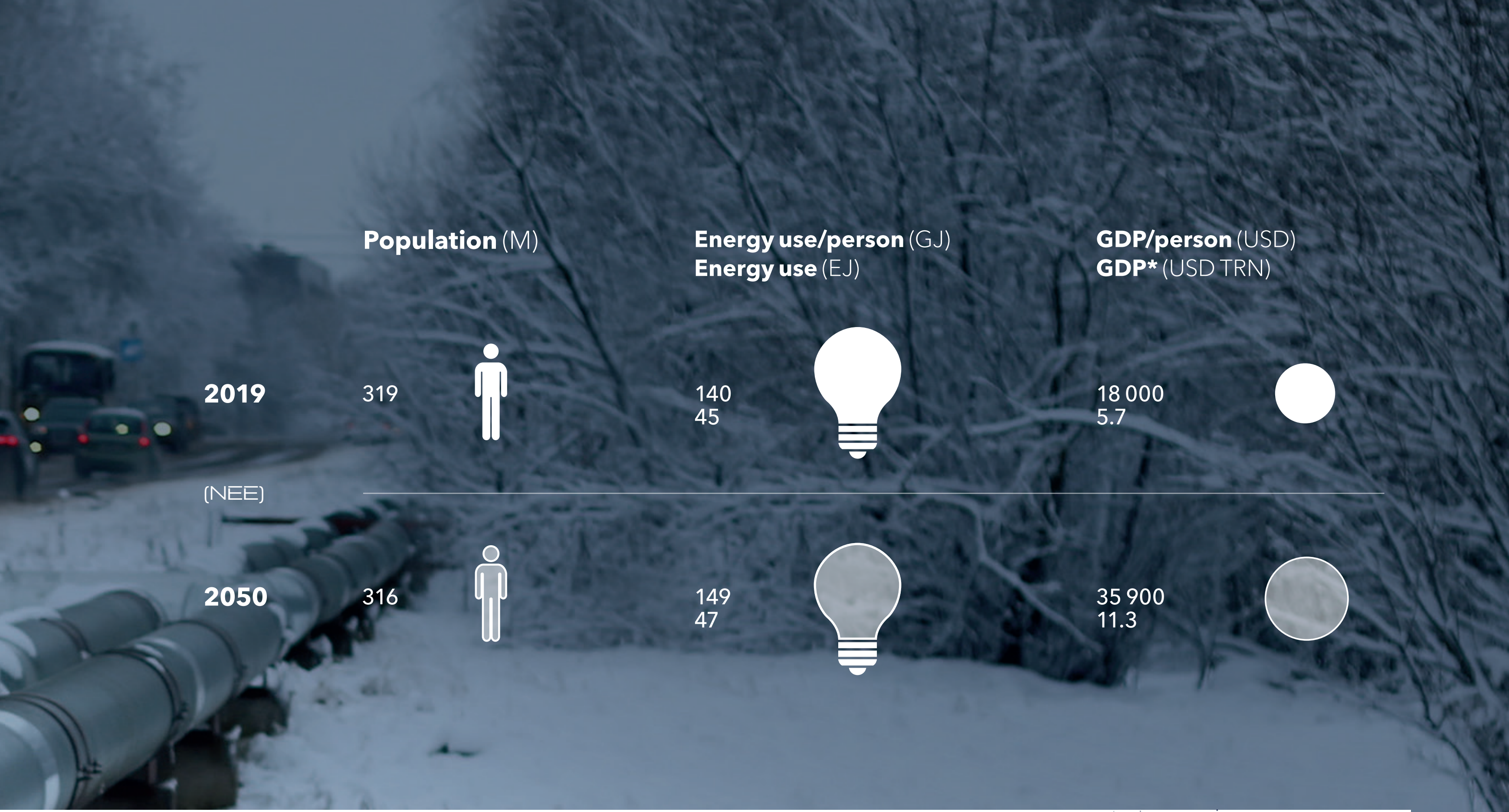
In this region, Russia is dominant in size, population, and economy. The Russian Federation is the world's second-largest producer of hydrocarbons. Energy resources are important for regional exporters; for example, the share of energy in Russian export revenues since 2009 varies from 42% to 71%.

Europe (EU), the countries of the Commonwealth of Independent States (CIS), and East Asian economies (China, Japan, Republic of Korea, Taiwan) are the main markets for NEE's hydrocarbon resources.

Uncertainty in world markets has increased significantly recently, including the unpredictable dynamics of oil prices, low growth in demand for the region's energy resources, and the probability that oil demand has peaked.

The dominance of fossil-fuels in energy consumption places North East Eurasia among the top-5 regions in terms of carbon intensity – a transition indicator in which the region will be highest by 2050. The region is at risk of falling behind in technology developments that are becoming standard worldwide, given the global decarbonization trend. For example, hydrogen is viewed solely as an export opportunity, not as a route towards reducing fossil-fuel consumption/emissions within the region.

Common to all NEE 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 of the Russian energy policy.



	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2019	319	140 45	18 000 5.7
(NEE)			
2050	316	149 47	35 900 11.3

Pointers to the future ›››

- Abundant fossil-fuel reserves, along with economic dependence and substantial political will to develop these, eclipse the energy transition as a priority. The largest contribution towards lower energy use and decarbonization will come from modernization and improved energy efficiencies in all sectors.
- The Russian Energy Strategy to 2035 considers East Asia and Pacific as emerging markets to balance westward energy flows. It is expected that overall energy exports to Pacific markets will reach equality with Atlantic ones. For Russian gas exports, the Energy Strategy to 2035 foresees retention of westward market volumes and steady growth eastward. Export infrastructure, such as the Nord Stream 2 and Power of Siberia 2 pipelines, will aim for diversification of transit routes. For the entire region, an increase in gas exports, as LNG, is expected.
- By 2030, Russia targets a 30% reduction in emissions, compared with 1990 levels. Its 2050 proposed long-term strategy effectively means increasing emissions towards 2030 from today's levels (WRI, 2020). Energy efficiency, reforestation, and carbon-free nuclear and hydropower are focus areas domestically. However, the EU's Green Deal and planned carbon-border adjustment mechanism, as well as hydrogen focus in e.g., Japan, makes hydrogen an export priority.
- Kazakhstan's National Concept for Transition to a Green Economy sets a timeline for 30% alternative- and renewable-energy sources (including nuclear) by 2030, and 50% by 2050. Ukraine's Low Emission Development Strategy for 2050 focuses on energy-efficiency measures, fossil fuel phase-out, and switching to renewables, but awaits an implementation plan.
- Kazakhstan's emissions trading scheme (ETS), with allowance prices averaging USD 1.1 t/CO2e in 2020, is insufficient to drive significant decarbonization. Ukraine plans to align its climate policy with EU regulation, including an ETS by 2025; and the EU's position on its carbon-border adjustment mechanisms in relation to Ukraine will depend on the readiness of this scheme.

7.6 NORTH EAST EURASIA

Energy Transition

With a flat population and a relatively slow transition to electricity, efficiency improvements generally counter the effects of economic growth, resulting in a comparatively flat energy demand. North East Eurasia's fina energy demand, as shown in Figure 7.6.1, will stay at current levels. Although buildings will see an increase in demand throughout the forecast period, after the 2040s, both transport and manufacturing will see a slight reduction in demand.

As Figure 7.6.1 shows, the share of electricity in the final energy demand will continue to grow, but more slowly than in any other region, rising from 15% in 2019 to 22% in 2050. This is the second-lowest of all regions, after Sub-Saharan Africa. The buildings and transport sectors are both increasing their use of electricity, but for manufacturing, the electricity share will remain at around 28% throughout the forecast period, mainly due to lower fossil-fuel prices in relative terms. The 2050 electricity mix will be dominated by gas, with 66% of generation, up from 44% today. Solar and wind will grow slowly compared with other regions. The coal share of electricity supply will decrease from 20% in 2019 to 3% in 2050, and nuclear generation is relatively flat.

The region's primary energy mix reflects its resource abundance and remains dominated by fossil fuels, as shown in Figure 7.6.2. Oil will be the main energy source in the transport sector and natural gas in the buildings and power sectors. In 2050, natural gas, oil, and coal will still cover more than 88% of the region's primary energy use, nuclear will be 5%, and, at less than 7%, renewable energy will be the lowest of any region.

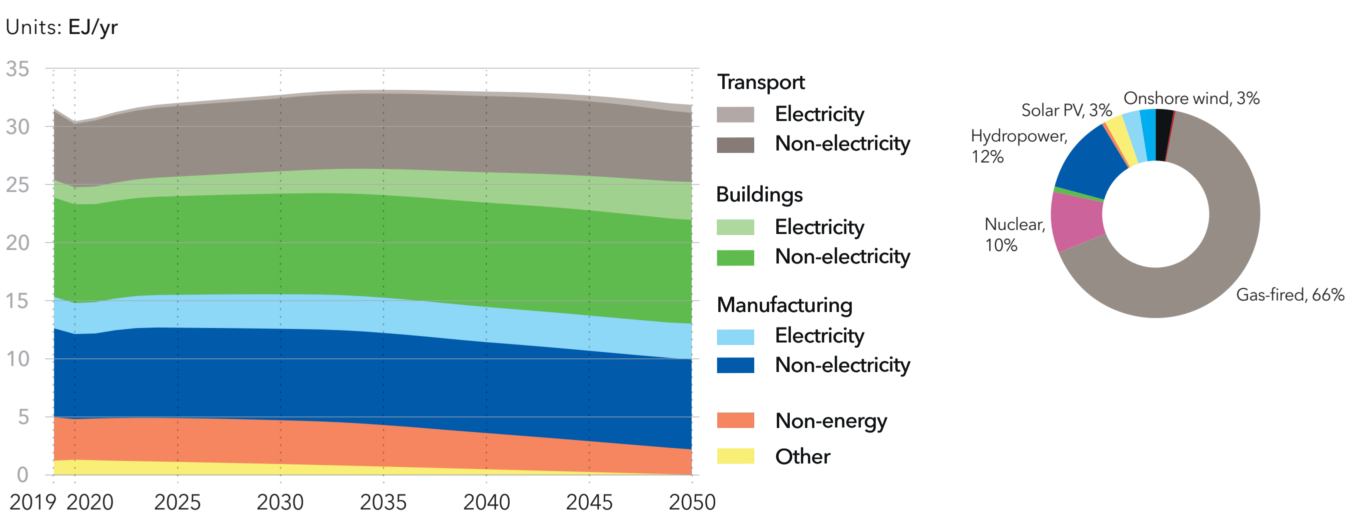
Energy Transition Indicators

Figure 7.6.3 presents developments in North East Eurasia on three main energy-transition indicators: electrification, energy-intensity improvements, and decarbonization (definitions and regional comparisons are given in Section 7.11).

FIGURE 7.6.1

North East Eurasia final energy demand by sector

2050 electricity mix

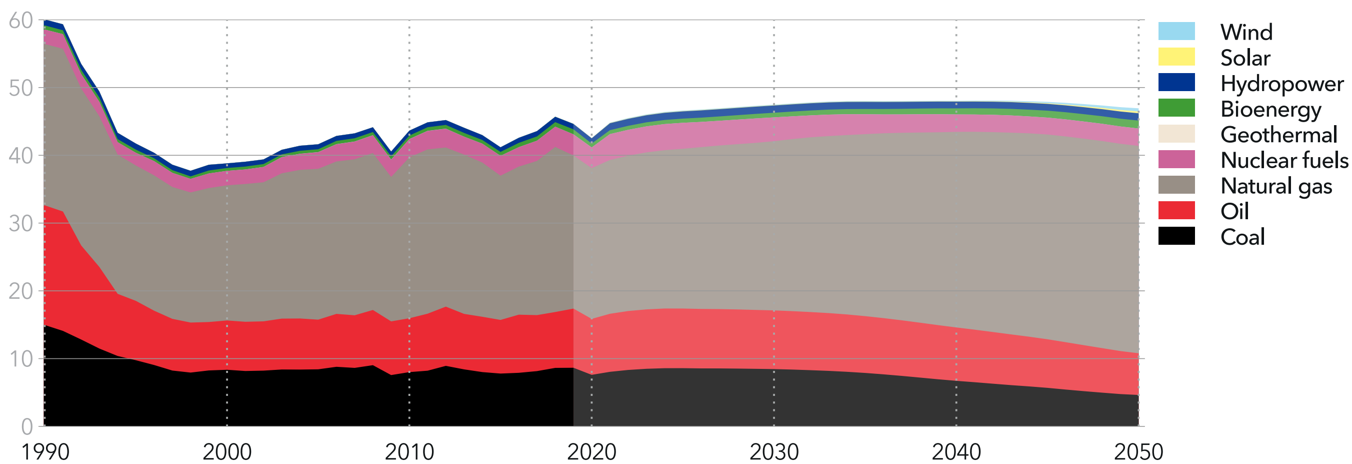


- Although, the region will increase its electricity share in the final energy demand mix to 22% (mainly after 2030), it still represents the second-lowest electrification value of all regions.
- The almost 50% reduction in the region's energy intensity is a significant improvement; however, it remains the region with the highest energy intensity of all, at 4.2 MJ/USD in 2050.
- Only a minor reduction in carbon intensity is achieved, declining to 52 tCO_2/TJ in 2050, again remaining one of the highest of all regions, just below the Indian Subcontinent and the Middle East and North Africa.

FIGURE 7.6.2

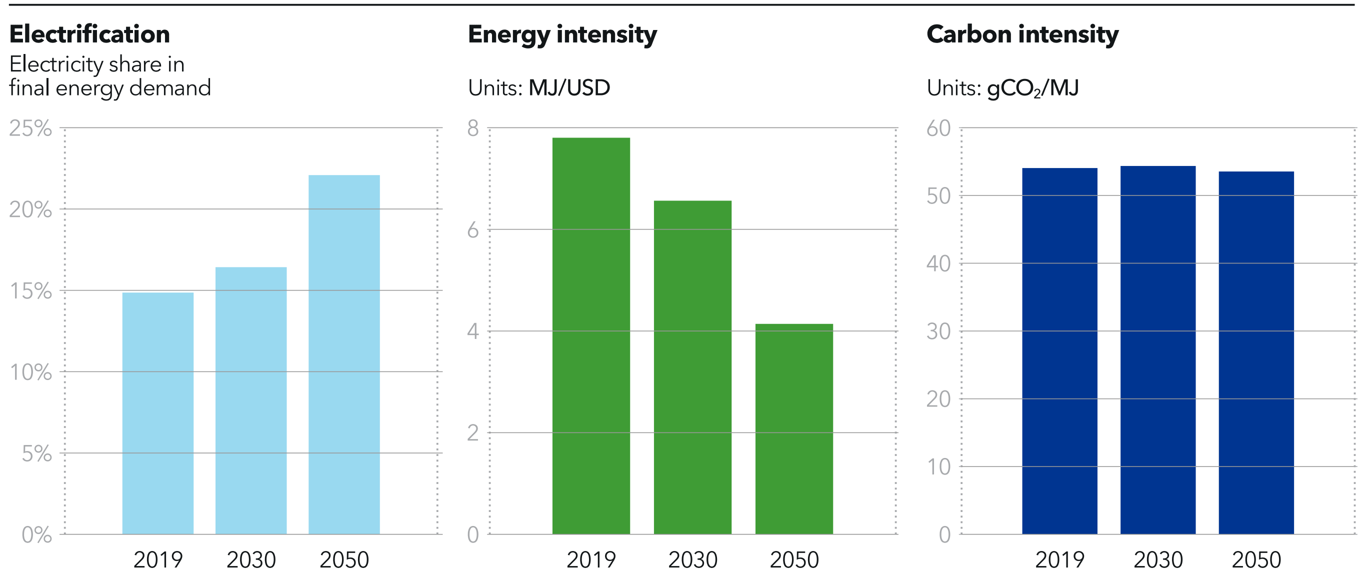
North East Eurasia primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.6.3



Emissions

Slow adoption and low carbon prices are expected, although the region is likely to embrace some form of carbon pricing to avoid carbon-border adjustment mechanisms from the EU. We project the region's average carbon price to be USD 20/tCO_2 by 2050.

Energy-related emissions from North East Eurasia, which have been stable over the last two decades, are likely to continue to remain at around the same level as today in 2050. Shares will remain even among the demand's main sectors, and manufacturing and buildings will dominate emissions in 2050.

Natural gas is already the largest emitter in the region today, and towards mid-century its share will increase, with gas emissions more than double those from oil and coal combined. The expected uptake by CCS is minor at 74 MtCO_2, meaning that under 3% of total emissions in 2050 are captured.

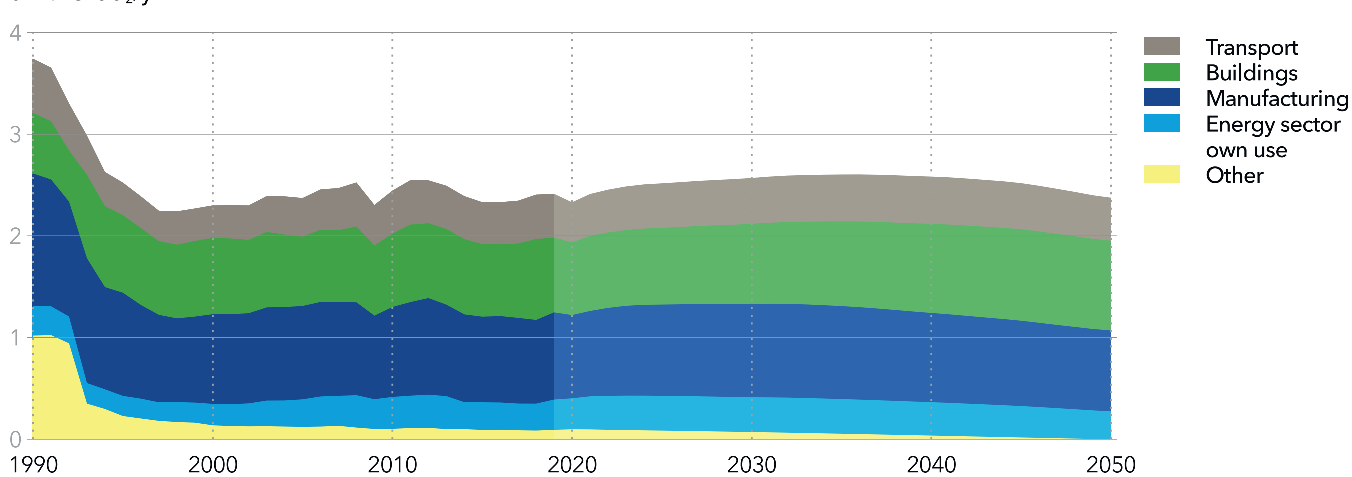
Interpretation and calibration of country NDC pledges in the region, indicate that the regional target for reducing energy-related emissions is 26% by 2030, relative to 1990. Our Outlook indicates that energy-related emissions will be down 31% by 2030, meaning that the region as a whole reaches its climate goals. By 2050, emissions are expected to fall by 2% compared with 2019: This reflects that emissions have been falling since 1990, and that they will increase somewhat before returning to today's level in 2050. Remaining energy-related emissions are then 2.4 GtCO_2/yr. There is some talk of climate-neutrality goals within the region, but these are mostly long term and beyond 2050.

North East Eurasia's 7.7 tonnes CO_2/person is the highest of all regions, nearly twice that of North America, which is the second highest. The fossil-rich region has a slow transition and few incentives for change.

FIGURE 7.6.4

North East Eurasia energy-related CO_2 emissions by sector

Units: GtCO_2/yr



Hydrocarbons or hydrogen?

Russia, the dominant energy heavyweight in the North East Eurasia region, is set to diversify export routes for its oil, gas, and coal resources. Thousands of kilometres of pipeline infrastructure, as well as railway, are being built to strengthen its position in supplying energy needs, both East and West. The prospect that both Europe and Asia will rely on natural gas as a bridging fuel in their transitions is one main assumption driving Russia's infrastructure expansion. Up until 2045, North East Eurasia is expected to be the world's-largest natural gas exporter, but will be overtaken at that point by the Middle East and North Africa region (Figure 7.6.5). However, it is a strategic bet on the importance of natural gas in the global energy transition.

In Russia, blue-hydrogen production has tremendous potential given the combination of the world's largest gas reserves, along with carbon and capture technology. The 'Energy Strategy until 2035' states Russia's ambition to become one of the main producers and exporters of hydrogen, with export targets at 0.2 million tonnes (240 PJ) by 2024 and 2 million tonnes (2,400 PJ) by 2035. The 'Roadmap for hydrogen development until 2024' sets the framework for achieving these goals. Our forecast estimates North East Eurasia will produce about 200 PJ by 2035 and 1,100 PJ by 2050, purely from natural gas, which is somewhat below the goals of the strategy stated by Russia.

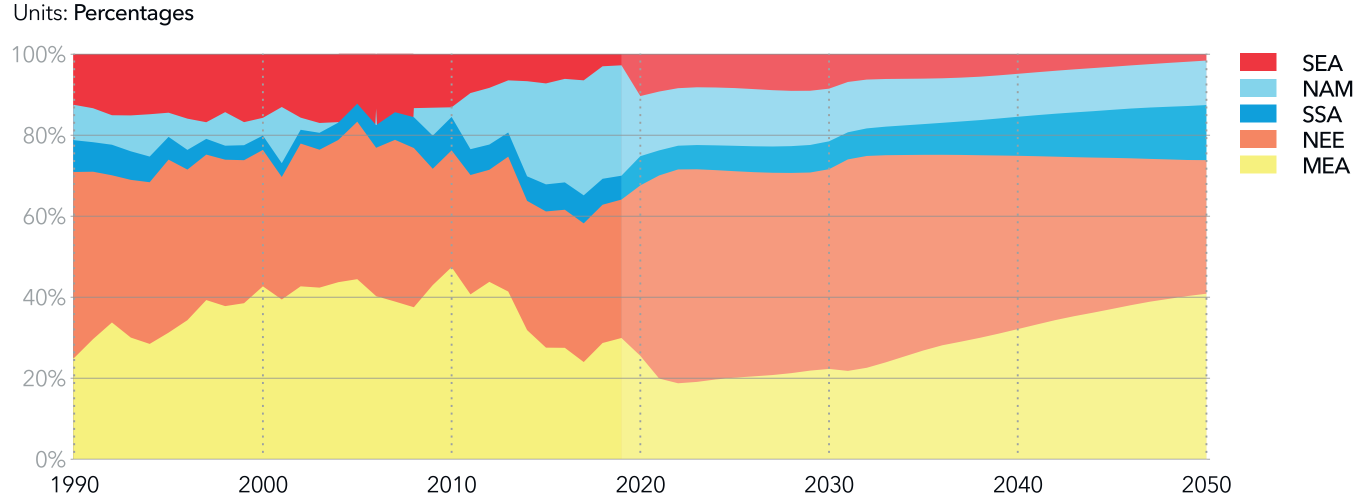
According to SWP (2021), referring to proposed concepts for hydrogen development in Russia, there are plans to export between 7.9 million and 33.4 million tonnes (between 9,480 and 40,080 PJ) by 2050. However, while pursuing blue hydrogen for export purposes, plans for uptake in the home market are lacking, setting up Russia, and thus the North East Eurasia region as an emissions laggard.

Counting on lasting success of supporting the green transition abroad while missing the opportunity to transform the domestic economy is risky.

FIGURE 7.6.5

Regional mix of net natural gas exports by source

Units: Percentages



Excludes intra-regional trade. Historical data source: IEA WEB (2020)

7.7 GREATER CHINA (CHN)

This region consists of Mainland China, Hong Kong, Macau, and Taiwan

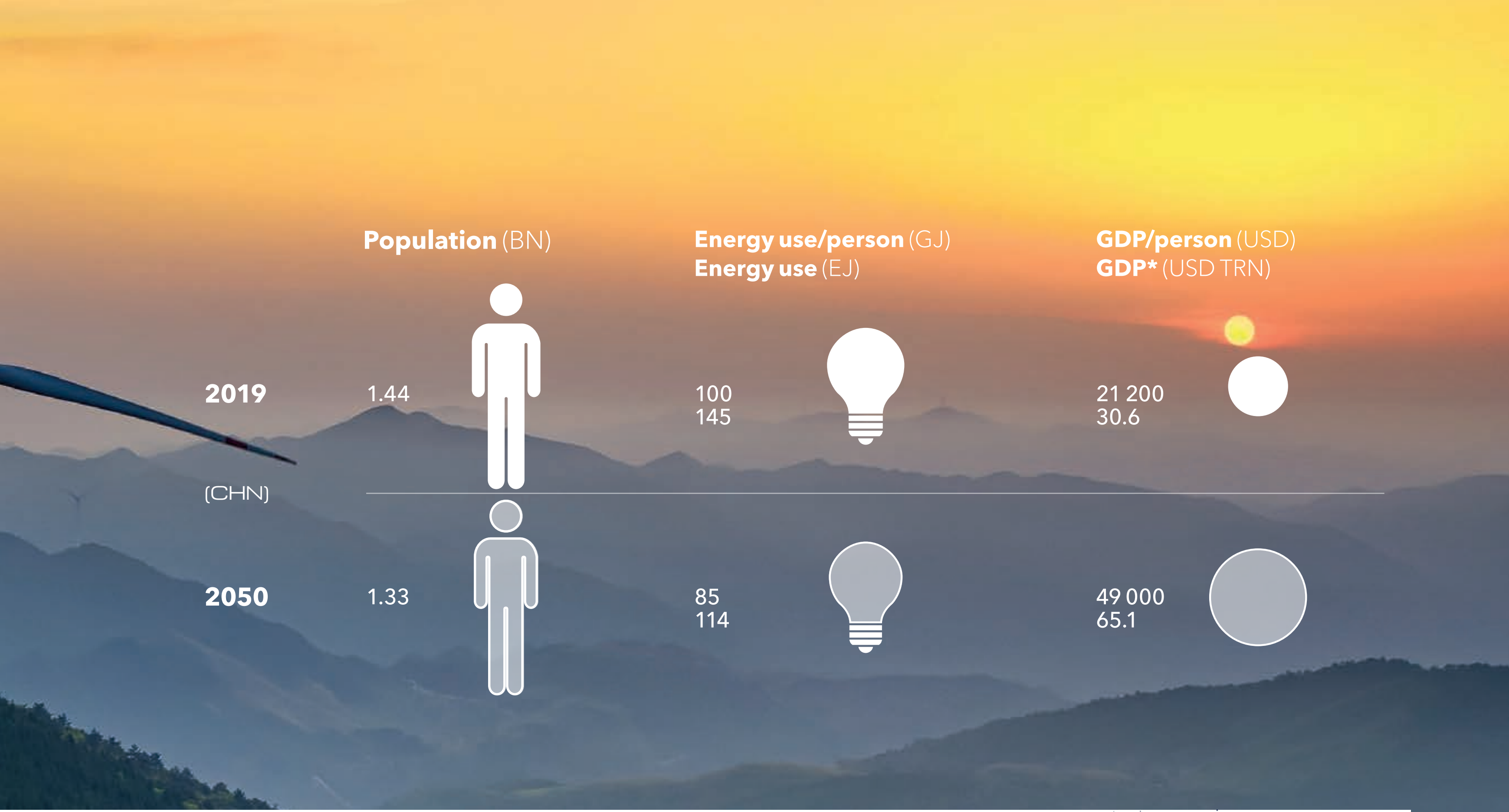
Characteristics and current position

China is both the world's biggest consumer of coal and the largest investor in renewable-energy technologies. At 934 GW in 2020 (NEA, 2021), its renewables capacity was more than 30% of the global total. At that time, China's wind capacity was 281 GW, (96% onshore and the remainder offshore), and solar PV capacity was 253 GW.

China has committed to reaching peak emissions before 2030, and to achieving carbon neutrality by 2060. Plans to achieve the 2030 target include: decreasing carbon-emission intensity (tCO_2 per unit GDP) by more than 65% from that of 2005, increasing the non-fossil share in primary-energy consumption to around 25% (currently about 16%), and renewables generating at least 35% of power (now about 27%), with combined wind/solar capacity above 1.2 TW (NEA, 2021).

Energy security and air quality are top priorities, alongside decarbonization. National action plans delivered positive results in 2020 (MEE, 2021a), and efforts continue, as heavy-pollution episodes still occur (Zhang et al., 2020). Carbon intensity fell 48.4% between 2005 and 2020, curbing previously rapid CO_2-emissions growth (MEE, 2021b). Post-Covid emissions rebounded in 2020 due to a surge in coal use, driven by heavy industry and infrastructure projects (IEA, 2021).

China aims to shift from high-quantitative growth, based on resource-intensive manufacturing and exports, to high-quality growth. Its dual-circulation strategy is to spur domestic demand for medium- and high-end products, while boosting economic resilience to global market dynamics. Tactics include speeding development of 'new infrastructure', such as intercity high-speed railways and creating the world's largest charging network for EVs. Policy support has led to China having more than 5.8m new EVs, some 50% of all EVs sold worldwide (CAAM, 2021). New EV sales in China in 2020 - of more than 1.3m - lagged just behind Europe's 1.4m (S&P Global, 2021).



Pointers to the future ▸▸▸

- China's carbon-neutrality pledge is important for global climate ambitions but lacks a hard target for reducing emissions towards 2030.
- China aims to limit increases in coal consumption over the14th Five-Year Plan (FYP) 2021-2025, and phase downcoal use during 2026–2030.
- A national plan for peak carbon emissions by 2030 is imminent (winter 2021/22), and industry-specific plans will follow. Provincial plans focus on increasing renewables. Ongoing reform of financial support, shifting to subsidy-free, may have a short-term impact on developments. However, continued renewables growth is expected, relying on market-oriented support schemes such as renewables obligations and tendering systems (Heggelund, 2021).
- China will soon overtake Japan as the largest importer of LNG, as policy continues to drive coal-to-gas switching. There will be more LNG terminals by 2030, while natural gas pipelines and storage buildout will continue. Natural gas-fired power generation will play a minor role, mostly as peaker plants.
- Various initiatives will reduce industry's energy intensity. 'Made in China 2025', promoting innovation in core sectors, will trigger industry electrification and upgrades in processing technology. More pilot projects will set hydrogen on course to account for some 10% of energy end use by 2050.
- China is developing a value chain for green-hydrogen fuel cells, focusing on long-haul heavy trucks and buses. Several hydrogen-fuel-cell buses are already operating in demonstration zones (State Council, 2020). There will be approximately 350 hydrogen-refuelling stations in 2025, and 1,000 by 2030 (CICI, 2020).
- China's carbon-emissions trading scheme (ETS) started trading mid-July 2021, at below USD 8/tCO_2 (Global Times, 2021), with the power sector's 2,225 powerplants accounting for around 40% of GHG emissions. The scheme will expand to cover all high-emission industries, but the timescale is currently unknown. CCS is expected to develop in Greater China as a result of mandates.

7.7 GREATER CHINA

Energy Transition

Greater China's final energy demand has nearly tripled over the last two decades, but at a declining growth rate. Figure 7.7.1 shows that the growth rate will ease further in the next decade, before the trend reverses and final energy demand reduces. The drop in demand is mainly due to population reduction and aging, and due to energy-efficiency gains overshadowing more modest growth in manufacturing products after 2035. There will even be a decline in base materials in the same period, as rising wealth, and consequent loss of industrial competitiveness, forces a de-industrialization in several industrial strongholds.

The share of electricity in final energy demand will continue to increase, rising from 23% in 2019 to 55% in 2050, the highest share among all regions. Manufacturing will see particularly strong electrification. Transport (China is a frontrunner in EVs) and buildings sectors will see a rapid shift to electricity; buildings rising from a 28% share today to 70% in mid-century. The 2050 electricity mix will be dominated by wind and solar, each with a 36% share. Hydropower will also be among the main contributors, taking the renewable electricity share to 86%.

Figure 7.7.2 illustrates a complete turnaround in Greater China's energy mix. Coal, by far the largest primary energy source currently, will decline in coming decades to make up only 17% of the energy supply in 2050. Oil is the second-largest energy source and will grow for another five years, when electrification of the vehicle fleet significantly impacts the demand for oil. The use of natural gas will increase over the next 15 years before starting to decline, mainly due to falling demand from the manufacturing sector, as base-materials output declines after 2035. Significant growth is expected for renewable energy sources, and China will have the second-highest wind share (after Europe) and the highest solar share of all regions.

Energy Transition Indicators

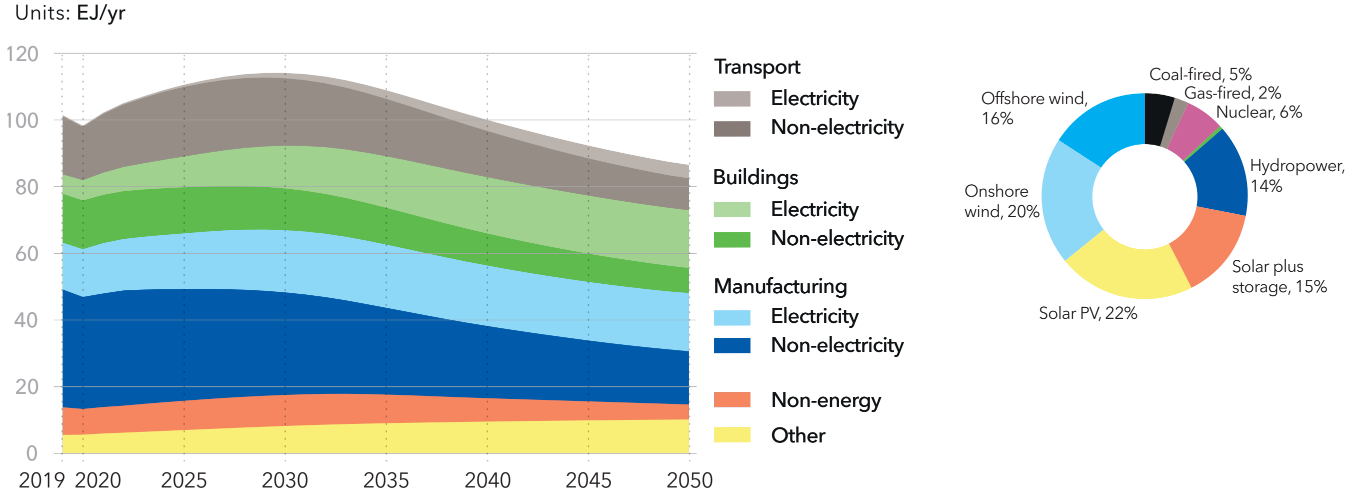
Figure 7.7.3 presents Greater China's developments on three main energy-transition indicators: electrification, energy-intensity improvements, and decarbonization

FIGURE 7.7.1

Greater China final energy demand by sector

Units: EJ/yr

2050 electricity mix



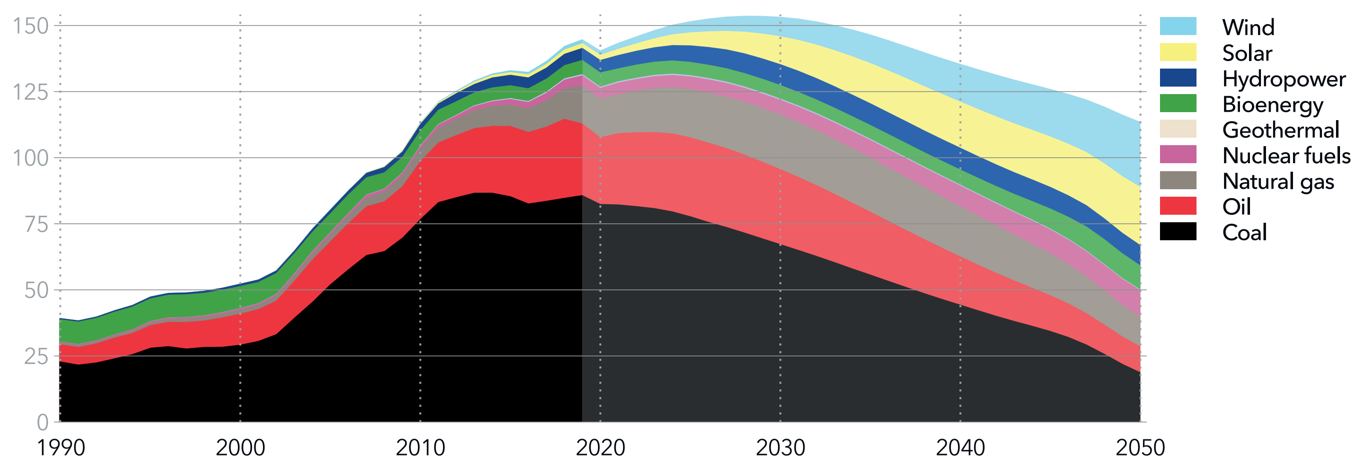
(definitions and regional comparisons are given in Section 7.11).

– Around 55% of the final-energy demand will be supplied by electricity in 2050. This is the highest of all regions and results from electrification of all demand sectors.
– The region's energy intensity will reach 1.7 MJ/USD, showing a similar pattern between 2019 and 2050 to that of many other world regions that achieve continuous efficiency improvements and electrification of energy end use.
– Carbon intensity will decline at a world-best pace after 2030, falling by almost two thirds and reaching a level comparable to that of North America and OECD Pacific, but trailing Europe.

FIGURE 7.7.2

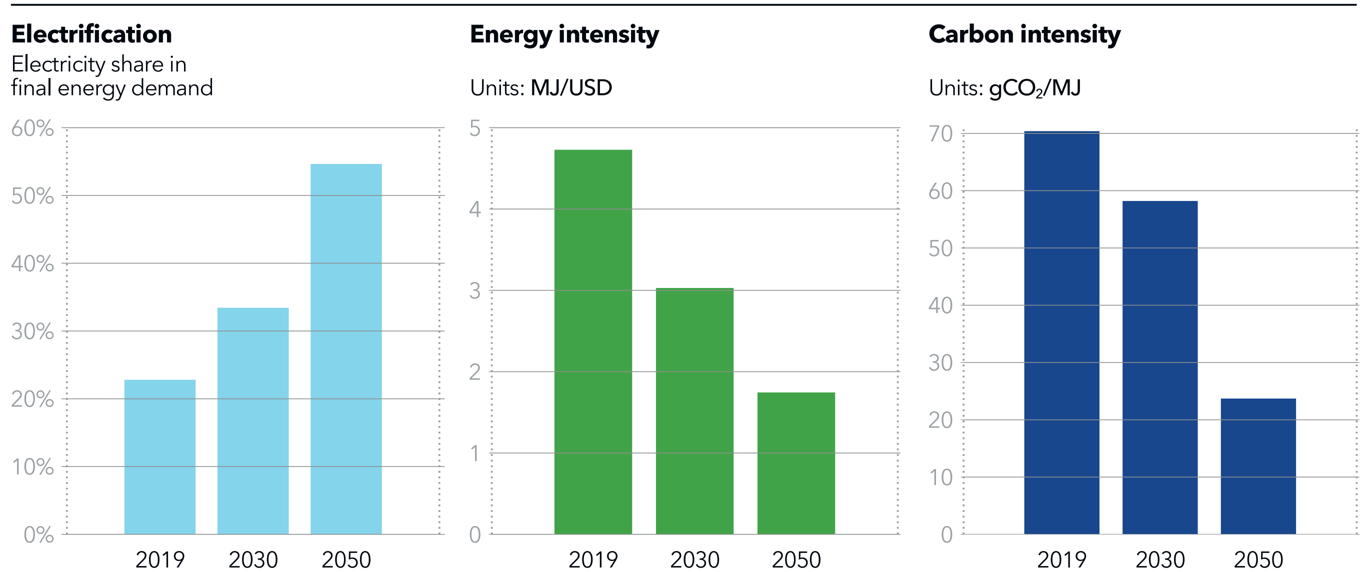
Greater China primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.7.3



Emissions

Greater China's energy-related emissions are around 30% of global emissions today, so their future trajectory will have a worldwide impact. Emissions from manufacturing have already peaked and will do so in transport and buildings around 2025. Coal is currently the source of more than 75% of China's CO_2 emissions and while this share will fall, coal remains the largest emissions source towards 2050.

The forecast of 434 $MtCO_2$/yr CCS capacity in Greater China in mid-century will be the highest of all regions, after rising rapidly from 39 $MtCO_2$/yr CCS in 2040. A combination of ample emission sources to choose between, along with a high CO_2 price, explains this rapid rise. Even so, CCS in Greater China in 2050 will capture only 13% of the region's total energy-related CO_2 emissions.

We project an average carbon price of USD 60/tCO_2 by 2050, a level exceeded only by Europe. China's nascent emission trading system (ETS) could eventually – after 2030 – link with carbon-pricing systems in neighbouring countries like South Korea and Japan (Heggelund et al., 2021).

China's targets include peak CO_2 emissions before 2030 and achieving more than a 65% reduction in carbon intensity (below 2005 levels) by the same year. Exact comparisons are difficult as our model does not regionalize non-energy-related CO_2 emissions. However, with CO_2 emissions modelled to start falling from 2025, our forecast trend indicates that it will easily achieve the 2030 target. Our Outlook suggests a reduction of approximately 70% in carbon intensity by 2030, meaning that the target should be achieved.

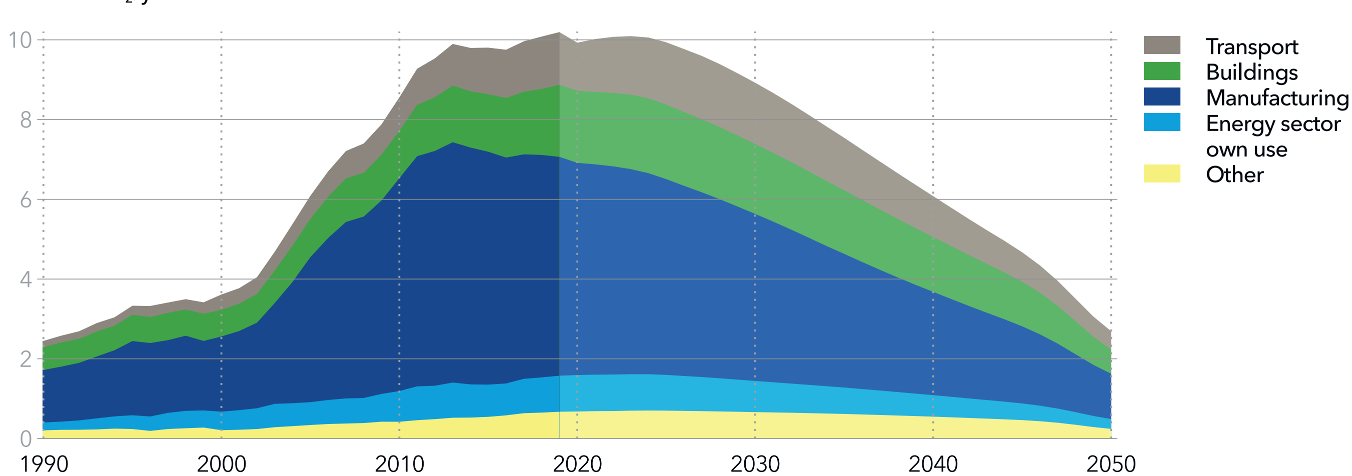
By 2050, Chinese energy-related emissions are forecast to be 2.7 $GtCO_2$/yr. This equates to a 74% reduction compared with that in 2019. China is expected to enhance its Nationally Determined Contributions to a 'net zero by 2060 pledge' before the COP26 meeting in November 2021, although it did not meet the end of July cut-off date for submissions to be included in the forthcoming United Nations Framework Convention on Climate Change (UNFCCC) synthesis report.

The region will emit 2.2 tCO_2/person in mid-century, somewhat below the global average, reflecting the rapid transition from coal after 2030. This is driven by growth of the service sector, lower industrial output, and accelerated decommissioning of coal-power plants as solar and wind energy start to dominate power production.

FIGURE 7.7.4

Greater China energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Electrification of road transport

Greater China will have more vehicles on the road than North America and Europe combined in 2050. Thus, changes in the road transport sector in China are relevant globally.

Our Outlook shows that by 2028, BEV sales will have overtaken sales of every other type of road vehicle in China. This watershed occurs earlier than in all other regions, except Europe. By 2048, 99% of vehicle sales will be BEVs. By 2037 there will be more EVs than ICE vehicles on the road in Greater China (Figure 7.7.5). Coincidentally, the peak for numbers of passenger vehicles will also occur in 2037.

Concerted and sustained policies designed to boost adoption of EVs, such as rapid roll-out of charging infrastructure and mandates to car manufacturers to include production of EVs, will be implemented. In addition, Greater China's manufacturing industry will be at the forefront of advances in the range of EVs and to lower battery costs, both of which support mass adoption of such vehicles. This is reflected in our model results, where Greater China has one of the lowest total-cost-of-ownership (TCO) levels for EVs.

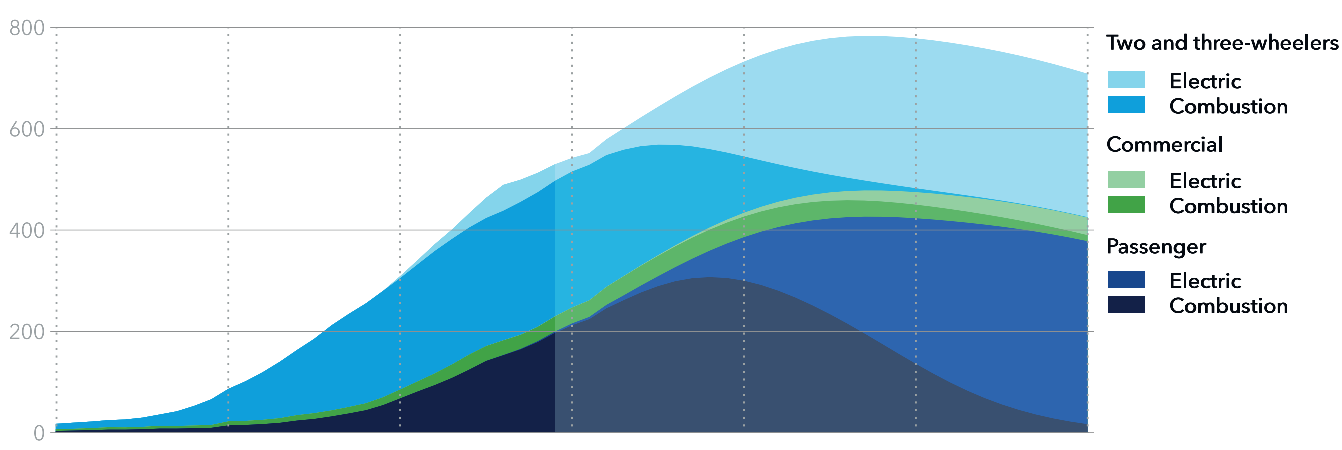
A two-fold effect of less tailpipe CO_2 emissions from decreased use of oil, while also using increasingly decarbonized electricity, will lead to significant reductions in CO_2 emissions from road transport. Furthermore, this reduction in oil use in road transport in China will generate the knock-on effect of the region achieving peak oil use in 2026. This will assist in meeting the region's ambitions of weaning itself off often-imported oil, as discussed in the Section on Energy Dependence.

Electrification of road transport, and the accompanying expansion in EV-manufacturing capacity, will have spill over effects on knowledge transfer; the availability of markets will also spur EV uptake in neighbouring regions. Furthermore, some countries in South East Asia will act as manufacturing satellites of Greater China, especially for the automobile industry. This will, in turn, speed up the electrification of road transport in those countries.

FIGURE 7.7.5

Number of road vehicles in Greater China

Units: **Million vehicles**



Combustion vehicles include ICEs and PHEVs. Electric vehicles include BEVs and FCEVs.
Historical data source: Marklines (2021), IEA EV Outlook (2021), OICA (2016)

Superpower in renewables

Everything is big in China. This is not unexpected, given that the region has 18% of the world's population, 22% of global GDP, and 24% of the global primary-energy use. In the renewables industry, the region's dominance is even larger: China produces 30% of the world's hydropower, 31% of solar PV power, and 28% of wind power.

As Figure 7.7.6 indicates, China's production of power from solar PV will grow 15-fold, reaching 5.5 PWh in 2050. By then, China's global share will have been reduced, albeit to a still-impressive 25%. Similarly, Figure 7.7.7 shows that power production from wind will grow more than 10-fold, reaching 5.1 PWh in mid-century, which, at that point, will still represent 29% of the world's wind-power production. In 2050, China will be the largest regional player in onshore wind, offshore fixed wind, and offshore floating wind.

For China, one challenge is that whereas the land space that is available for wind and solar PV generation is mostly located in the north and west, which also has the best wind and solar conditions, the majority of the population lives in the south and east, where space is scarcer. Hence, electricity from solar PV and onshore wind will increasingly be transported over long distances, requiring a massive build-out of the national grid.

China's share of equipment production – e.g., wind turbines, blades, PV panels, and inverters – is even larger. We do not forecast this development in our model, but the share may reduce over time as several countries will probably want to ensure a more independent supply chain for critical energy equipment.

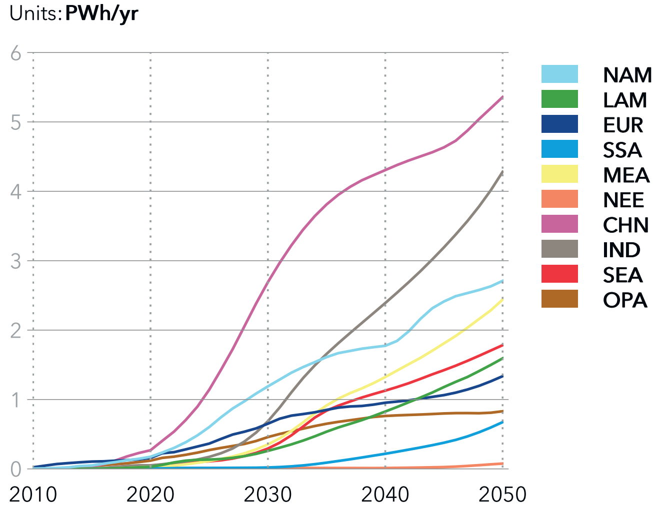
The storage or battery industry, which is essential to the renewables industry, is also dominated by China, where considerably more than half of all Lithium-ion batteries for EVs are produced.

Everything is big in China.

FIGURE 7.7.6

Grid-connected solar electricity generation by region, including solar+storage

Units: **PWh/yr**

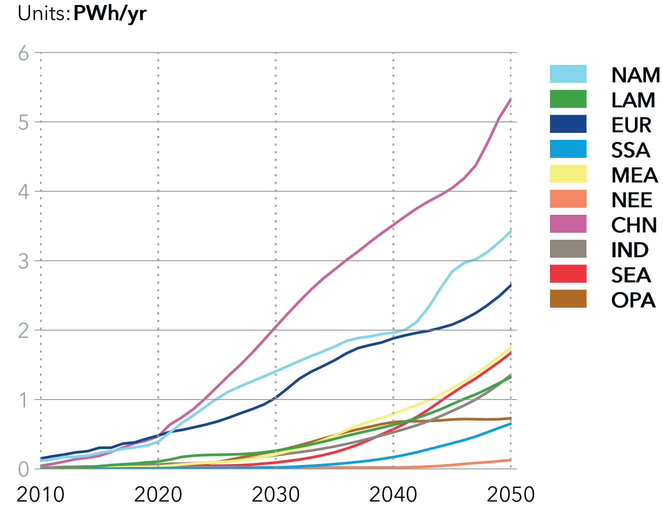


Historical data source: IEA WEB (2020), GlobalData (2021)

FIGURE 7.7.7

Grid-connected wind electricity generation by region

Units: **PWh/yr**



Historical data source: IEA WEB (2020), GlobalData (2021)

Peak coal in China

In April 2021, President Xi announced that China will reach peak coal by 2025. As China's coal use represented more than 22% of global CO_2 emissions in 2019, this has real implications for the world reaching its Paris Agreement ambitions. Our model indicates that China's peak coal is, in fact, already behind us in 2019, and that coal use by 2025 will have decreased by 10% from 2019 levels.

The power generation and manufacturing sectors are the major coal consumers in China. According to our Outlook (Figure 7.7.8), coal consumption in both will decline from 2020 onwards.

In China's manufacturing sector rapid electrification will result in coal demand in the sector being overtaken by electricity in 2036.

China's power generation will also shift, moving from coal supplying 60% of electricity generation in 2020, to less than 5% in 2050, despite an increase in 2021. More importantly, the share that coal loses will be taken by renewables, such as solar PV and wind. Coal use in buildings, which is relatively small, will fall in the coming years and will be largely replaced by natural gas.

These tandem transitions, happening simultaneously in the manufacturing and power sectors, hasten the transition to cleaner energy sources in China. The phasing out of coal in the power sector leads to decarbonized electricity, satisfying more of the energy demand from the manufacturing sector.

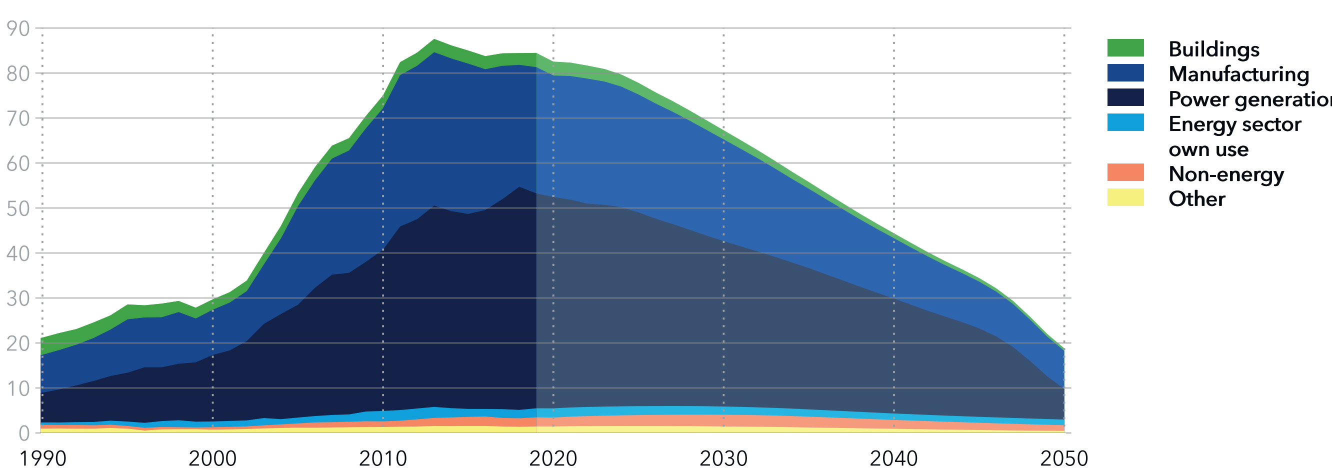
This transition is aided by the technological knowledgebase that has been built up by the region in past decades, and by the strong manufacturing capacity already present. As a manufacturing powerhouse, the region has the capability to ramp up the necessary production for such a transition, e.g., increasing manufacturing of solar PV modules. It is also the result of socio-political willingness, in part motivated by the need to reduce local air pollution, which has several co-benefits, including improved health among its residents.

It should also be noted that while China transitions away from coal, the global effect on climate will not be as large if the country exports its coal and coal-related technology to "Belt and Road" countries.

FIGURE 7.7.8

Greater China coal demand by sector

Units: **EJ/yr**



Historical data source: IEA WEB (2020)

Energy dependence – a continued situation for oil and gas

Energy security and energy independence, goals for most countries and regions, are bolstered by the energy transition and strong growth in domestically-produced renewables. As a global superpower, energy independence is also a clear goal for China, and the 'made in China' ambition is also relevant from an energy-independence perspective.

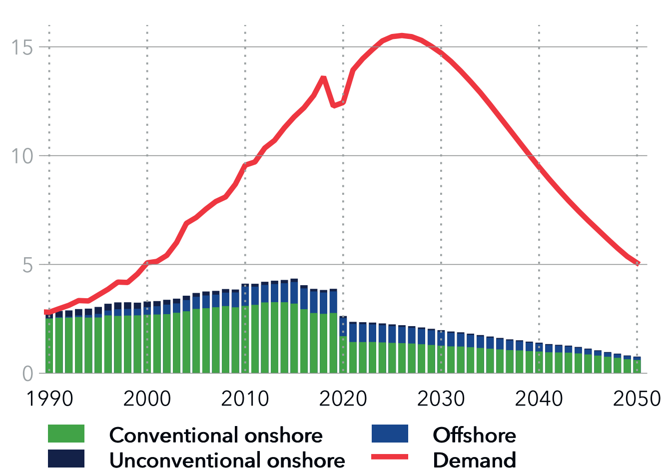
Domestically mined coal has dominated China's energy in recent decades, and only a small proportion of coal used has been imported. Our Outlook shows that in the coming decades, coal's share in energy use will reduce rapidly. There will be strong growth in renewables, and wind turbines and solar panels installed in China will be produced there too; the same applies to batteries deployed in the grid and to EVs. Unlike with coal, some of the raw materials and minerals needed for renewable energy might not exist domestically, and China has worked with governments around the world to secure a stable supply of those needed in the new energy system. The main challenges today, and in the coming decades, are likely to be in oil and gas. Figure 7.7.9 and Figure 7.7.10 show that the vast majority of China's oil and gas is currently imported, and this will continue throughout the forecast period. Although absolute demand and import of both oil and gas will more or less halve between 2030 and 2050, import needs in 2050 will remain at around 4 million barrels per day (mbpd) of oil and 200 Gm3/yr of gas. Reserves, along with the global competitiveness of Chinese oil and gas, are insufficient to ensure oil and gas independence.

This is a situation to which the Chinese authorities are accustomed, and bilateral agreements, in particular with Russia and Middle Eastern countries, have ensured a secure supply of oil and LNG for China. Further, energy trade often seems to survive other political disagreements, as demonstrated by the April 2021 LNG-import record from Australia. Nevertheless, continued dependence on energy imports is not ideal for China; the pathway to full energy independence is to ensure an even-faster transition away from oil and gas.

FIGURE 7.7.9

Greater China crude oil production and demand

Units: **Mb/d**

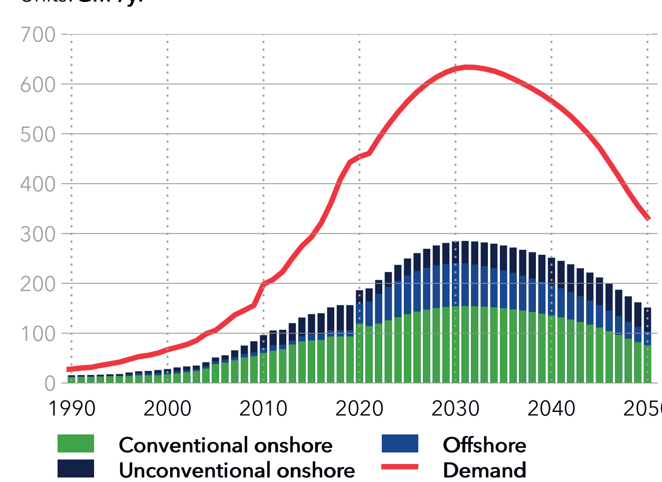


Historical data source: IEA WEB (2020)

FIGURE 7.7.10

Greater China natural gas production and demand

Units: **Gm^3/yr**



Historical data source: IEA WEB (2020)

Achieving carbon neutrality

In September 2020, President Xi Jinping gave a landmark speech promising that China will reach peak emissions before 2030, and become a carbon-neutral economy by 2060. With China presently emitting 27% of global GHG emissions, including 29% of all energy-related CO_2 emissions, President Xi's statements are important steps towards efforts to slow the rising trajectory of global emissions.

China's ambitions on carbon neutrality do not state clearly whether CO_2 or GHG are in focus, but further information suggests that CO_2 only is in focus. The country's GHG emissions in 2019 are estimated to have been 13.9 $GtCO_2$ (Rhodium, 2020), of which energy-related CO_2 emissions were 10.1 Gt (73%). Our ETO model, which gives regional results for energy-related CO_2 emissions only, covers most, but not all, of these.

The previous section on emissions provides some commentary on the 2030 peak-emissions goal. Figure 7.7.11 below illustrates the 2020 to 2050 emission trajectories for the main demand categories of manufacturing, buildings, and transport, and extrapolates the 2040–2050 trend towards 2060. With 2050 emissions from the three sectors at 1.1, 0.6, and 0.4 $GtCO_2$, respectively, all are very close to zero in 2060 if the trends continue.

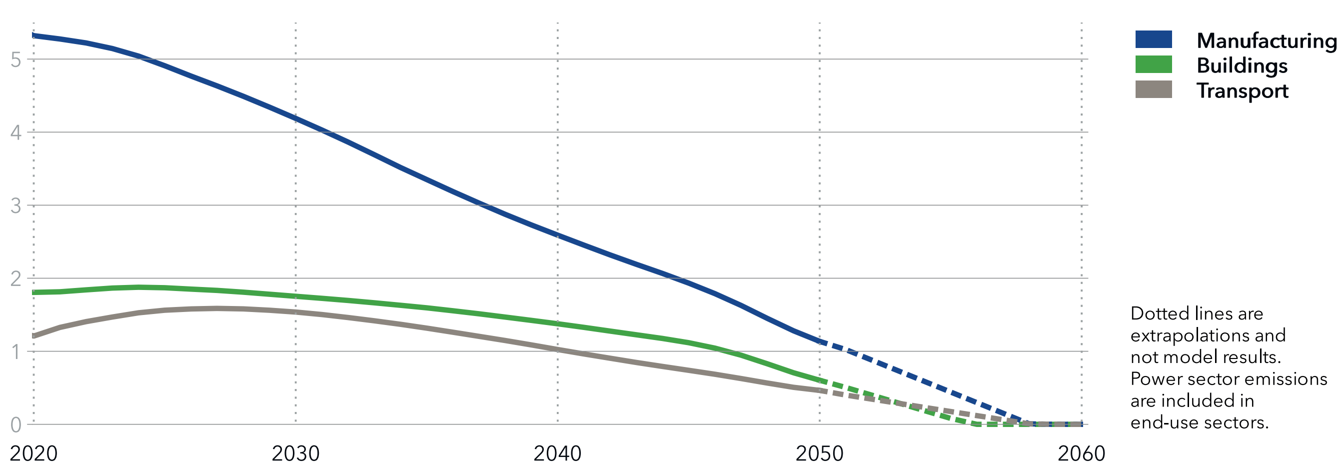
Based on this, it is clear that DNV's Outlook finds it likely that China's energy-related CO_2 emissions will be approaching zero in 2050. Without going into detail, it is evident that reforestation, afforestation, and various other carbon-removal technologies hold the potential for negative emissions. It also seems clear that the 2060 carbon-neutrality target is within reasonable reach.

It seems clear that the 2060 carbon-neutrality target is within reasonable reach.

FIGURE 7.7.11

Greater China energy-related CO_2 emissions by sector

Units: **$GtCO_2$/yr**



7.8 INDIAN SUBCONTINENT (IND)

This region consists of India, Pakistan, Afghanistan, Bangladesh, Sri Lanka, Nepal, Bhutan and The Maldives

Characteristics and current position

Economic development and population growth in the Indian Subcontinent are driving up energy demand. Energy security and tackling air pollution are prime motivations for the transition, and policies supporting low-carbon energy developments are common. India's air was ranked the third-most polluted globally, behind Bangladesh and Pakistan, in 2020 (IQAir, 2021). This costs Indian businesses an estimated USD 95bn annually, equivalent to 3% of GDP (Confederation of Indian Industry et al., 2021).

Fossil fuels currently provide more than 70% of electricity, and India's energy choices will largely determine the region's transition pace. However, since 2017 annual renewables capacity additions have outstripped growth in coal-based thermal power. In 2020, India was among the top-five countries for total capacity additions in hydropower, solar water heating, and ethanol production (REN21, 2021). Government programmes promoting access to electricity and clean cooking have made significant progress.

Bangladesh is dependent on imported LNG, coal, oil, and power. Natural gas dominates power generation, followed by oil, and some plants burn heavy fuel oil and diesel. Renewables provided 3% of power in 2020, falling short of the 10% target. Off-grid rooftop solar has helped extend electricity access to more than 90% of the population (ESMAP, 2020).

Fossil fuels and imports dominate Pakistan's energy mix, complemented by hydropower, which is affected by water levels falling in the summer. Pakistan is partnering with China to finance and develop coal-fired generation. Governance and security issues have deterred private investments.

The IND region is in the frontline of extreme-weather events and slowly rising sea levels. In the past decade, India, Afghanistan, Bangladesh and Pakistan have all ranked among the top-10 countries most affected by extreme-weather events on the Global Climate Risk Index (Germanwatch, 2021).

	Population (BN)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2019	1.83	25 46	6 880 12.7
(IND)			
2050	2.29	40 92	21 000 48.2

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

Pointers to the future

- India had 90 GW of renewables in December 2020, making the short-term target of being 'well beyond' 175 GW by 2022 look challenging. India is targeting 450 GW of renewables by 2030; its National Electricity Plan (NEP 2018) projects a renewables share beyond 40% by 2027, with growth dominated by solar, followed by wind; both have future 'must-run' status to avoid curtailment, unlike coal. Major reforms, including a real-time electricity market and future fixed-minimum percentages for renewables, will assist the transition. Climate policies will encourage green hydrogen for decarbonizing transport and industry (Hall et al., 2020). National initiatives on e-mobility and battery energy storage will progress integration of renewables, flexibility options, and storage developments. A national air quality programme aims for 20–30% less airborne particulate matter by 2024, with supporting initiatives on transport fuels, and some limits being set on coal-plant emissions. However, the latter is facing delays in implementation.
- Bangladesh will strengthen renewable energy and energy-efficiency programmes to bridge its shortfall in energy supply. It aims for 20% lower energy intensity (compared with 2013) and 1,700 MW utility-scale solar and 250 MW rooftop solar by 2030. A national plan aims for renewables comprising 40% of the power mix by 2041 (PV Magazine, 2020). Of 18 scheduled coal-fired plants, the government recently cancelled 10 due to solar's falling costs and difficulty in raising funds for coal investments.
- Given the ample potential solar and wind resources, Pakistan is targeting 30% renewables in the power mix by 2030, driven by a shift to supporting capacity tenders and competitive bidding. The risk of a long-term financial lock-in to thermal energy resources and coal capacity will increase should investments channelled by the China-Pakistan Economic Corridor advance with coal-fired generation.
- A common minimum grid code for cross-border electricity trade among South Asian countries will also boost renewables in the region (Powerline, 2020).

7.8 INDIAN SUBCONTINENT

Energy Transition

A rapidly growing, more prosperous population will see the GDP increasing by more than 3.5-fold by 2050. Energy demand will also rise – almost doubling – but not at the same rate as GDP owing to efficiency gains across all sectors. (Figure 7.8.1). The largest increase comes from manufacturing, as the region works to satisfy a rising share of a global appetite for industrial processes and products, and transport will also grow strongly.

Coal is currently the region's largest source of energy and will grow before peaking around 2030 (Figure 7.8.2), and then tapers off primarily due 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 the electrification of transport sends oil into decline. Natural gas use will triple over the forecast period and eventually overtake coal as the largest energy source. Despite the rapid growth of renewables, fossil-fuel energy sources will still represent around 60% of the energy mix in 2050. The share of electricity in final energy demand will more than double, rising from 16% in 2019 to 37% in 2050. The 2050 electricity mix will be dominated by solar at almost 50%, with renewables in total making up over 75% of the mix. Coal has around 13% of the electricity-generation mix, with gas coming in at 8%.

Energy Transition Indicators

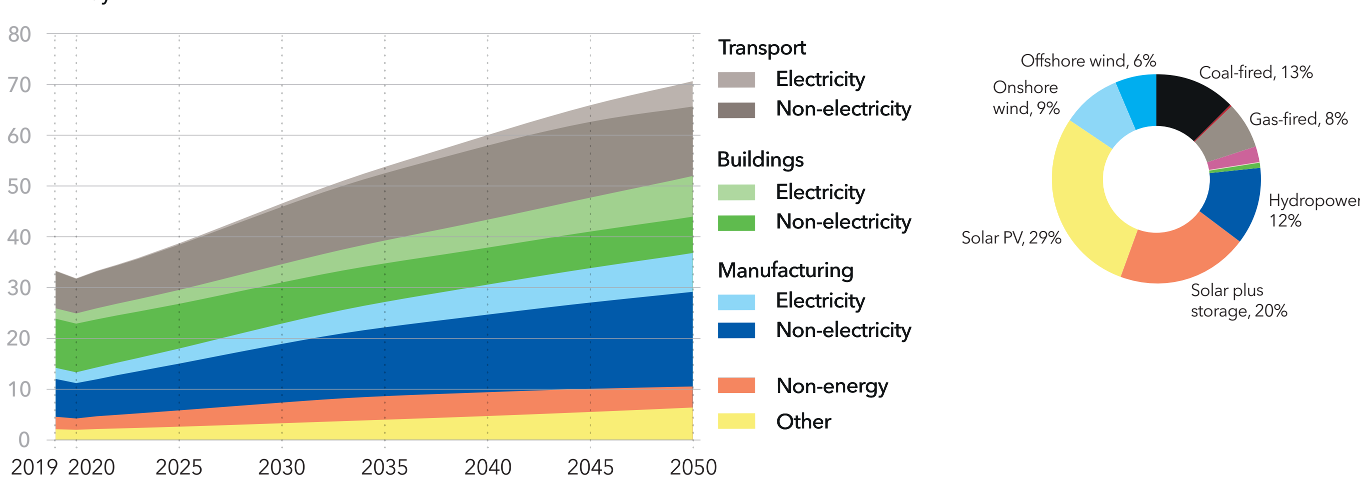
Figure 7.8.3 presents the Indian Subcontinent developments on three main energy-transition indicators: electrification, energy-intensity improvements, and decarbonization (definitions and regional comparisons are given in Section 7.11).

– The region's electricity share in final energy demand will more than double from 2019 onwards, reaching a 37% share in 2050; this is comparable to developments in Latin America and Europe.

FIGURE 7.8.1

Indian Subcontinent final energy demand by sector **2050 electricity mix**

Units: EJ/yr



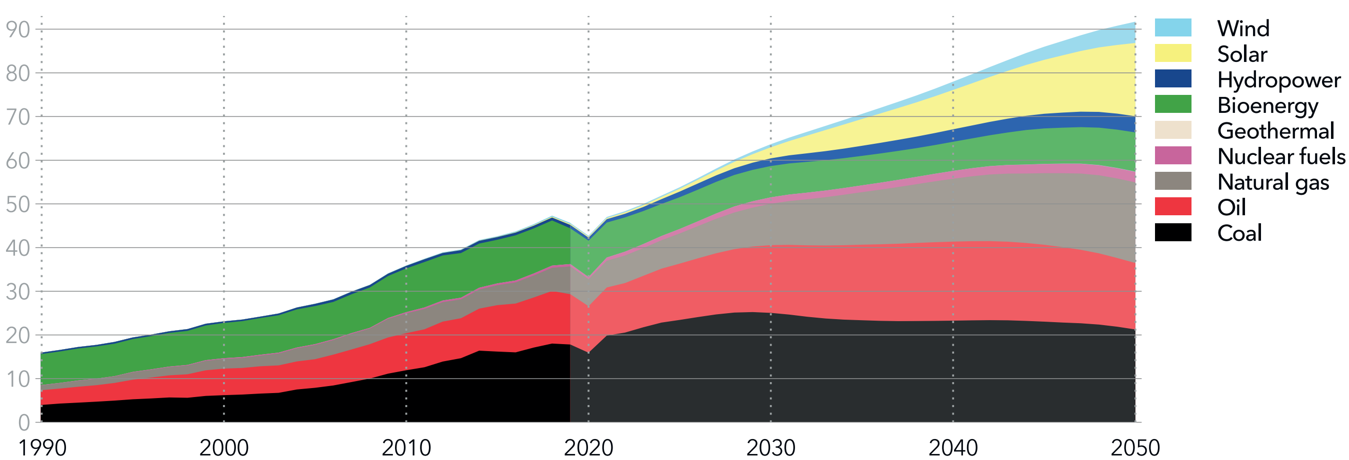
– Energy intensity will be down to 1.9 MJ/USD, which is similar to that in more than half of the regions.

– Carbon intensity in the region will be reduced by a third to 42 tCO_2/TJ, which is the second-highest globally and comparable to levels in North East Eurasia and the Middle East and North Africa.

FIGURE 7.8.2

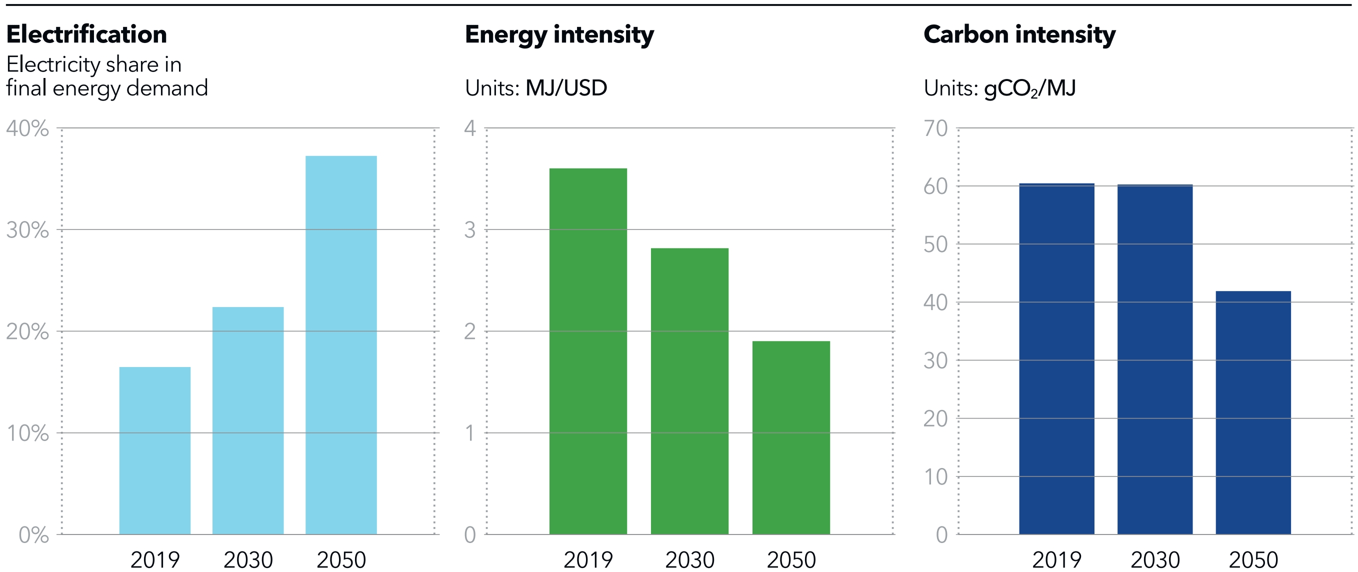
Indian Subcontinent primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.8.3



Emissions

We project the region's average carbon price to be USD 35/t CO_2 by 2050, with explicit carbon-pricing instruments expected no earlier than the mid-2020s. The prime drivers of carbon-price developments will be access to climate finance, potential future carbon-border adjustment mechanisms, 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 in the lower range among the regions. They will not peak until the early 2040s, driven by strong increases in manufacturing and transport emissions (Figure 7.8.4).

Emissions today are dominated by coal, which will remain the largest energy provider despite its role in the mix reducing from 2030 onwards. Consequently, coal dominates emissions, accounting for more than 62% of the total when peaking in 2029, and only declining to 52% in 2050.

We see CCS capacity reaching 105 $MtCO_2$/yr in mid-century after steady growth, equating to only 3% of the region's energy-related emissions. There is relatively little support for CCS from the carbon price.

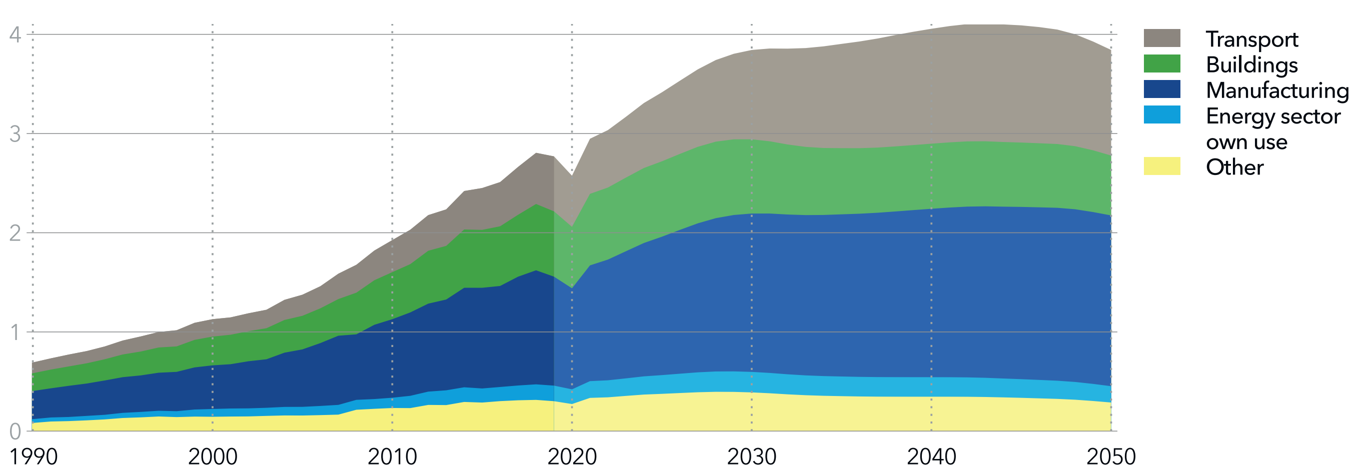
NDC pledges indicate that the region aims to limit growth in emissions to no more than 503% by 2030 relative to 1990. Our Outlook indicates energy-related emissions increasing by 455%, suggesting that the target is not ambitious. There are some uncertainties in comparing these numbers as some major countries in the region also include non-energy-related CO_2 emissions in their targets.

In 2050, the region's energy-related emissions are expected to be 3.84 $GtCO_2$/yr. This is a 39% increase compared with 2019, and while that is far from net zero it nevertheless is an impressive containment of emissions growth relative to a near doubling in energy demand across the subcontinent. With this emission level, India's 2050 target that 'per capita emissions will never exceed those of the developed world' will be well within reach. For the Indian Subcontinent, estimated emissions will be 1.76 tCO_2/person compared with over 3 tCO_2/person in North America and OECD Pacific, and 1.7 tCO_2/person in Europe.

FIGURE 7.8.4

Indian Subcontinent energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Accelerated access to electricity

With 2.3 billion people in 2050, the Indian Subcontinent will have by far the highest population among the world regions. Currently 5% of households in the region lack access to electricity, and 30% of households lack access to modern cooking and water heating. Given the relatively low levels of access to modern energy for cooking and water heating and the large number of people involved, energy equity demands an acceleration in energy access. How such access to electricity and modern energy takes place will have wide-ranging social and environmental implications for the future.

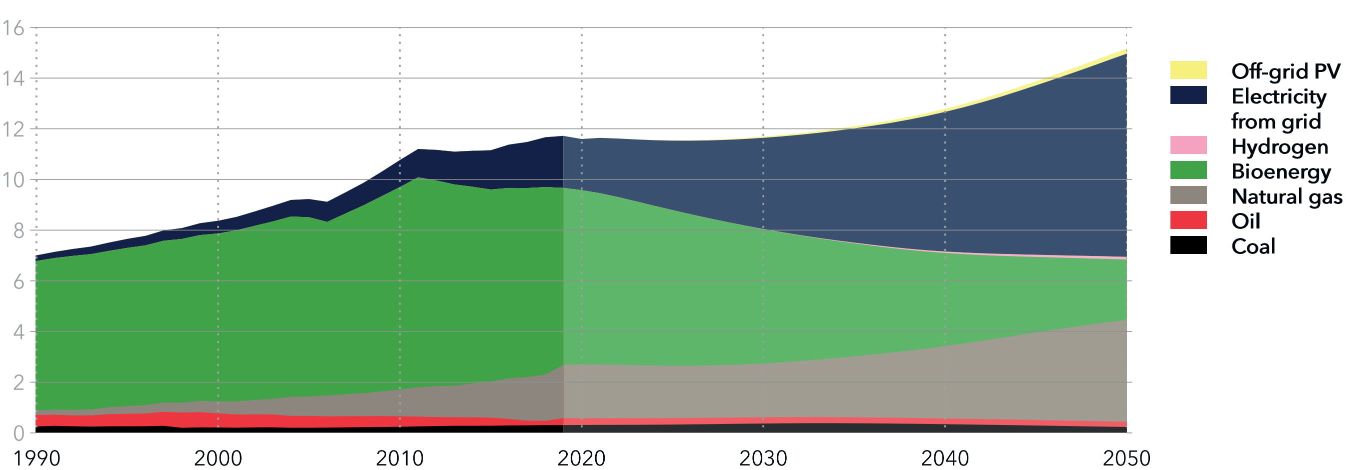
Our Outlook shows that the electricity demand of the Indian Subcontinent will increase 5-fold by 2050, in part spurred on by the electricity demand from buildings. Electricity will provide more than 50% of the final-energy demand (Figure 7.8.5), including water heating, cooking, and space cooling. This will increase access to electricity in both residential and commercial segments, and, in turn, improve access to modern energy services for the region's people. Our Outlook forecasts that by mid-century, 94% of households will have access to modern water heating, and almost 98% to modern cooking. Overall, the goal of universal electricity access in the region will be achieved.

Our prediction that the use of coal and natural gas for power generation in the region will peak in 2031, suggests that the expansion in energy access will not occur at the expense of decarbonization. By 2050, more than 85% of power generation will come from solar PV, wind, hydropower, and geothermal power. Despite the lateness of the region's shift to renewable electricity, the substantial gains in energy access are therefore well aligned with the aims of the Sustainable Development Goal (SDG #7). Providing access for hundreds of millions of individuals to modern energy services will not compromise the climate pledges of the region's countries, or GHG mitigation from the power sector, while vastly improving the quality of life for people in the Indian Subcontinent.

FIGURE 7.8.5

Indian Subcontinent buildings energy demand by carrier

Units: **EJ/yr**



Historical data source: IEA WEB (2020)

7.9 SOUTH EAST ASIA (SEA)

This region stretches from Myanmar to Papua New Guinea and includes Thailand and the Philippines

Characteristics and current position

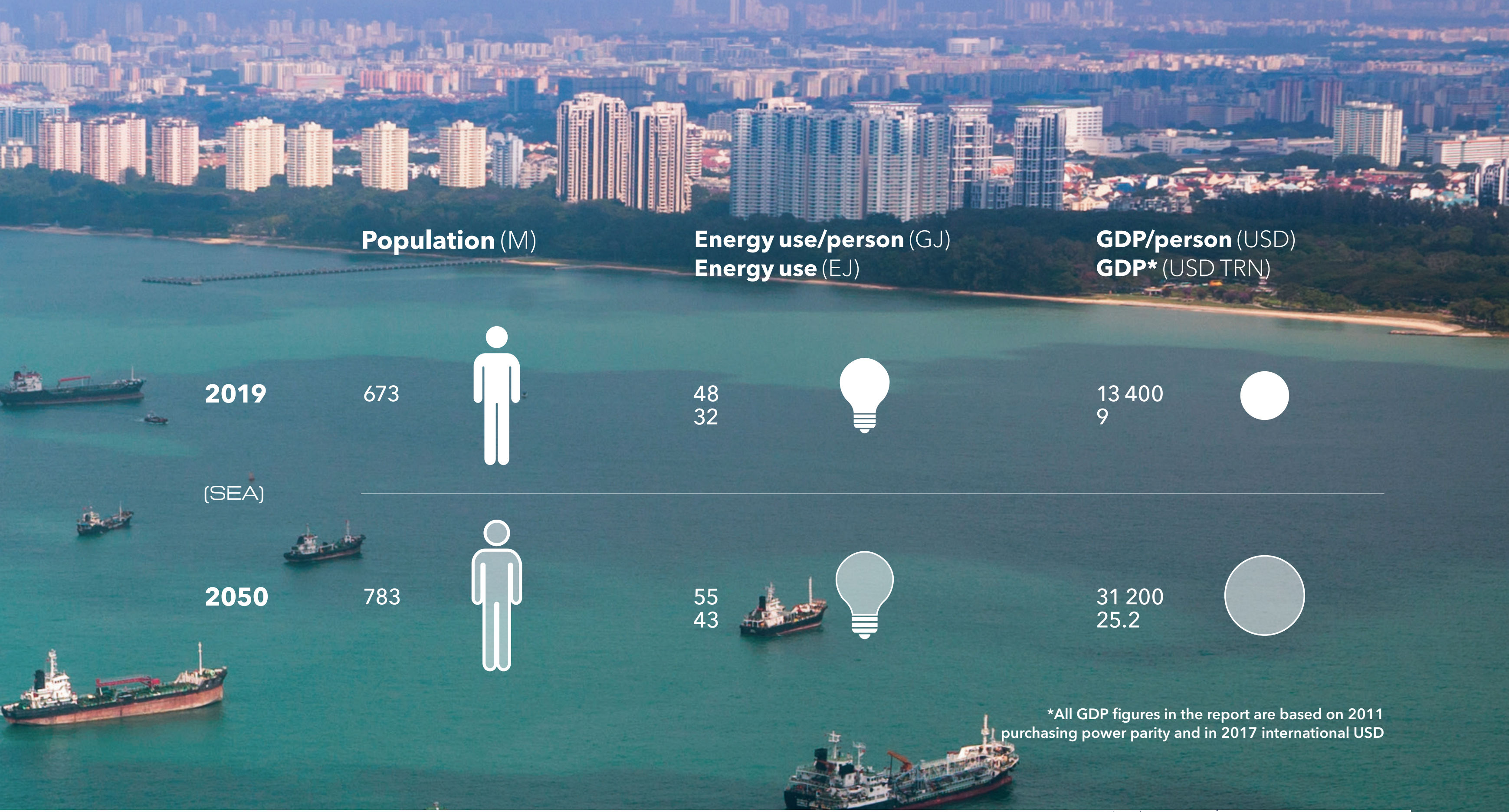
Indonesia, Thailand, and the Philippines are the largest economies in the region, and Singapore has the highest GDP per person. The region's economic weight is growing, and so is its carbon footprint, despite being one of the regions most vulnerable to climate change. Thailand and the Philippines are among the top-10 countries most affected by extreme-weather events on the Global Climate Risk Index (Germanwatch, 2021).

Meeting increasing energy demands from growing populations and economies is a key priority for SEA countries. Pursuit of economic growth and energy security are the most prominent common features of national energy policies. An expanding urban middle class is the main driver of electricity demand in residential and service sectors, and a flourishing manufacturing sector pushes up industrial energy demand.

Reliance on hydrocarbons is high, mostly oil for transport, and coal and gas for electricity. Despite declining regional natural gas production levels, SEA will remain a net-gas exporter. Policies advancing 'clean' diversification aims to reconcile growth with concerns over air quality and health, and to enhance national self-reliance.

Thailand leads SEA in renewables, and Singapore is pioneering smart-grid technology, EV uptake, and considering hydrogen as a fuel. Vietnam shows fastest growth in wind and solar, with supportive policies motivated by declining hydrocarbon sources. In 2020, the Philippines announced an end to new coal-power plants, though coal has risen to about 50% of its electricity mix. Corporate renewable procurement is emerging as a driver of renewable electricity, as global multinationals seek to reduce supply-chain carbon footprints.

Despite interest in decarbonization options, such as CCS and hydrogen, these are hampered by lack of carbon-pricing. Public funding has spurred fossil-based technologies; e.g., subsidies for production and consumption, export credit guarantees as in Japan and South Korea, and coal power-plant sales from China. These slow down the transition towards renewable technologies and energy efficiency.



	Population (M)	Energy use/person (GJ) / Energy use (EJ)	GDP/person (USD) / GDP* (USD TRN)
2019	673	48 / 32	13 400 / 9
2050	783	55 / 43	31 200 / 25.2

(SEA)

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

Pointers to the future ▸▸▸

- Electricity is edging out traditional bioenergy. Gas demand will grow until 2030, before declining 26% by 2050. The region's traditional two-wheeler vehicle fleet will electrify, but the slow transition from oil reflects the high cost of EV ownership for the growing urban middle-class. The share of fossil energy – mostly oil and natural gas – in the primary-energy mix will be 75% in 2030 and 43% in 2050. Cheap coal from Australia and Indonesia, and less demand elsewhere, will flood the regional energy market, delaying transition mechanisms.
- The potential for regional renewables is significant. ASEAN member states (ASEAN, 2020) are targeting the following goals by 2025: 30% lower energy intensity than in 2005; 23% of renewables in primary-energy supply compared with 17% in 2019; and 35% renewables in installed power capacity. The latter looks achievable, with a forecast share of 38%.
- 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, ambitions to create jobs and domestic module-manufacturing capacities in renewables will support deployment.
- Barriers to investment include: regulatory uncertainty, fiscal support for, and vested interests in, hydrocarbons, and bank-dominated funding categorizing large-scale renewable projects as risky (ADBI, 2018). Renewables will struggle to secure private funding due to tacit support for fossil fuels. Climate-motivated shifts in foreign direct investment could be a game-changer that will overcome these obstacles.
- Electricity-market restructuring is unfolding in Malaysia, Philippines, and Vietnam, with a transition from vertically integrated market structures towards competition and customer choice. This will encourage new and more-efficient generation. In the future, cross-border power-grid interconnections and multilateral trading will spur variable renewables. The Laos-Thailand-Malaysia- Singapore Power Integration Project is one step towards this.

7.9 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 7.9.1). The largest increase will come from buildings, associated with population growth and an increase in income per capita. These will lead to more space and higher comfort levels through cooling and appliances. There will also be growth in the energy demand from transport and manufacturing sectors.

Figure 7.9.1 shows the share of electricity in final energy demand continuing to rise, advancing from 17% in 2019 to 41% in 2050. All three main sectors will see strong electrification. The 2050 electricity mix is dominated by solar and wind, generating 38% and 35% of electricity, respectively, followed by hydropower.

Oil is currently the largest energy carrier and will grow for another 15 years before succumbing to increasing competition from electrification (Figure 7.9.2). In the next decade, renewables will see the largest growth, with solar and wind making up 16% and 15% of the final energy supply. Coal will grow initially but will peak in about five-years' time. Beyond 2030, coal will still out-compete natural gas in manufacturing, with both coal and natural gas challenged by growing renewables in the power sector. Despite the strong growth in renewables, the fossil-fuel share remains high, at 44% in 2050.

Energy Transition Indicators

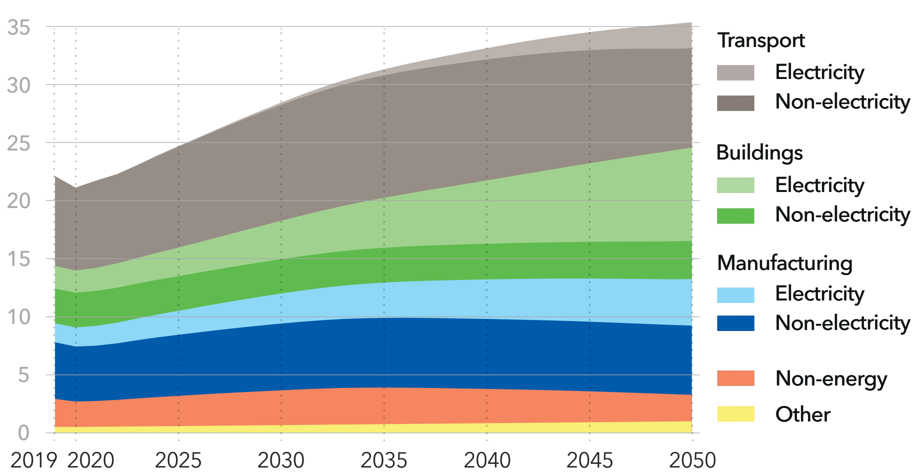
Figure 7.9.3 presents South East Asian developments on three main energy-transition indicators: electrification, energy-intensity improvements, and decarbonization (definitions and regional comparisons are given in Section 7.11).

– The region's energy-system transformation shows electricity more than doubling to supply 41% of final-energy demand by 2050.

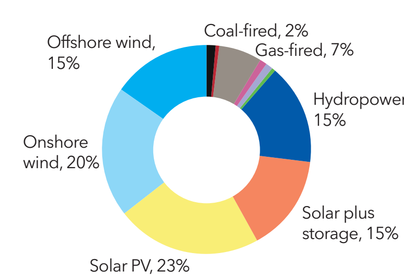
FIGURE 7.9.1

South East Asia final energy demand by sector

Units: EJ/yr



2050 electricity mix



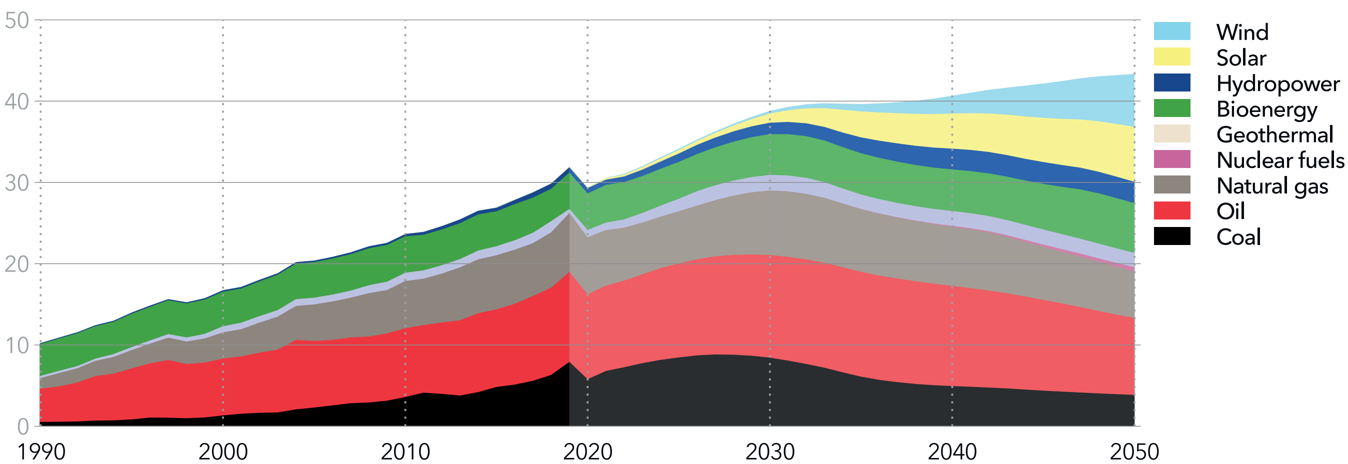
– Between 2019 and 2050, energy intensity will improve by more than 50%, becoming the second-lowest of any region, with a change only slightly less than that of developed regions such as North America.

– Between 2019 and 2030, there will be little reduction in carbon intensity, but the decades after 2030 will see reductions that reach almost 50% by mid-century. South East Asia's 2050 carbon intensity is comparable to those of Latin America and OECD Pacific.

FIGURE 7.9.2

South East Asia primary energy consumption by source

Units: EJ/yr

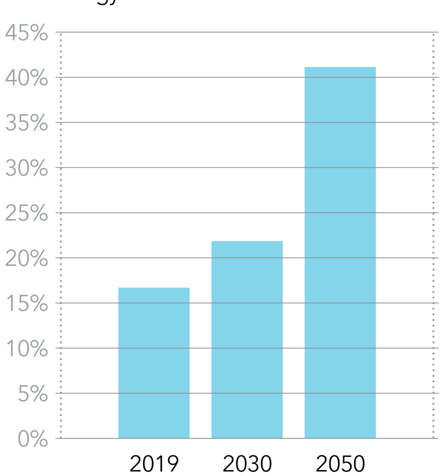


Historical data source: IEA WEB (2020)

FIGURE 7.9.3

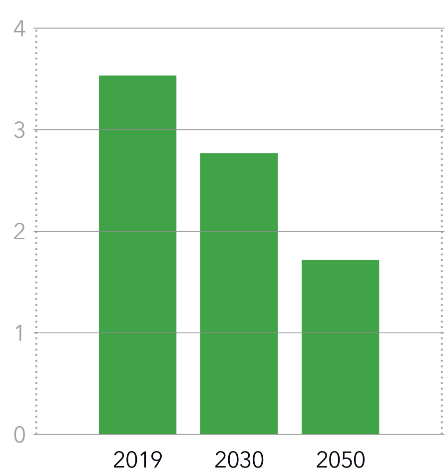
Electrification

Electricity share in final energy demand



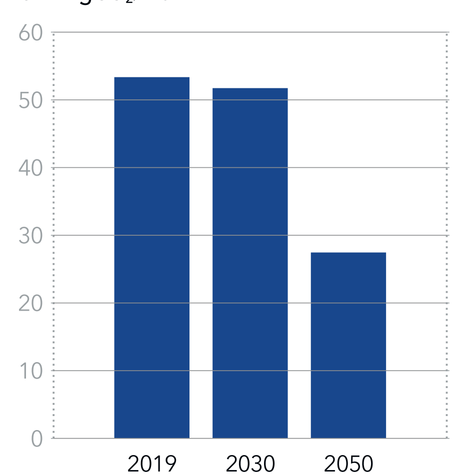
Energy intensity

Units: MJ/USD



Carbon intensity

Units: gCO_2/MJ



Emissions

We project the region's average carbon price to be USD 40/t CO_2 by 2050. The application of explicit carbon-pricing instruments is currently limited, and the likely first step is the 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 to happen 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 adjustment mechanisms with trade partners, and access to climate finance.

South East Asia's energy-related emissions are increasing and will peak in 2030 before returning to levels lower than today's in 2050. Emissions from transport, manufacturing, and buildings follow the same pattern in our Outlook (Figure 7.9.4).

Emissions from coal and oil currently dominate but will both peak and decline over the forecast period. Emissions from natural gas will also follow this trend, peaking in the early 2030s before dropping.

We forecast CCS capacity of 112 MtCO_2/yr in 2050, equating to only 8% of energy-related emissions due to the relatively low projected carbon prices.

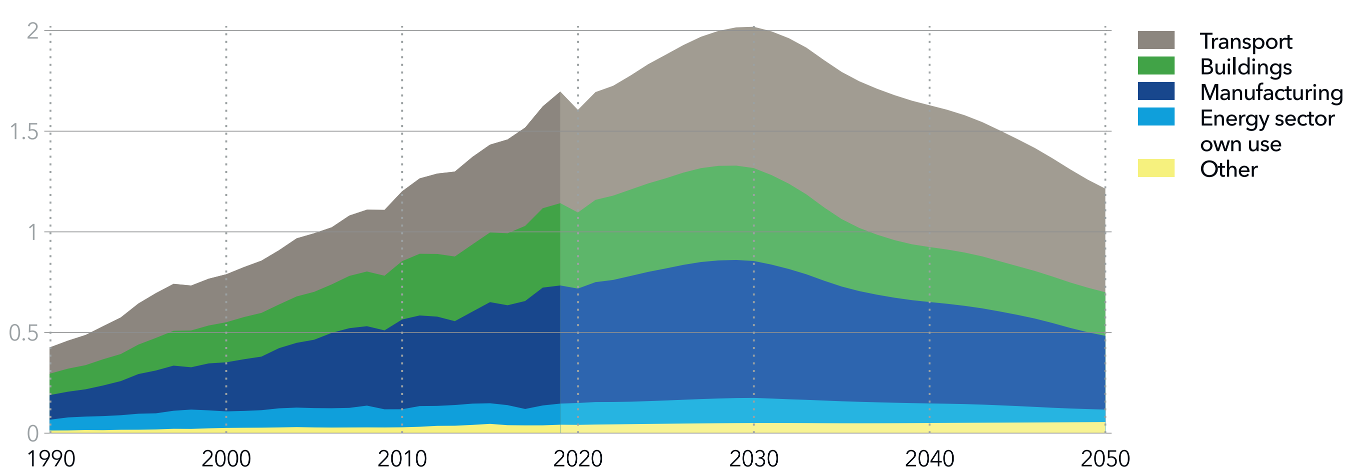
NDC pledges indicate a regional target of limiting increases in emissions to no more than 502% by 2030 relative to 1990. Our Outlook shows energy-related emissions increasing by 372% by 2030, suggesting that these unambitious pledges will be met. There are some uncertainties in the comparisons of targets and forecasts, as some countries are unclear about whether the targets in their NDCs also include non-energy-related CO_2 emissions. By 2050, the region is expected to reduce its energy-related emissions to a total of 1.21 GtCO_2/yr, a 28% decrease compared with 2019. None of the countries in this region have indicated any targets for mid-century.

The region's emissions in 2050 will be 1.74 tCO_2/person, somewhat below the global average.

FIGURE 7.9.4

South East Asia energy-related CO_2 emissions by sector

Units: GtCO_2/yr



Increased vehicle ownership and electric vehicles

Our Outlook shows two different transition stories unfolding in the passenger vehicle segment of road transport in South East Asia. The region will see a 54% increase in private vehicle ownership between 2020 and 2050. Until the late 2030s, this rise will be dominated by two and three wheeler ownership, rather than car ownership. But from 2040, increasing prosperity will drive greater car ownership and a slowing of two and three wheeler ownership, which will peak in 2042 (Figure 7.9.5).

Similarly, vehicle ownership divides by fuel type. Our Outlook forecasts a rapid transition to electric two and three wheelers, with BEVs overtaking their ICE counterparts in 2028.

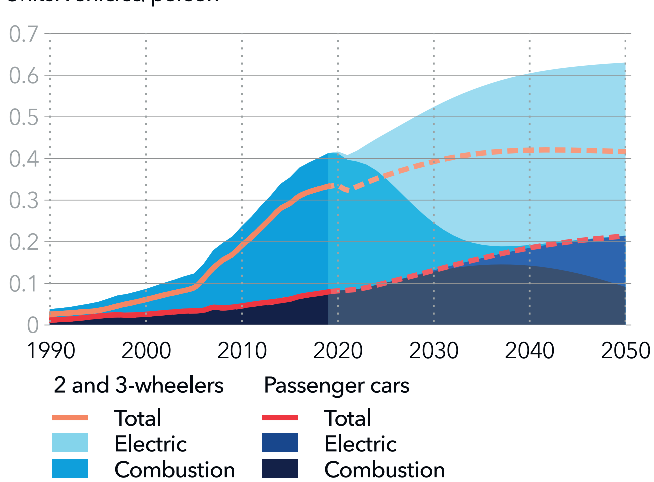
Electrification of the region's passenger car fleet happens much later, in 2048. Before that, the higher relative TCO of BEVs in South East Asia compared with the world average, will result in passenger-BEV numbers lagging (Figure 7.9.6).

The region's countries lack comprehensive strategies for electrification of road transport, both in terms of development of charging infrastructure and incentives for consumer-driven uptake. Despite the many co-benefits of BEV, such as less local air pollution and lower noise levels in urban areas, the passenger vehicle segment poses a challenge to South East Asia's phase-out of fossil fuels in road transport.

FIGURE 7.9.5

South East Asia passenger-vehicle ownership

Units:Vehicles/person

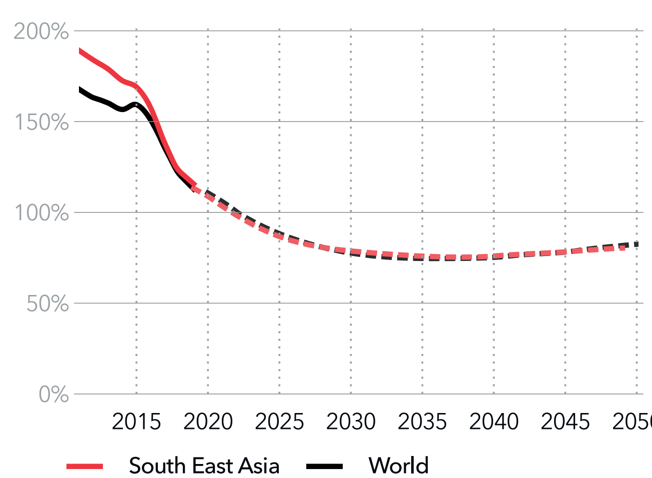


Historical data source: Marklines (2021), IEA EV Outlook (2021), OICA (2016)

FIGURE 7.9.6

Relative total cost of ownership (TCO) of passenger EVs in South East Asia and the World

Units:TCO of EV relative to ICE



7.10 OECD PACIFIC (OPA)

This region consists of Australia, New Zealand, Japan and South Korea

Characteristics and current position

The mature economies in the OPA region have diverse energy use and resources. Australia is a net exporter of energy. New Zealand, Japan and South Korea are dependent on imported energy. New Zealand committed to carbon neutrality in 2019, Japan (the world's 5th biggest emitter) and South Korea (the 8th) announced 2050 carbon-neutrality pledges (October 2020).

Australia exploits its coal and gas resources for domestic energy use and for export revenue. There is significant interest in hydrogen for export. Carbon emissions are declining slowly. Its national 2020 renewables target, the main driving policy mechanism, has been met with rapid growth in wind, and utility-scale solar. Rooftop solar continues to grow strongly.

New Zealand relies heavily on renewables for electricity, particularly hydropower and geothermal, and to a lesser extent wind and solar; but fossil fuels still dominate energy supply though there is accelerated interest in hydrogen. A longstanding ETS system is in place.

Japan imports 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 shortfalls in power supply have been balanced with imported fossil fuels and greater coal-fired generation. Japan plans to increase offshore wind capacity and innovate decarbonization technologies.

South Korea is a major importer of coal, oil, and LNG. With its export-led industry structure, manufacturing energy use has constantly grown. Power generation has coal, nuclear and natural gas (LNG) responsible for 40%, 26% and 26%, respectively in 2019, and renewables at about 7%. Nuclear phase-out and tackling air pollution for public health are prime motivations, driving a shift from nuclear and coal to LNG and renewables. Efforts to become a global hydrogen powerhouse have grown since 2017, and gas is seen as a bridge fuel in the transition.

	Population (M)	Energy use/person (GJ) Energy use (EJ)	GDP/person (USD) GDP* (USD TRN)
2019	207	174 36	41 200 8.5
(OPA)			
2050	194	119 23	57 200 11

*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 towards Paris Agreement achievement and on carbon pricing. Renewables are growing, but market design will need revising to facilitate continued deployment, also in pumped storage and batteries. The Federal government's COVID response emphasize a "gas-led" recovery. Already the world's largest exporter of LNG, Australia is starting to explore domestic use and export of hydrogen driven by the excellent renewable supply base, and state/territory level net zero aspirations.
- New Zealand law targets net zero by 2050 for non-agricultural emissions. A strengthened 2030 target is expected after an independent assessment found current plans inadequate in meeting the Paris Agreement. A 2050 Emissions Reduction Plan is imminent (2021) and new emissions-reduction policies will focus on renewable power, EVs, afforestation, and ending exploration for new oil and gas reserves.
- Japan enshrined carbon neutrality into law in May 2021, conditional on disruptive innovations. A green growth strategy is pursued to expand renewables, near-term coal-to-gas switching, CCUS, hydrogen, and battery storage. The government's hydrogen roadmap aims for 800,000 FCEVs and 900 refuelling stations, and industrialization of hydrogen-based power plants by 2030. Boosting the electricity network has high priority, given offshore wind and fuel-cell expansion. Existing nuclear power stations will be used as long as safety is secured.
- South Korean policies favour LNG, renewables, and electrification of transport. The 2050 Carbon Neutral Strategy (December 2020) outlines a comprehensive energy decarbonization strategy. The 9th Electricity Plan targets 40% renewables with a major role for offshore wind, 31% LNG, 15% coal, and 10% nuclear by 2034. Long-term decarbonization will focus on coal-to-gas conversion and CCUS in power and manufacturing. South Korea aims to become a leading hydrogen economy by 2040 with the Hydrogen Economy Roadmap for production facilities, use in transport, and fuel-cell businesses, building on existing strengths in FCEVs.

7.10 OECD PACIFIC

Energy Transition

OECD Pacific's final energy demand will begin to decline in the next few years and will continue to outpace the fall in population (Figure 7.10.1). 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 7.10.1 shows electricity's share in final energy demand increasing from 23% in 2019 to 45% in 2050, second only to Greater China. Manufacturing and transport will see especially high electrification. Renewables will dominate the 2050 electricity mix. Together with solar also being significant at 35%, with offshore and onshore wind making up respectively 16% and 14% of the mix, the fossil-fuel share in power generation will decline to 20% by then.

Electrification of transport will be the strongest driver for oil consumption declining 67% over the forecast period (Figure 7.10.2). Coal, currently the region's second largest primary energy source, declines in both the power and manufacturing sectors by 82% and 58% respectively. Unlike many other regions, natural gas use will decline throughout. In 2050, the fossil fuel share in primary energy supply is down to 46%.

Energy Transition Indicators

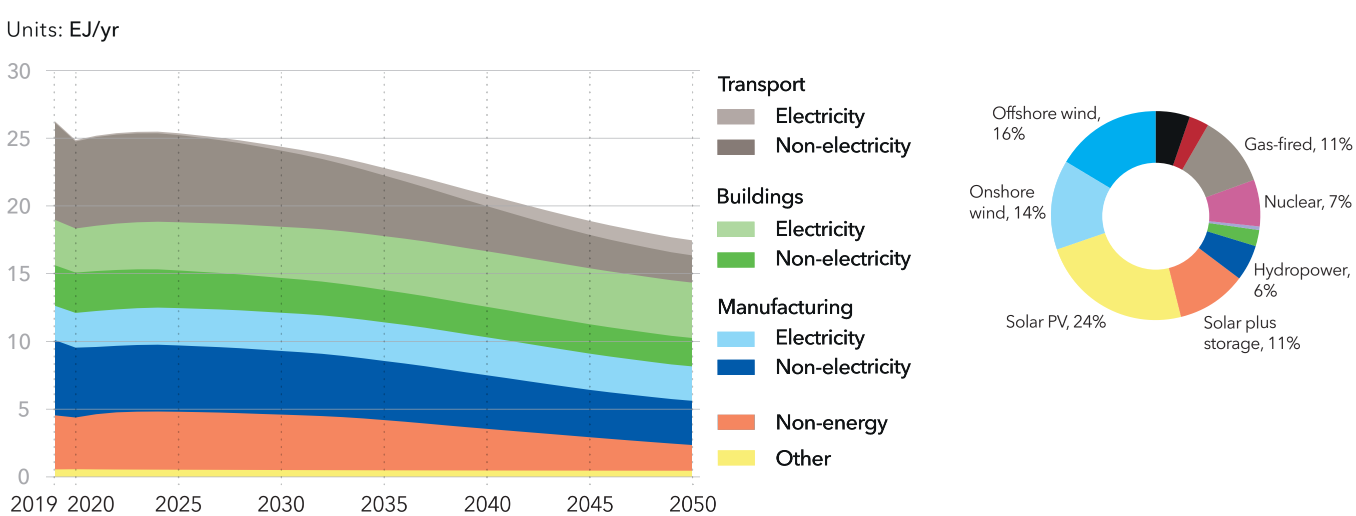
Figure 7.10.3 presents OECD Pacific developments on three main energy-transition indicators: electrification, energy-intensity improvements and decarbonization (definitions and regional comparison are given in section 7.11).

– The region's electricity share of final energy demand doubles to 2050, reaching 45%, which is the second highest electrification of all regions (after Greater China).

FIGURE 7.10.1

OECD Pacific final energy demand by sector

2050 electricity mix



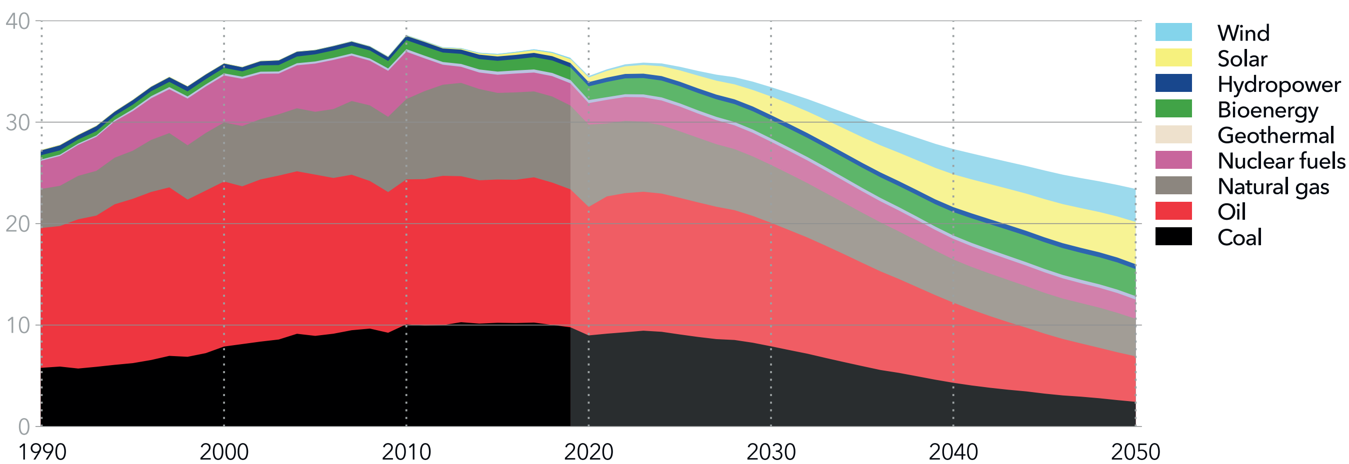
– Energy intensity is halved to a level of 2.2 MJ/USD, similar to developments in North America.

– The carbon intensity will decline to 26 tCO_2/TJ, representing a reduction of over 50%.

FIGURE 7.10.2

OECD Pacific primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

FIGURE 7.10.3

Electrification

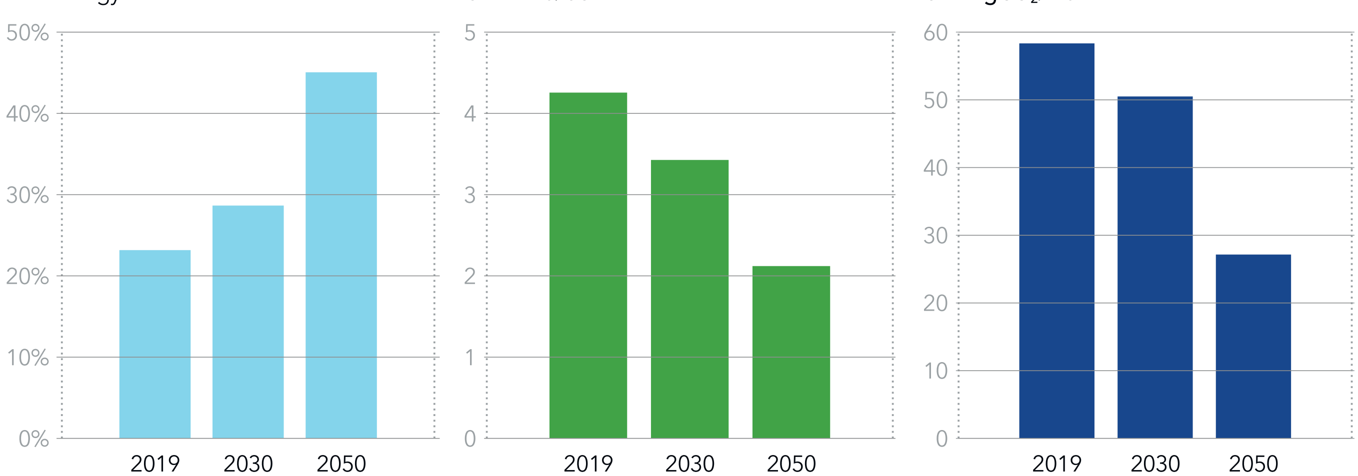
Electricity share in final energy demand

Energy intensity

Units: MJ/USD

Carbon intensity

Units: gCO_2/MJ



Emissions

We project the region's average carbon price to be USD 60/t CO_2 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 regional trajectory develops similarly to that of Greater China, also with possible linkages through systems in Asia.

OECD Pacific energy-related emissions have been fairly flat for a decade and are set for a 70% decline by 2050. The reduction will be strong in each of the three demand sectors (Figure 7.10.4).

Around half of today's emissions are from coal and this will decline by 75% by 2050. Oil and gas emissions will also decrease but will remain greater than those from coal from around 2040 onwards.

We project CCS capacity of 15 $MtCO_2$ in 2050, driven by a carbon price reaching USD 60/t CO_2 by then. This CSS capacity captures 2% of energy-related emissions by mid-century, a fairly low level. CCS uptake in OCED Pacific rises gradually in the 2020s and 2030s, stabilizing in the 2040s.

NDC pledges imply an OECD Pacific regional target of limiting energy-related emission increases to no more than 7.5% by 2030 relative to 1990. Our Outlook indicates energy-related emissions increasing 1% by 2030, suggesting that the target will be met and that the ambition level of the current pledges is low.

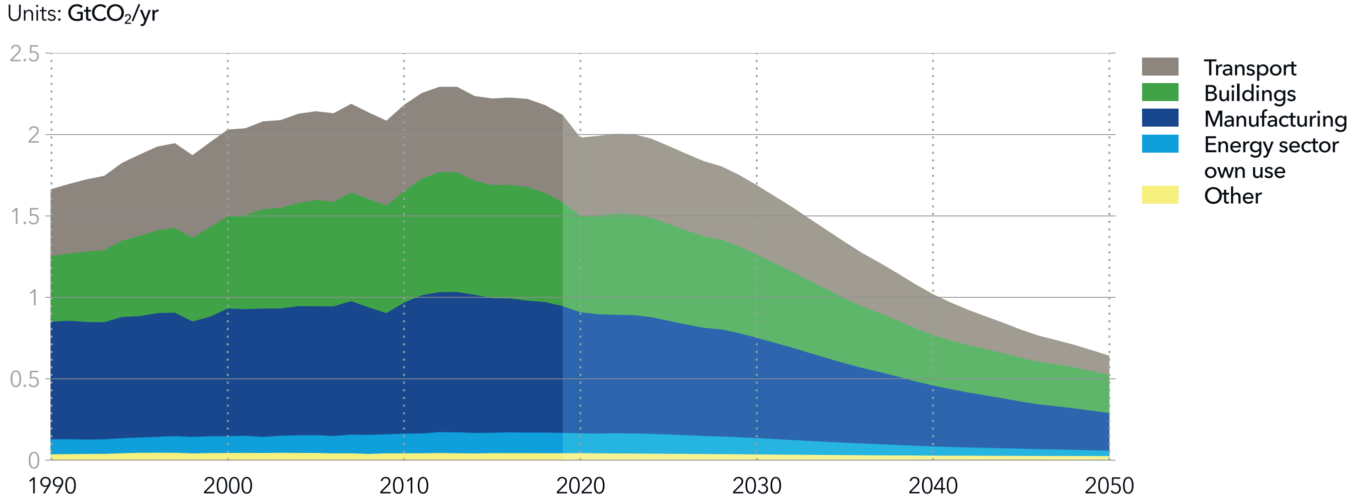
New Zealand was the first country in the region to adopt its net-zero emission target by 2050. However, South-Korea has announced its commitment to climate neutrality, and Japan has enshrined into law that it "will strive to reach net-zero emissions by 2050, conditional on disruptive innovations." For the region as a whole, energy-related emissions are expected to be 0.64 $GtCO_2$/yr in 2050

The region emits 3.4 tCO_2/person in 2050, somewhat higher than the world average. The emissions decline of 70% between 2019 and mid-century is among the higher declines seen in our Outlook.

FIGURE 7.10.4

OECD Pacific energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



A hydrogen frontrunner?

OECD Pacific countries are expected to be at the forefront of hydrogen uptake as an energy carrier. Hydrogen will represent 8% of final energy demand in the region by 2050, the second highest share after Europe. As shown in Figure 7.10.5, green hydrogen production will dominate in the region, and represent 86% of production by 2050. Green hydrogen from solar PV will clearly prevail, and account for the majority of the total production (55%) by 2050.

Figure 7.10.6 shows the uptake dynamics in different sectors. Hydrogen use as a heat source will ramp up in the manufacturing and buildings sectors, leading to a 10% and 4% share in their energy mixes by 2050, respectively. The transport sector (maritime, aviation and road) will have the highest uptake, with a fifth of energy being covered by hydrogen by 2050.

Objectives are particularly high in road transport, with countries like Japan, where the aim is to have 800,000 fuel cell vehicles on the road by 2030, according to the last Strategic Roadmap for Hydrogen and Fuel Cells.

Hydrogen will consequently cover 17% of road transport energy needs in the region by 2050, the highest global share.

Hydrogen will represent 8% of final energy demand in the OECD Pacific region by 2050, the second highest share after Europe.

FIGURE 7.10.5

OECD Pacific hydrogen production as energy carrier by source

Units:EJ/yr

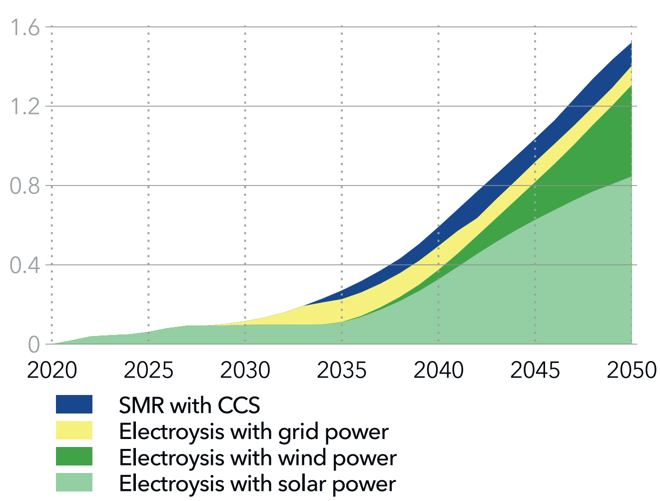
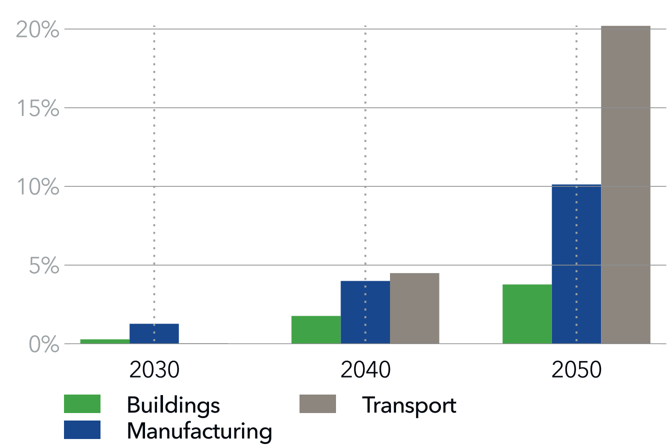


FIGURE 7.10.6

OECD Pacific hydrogen share in energy demand by sector

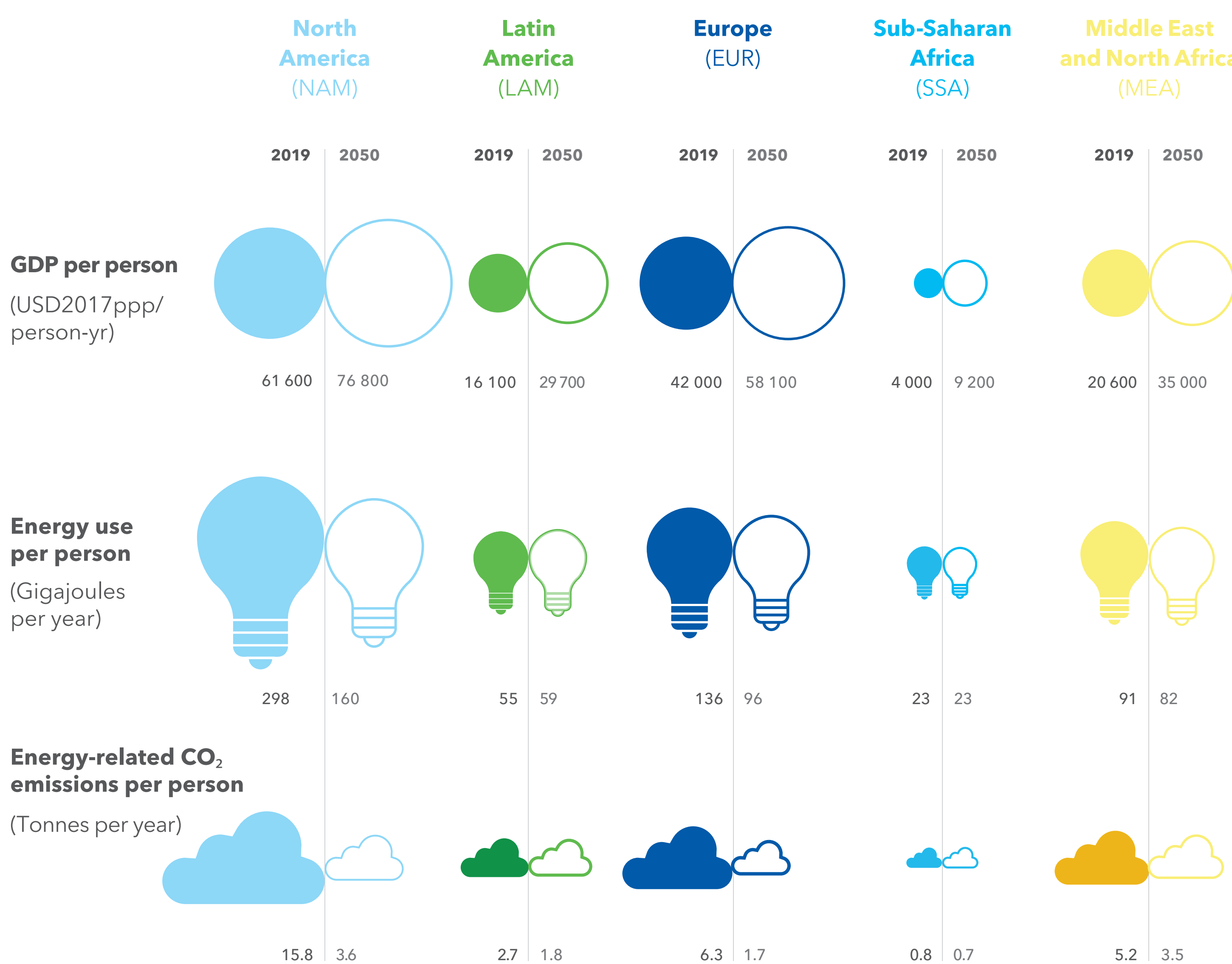
Units:Percentages

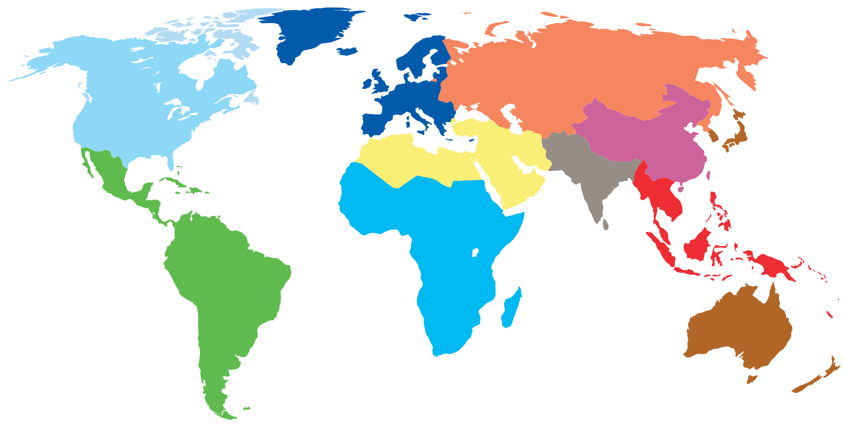


GDP, ENERGY USE AND EMISSIONS ACROSS OUR 10 OUTLOOK REGIONS

2019-2050 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 (2019 and forecast figures for 2050)





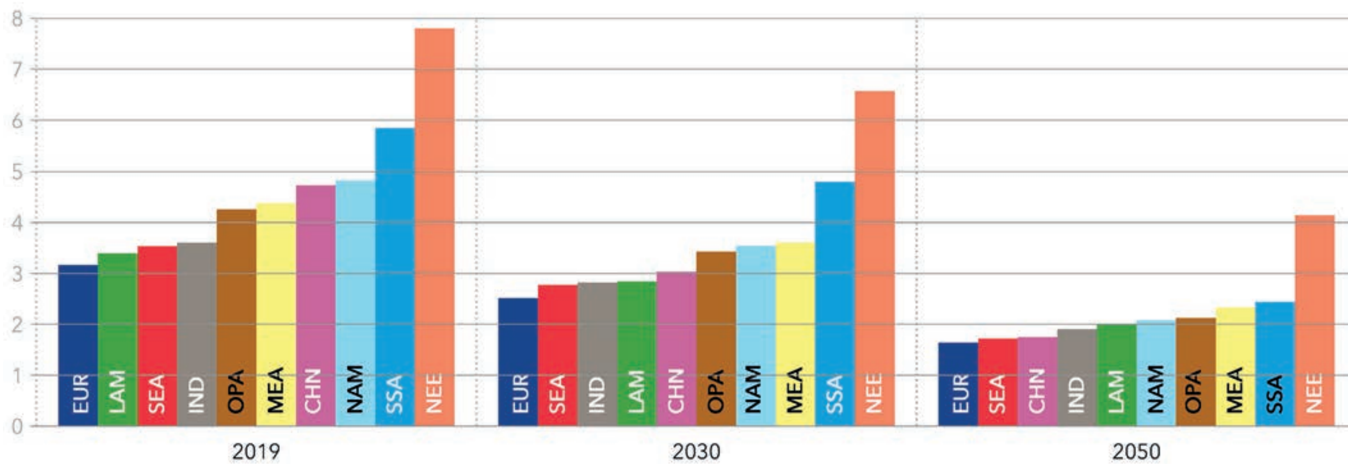
	North East Eurasia (NEE)		Greater China (CHN)		Indian Subcontinent (IND)		South East Asia (SEA)		OECD Pacific (OPA)		World	
	2019	2050	2019	2050	2019	2050	2019	2050	2019	2050	2019	2050
	18 000	35 900	21 200	49 000	6 900	21 000	13 400	31 200	41 200	57 200	18 000	31 200
	141	149	100	86	25	40	48	55	174	119	77	63
	7.6	7.5	7.1	2.0	1.5	1.7	2.5	1.6	10.2	3.3	4.4	2.0

7.11 COMPARISON OF THE REGIONS

FIGURE 7.11.1

Energy intensity of GDP

Units: **MJ/USD**

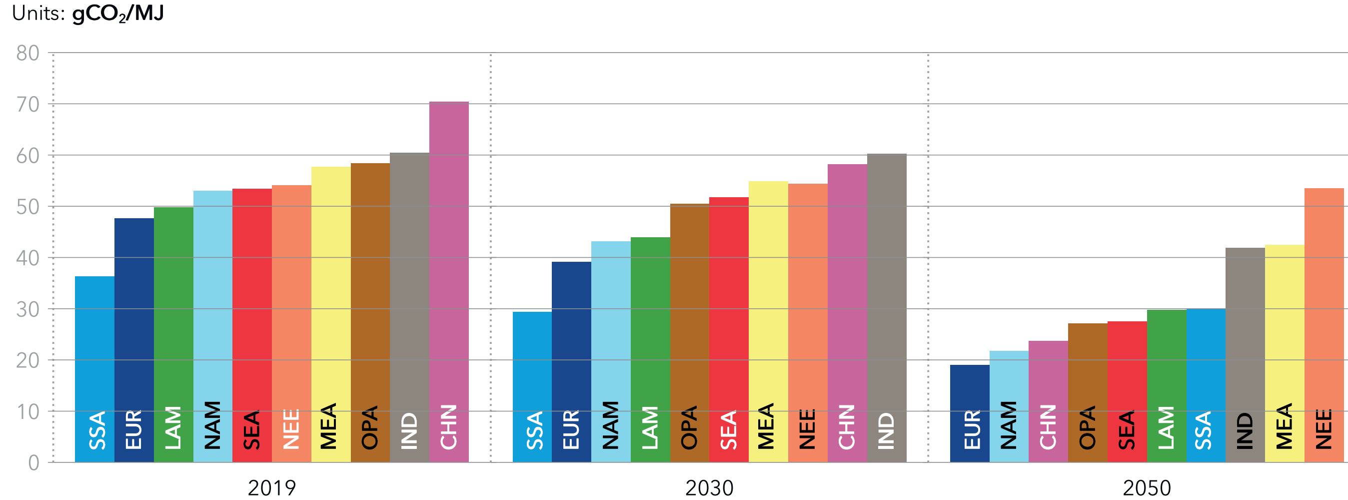


Energy intensity is measured as primary energy consumption per unit of GDP. All regions experience a decline in this measure. This is explained by efficiency gains, partly due to steady electrification of energy end-use. It is also because of the increasing share of renewables in electricity generation, through which electricity becomes more efficient as heat losses are smaller. Consequently, the decline in overall energy intensity accelerates. Despite a 53% decline between 2019 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, followed by South East Asia and Greater China.

FIGURE 7.11.2

Carbon intensity of primary energy consumption

Units: **gCO_2/MJ**

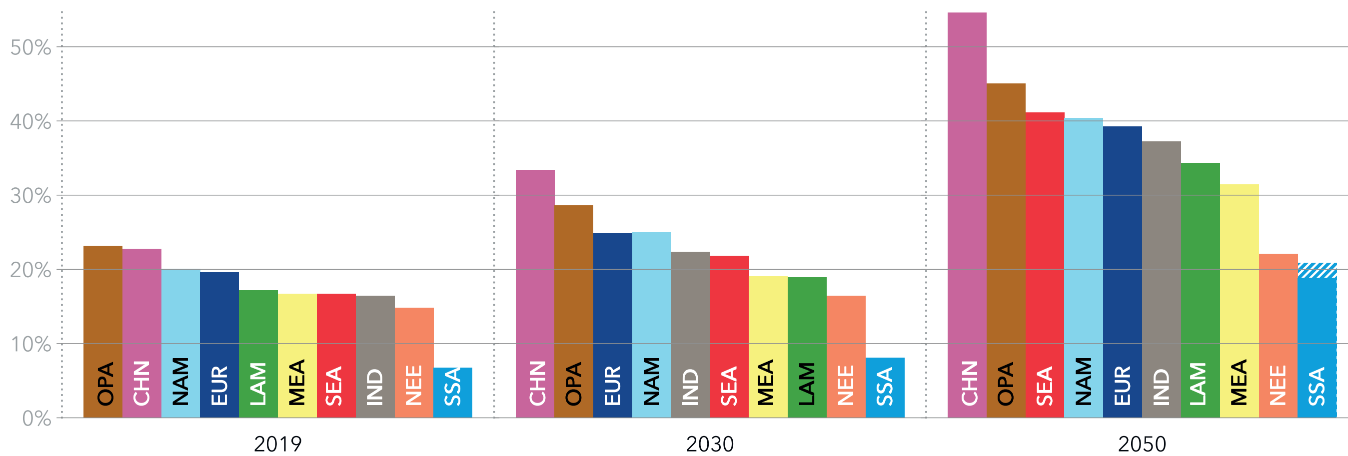


Carbon intensity is measured as tonnes of carbon dioxide per terajoule of primary energy consumption. Greater China and Europe have the most rapid decarbonization, with its carbon intensity declining by 66%, and 60% respectively. North East Eurasia and Sub-Saharan Africa will be the regions with least improvement in carbon intensity (1% and 17%). North East Eurasia will become the most carbon-intensive energy system in 2050.

FIGURE 7.11.3

Share of electricity in final energy demand

Units: **Percentages**



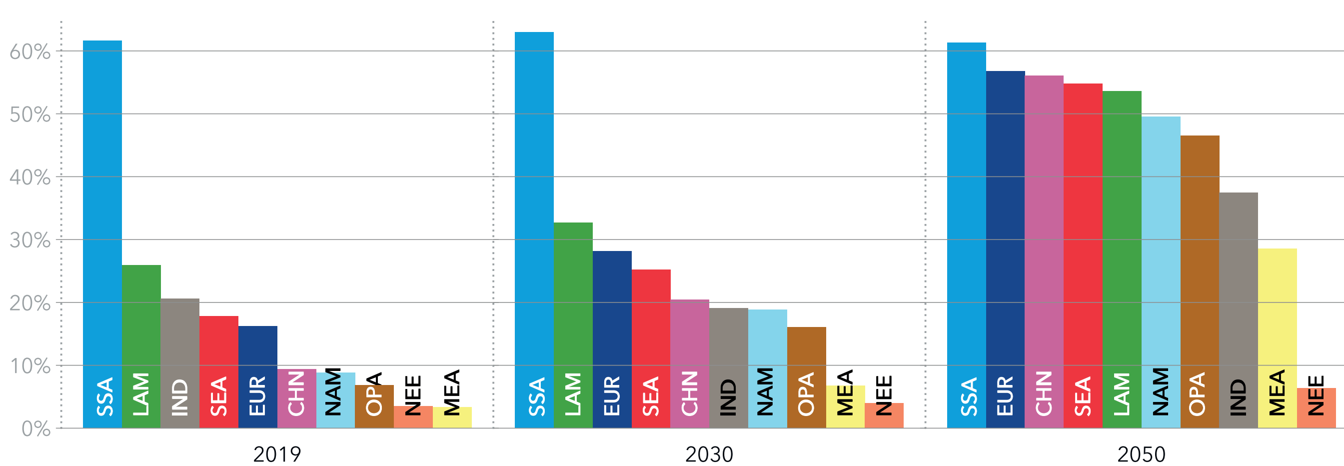
Shaded area represents offgrid-PV share.

Electrification is measured as the share of electricity in the final energy demand mix. This share is increasing everywhere. The pace will be fastest in Sub-Saharan Africa, where the share of electricity will almost triple, from 7% in 2019 to 19% 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 33% of final energy demand and further increase its lead to being the only region with over 50% of its energy demand from electricity by 2050.

FIGURE 7.11.4

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 2019 to 28% in 2050, but still the overall share of renewables in 2050 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 7% to 47%.

Highlights

Energy production and use represents 70% of global greenhouse gas emissions, of which most is CO_2. We forecast that energy-related CO_2 emissions in 2030 will be a mere 9% lower than they are today, and that emissions in 2050 will be at 19 Gt per year, a 45% reduction compared to 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 updated **carbon budget** associated with global warming of 1.5°C is exhausted in 2029 and the carbon budget for 2°C is exhausted in 2053.

From these calculations we derive a **global warming of 2.3°C by 2100** – a level considered dangerous by the scientific community. With significant effort, global warming could be slowed by changes to the energy system, but will need net-negative emissions technology in order to stop or reverse the warming.

Our forthcoming publication, *Pathway to net zero emissions,* will detail the DNV view on how to close the gap between the energy future we forecast and one that will limit global warming to 1.5°C.

8 EMISSIONS AND CLIMATE IMPLICATIONS

8 EMISSIONS AND CLIMATE IMPLICATIONS

The energy sector represents over 70% of annual greenhouse gas (GHG) emissions associated with human activities. The main contributor to these emissions is CO_2, which predominantly comes from the combustion of fossil fuels. In this chapter, we describe future CO_2 emissions and assess their climate implications.

Our Energy Transition Outlook gives an estimate of global energy-related CO_2 emission until 2050. Those, together with estimates about other, non-energy-related CO_2 emissions (e.g. cement and land-use) and energy-emissions estimates beyond 2050, allow us to derive the associated temperature response. We do not assess climate implications (e.g. flooding, drought or forest fires etc.) beyond the future average warming associated with the cumulative CO_2 emissions of our forecast.

8.1 EMISSIONS

Emissions from energy-related activities have grown continuously since the Industrial Revolution and 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 34.3 Gt CO_2 in 2019 (Global Carbon Project, 2020).

The effects of COVID-19 resulted in emissions dropping by approximately 5.8% in 2020 (IEA, 2021), a reversal unprecedented in recent history. But as economic activity is now picking up, energy use and emissions will follow. The pandemic has shifted the global emissions trajectory slightly down, as the economy and energy-use will need some years to regain momentum while decarbonization continues, and we still find 2019 to be the year of peak emissions in our forecast. The impact of the COVID-19 pandemic on cumulative global emissions, however, is very limited.

Based on the global energy demand in our forecast, global CO_2 energy-related emissions will climb back up 3% during 2021 and grow to 33 Gt CO_2 by 2023 before declining gradually to 31 Gt CO_2 in 2030, a level only 9% lower than 2019 levels. By 2050, energy-related emissions are expected to be 18.6 Gt CO_2, a 45% reduction compared with current levels (Figure 8.1).

Combustion emissions

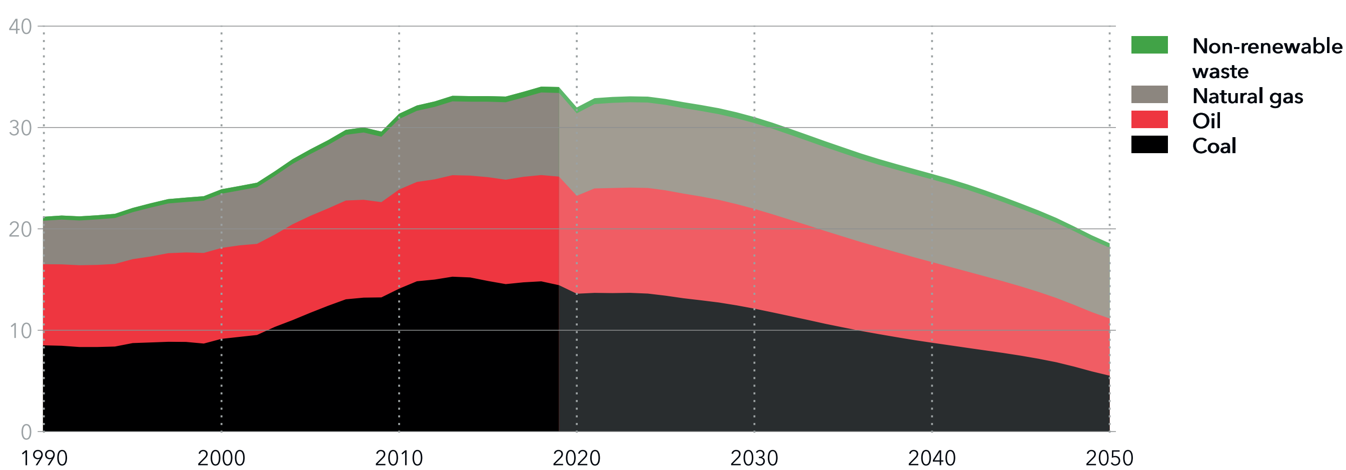
Figure 8.1 shows how coal is currently the main driver of energy-related CO_2 emissions, responsible for 42%, followed by oil and natural gas with 30% and 25%, respectively. Emissions of CO_2 from coal will see the strongest decline towards 2050 (62%) compared with 2019. Emissions from oil will almost halve by 2050 compared with 2019, whereas emissions from natural gas will grow towards 2030 and then drop back to a level 15% below today's emissions.

Towards 2050, coal and natural gas shift places in their relative contribution, with natural gas contributing 44%, while oil stays about the same at 30%. So, although in comparison with coal, natural gas combustion has 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.

FIGURE 8.1

World energy-related CO_2 emissions by fuel

Units: **$GtCO_2$/yr**



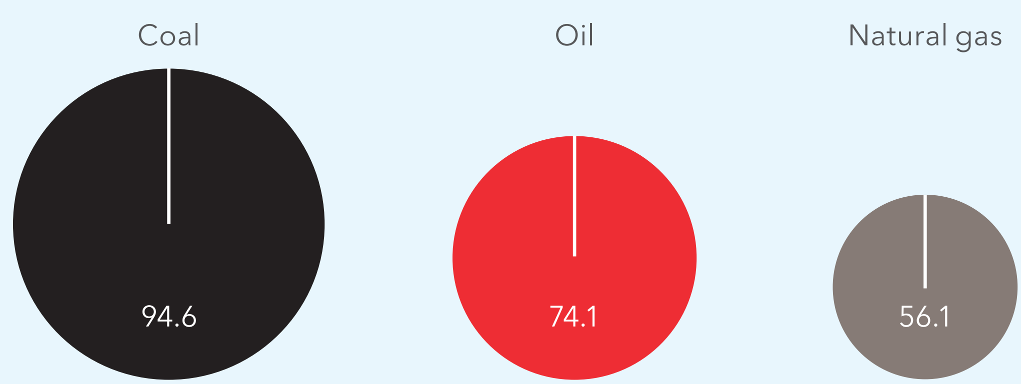
Combustion intensity

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 from electricity usage is dependent on the grid mix, but can be significantly higher per unit of energy due to large heat losses occurring at the power station, which is the reason for significant improvements in carbon intensity in all main sectors from electrification coupled with a shift to renewable energy sources in power production. Emissions from manufacturing processes are calculated differently and most of the process-related emissions come from chemical reactions in petrochemical and cement production.

Emissions per unit of energy from fossil fuels (and processes).

Emissions per unit of energy from fossil fuels

Units: tonne CO_2/TJ



Sector emissions

From a sectoral perspective, manufacturing is currently the largest contributor to energy-related CO_2 emissions with 12 Gt CO_2 emitted in 2019, some 35% of all annual energy-related emissions. The transport sector made up 26% of emissions, almost 9 Gt CO_2, while buildings which is the remaining major demand sector, emitted 8.5 Gt CO_2, 25% of global energy-related CO_2 emissions in 2019.

In 2050, manufacturing remains the highest-emitting sector, but with annual emissions reduced to 6 Gt CO_2. The transport sector will increase its share to represent 29% of emissions, however reduced to 5.4 Gt CO_2 in 2050, while the building share stays at about the same but reduced to 4.8 Gt CO_2 (Figure 8.2). The dynamics behind these emissions reductions are summarized as follows:

- The **manufacturing** sector emissions will decline steadily over the whole forecast period. Electrification, fuel-switching as well as CCS, all contribute to halving emissions from manufacturing.
- The **buildings** sector will, like manufacturing, see a steady decline in emissions towards a reduction of 44%, although we expect significant growth in the number of commercial and residential buildings. Continuous improvements in energy efficiency and switching to cleaner sources of fuel for heating, e.g.

electricity combined with heat pumps, will be the main reasons for these reductions.

– The **transport** sector had a sharp decline in emissions in 2020, due to changing travel patterns associated with the COVID-19 pandemic. In the longer term, the main trend of electrifying road transport will result in emissions declining by 40% by 2050. This is not just 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. However, it is only by the late 2020s that transport emissions start to decline, because even though a growing number of EVs reduce emissions, it is initially countered by transport growth and a lack of emission reductions in hard-to-abate sectors such as shipping and aviation.

As demand for energy peaks, CO_2 emissions start to decline, and the shift towards renewable energy sources adds to the decline. The carbon intensity of the energy system is used to measure decarbonization in tonne CO_2 per terajoule of primary energy consumption. Figure 8.3 shows the historical and forecast decarbonization for the three main demand sectors – transport, buildings, and manufacturing.

Regional emissions

The ten Outlook regions have different starting points and very differing emission trajectories over the forecast period. Greater China, currently the largest emitter by far, will reach peak emissions before 2030; emissions will then decline by 75% compared with 2019 levels.

The Indian Subcontinent will continue to grow its emissions, and increase by 40% to 2050, and Sub-Saharan Africa will show an increase of 55% compared with today. All other regions will reduce their emissions, with OECD Pacific, North America and Europe experiencing the biggest relative decline of around 70% each (Figure 8.4). North East Eurasia will have the highest emissions per capita at 7.5 tonnes/person in 2050, followed by North America and Middle East and North Africa at 3.5 tonnes/person (see the infographic on Energy, GDP and population, page 240). Regional emissions are described in more detail in Chapter 7.

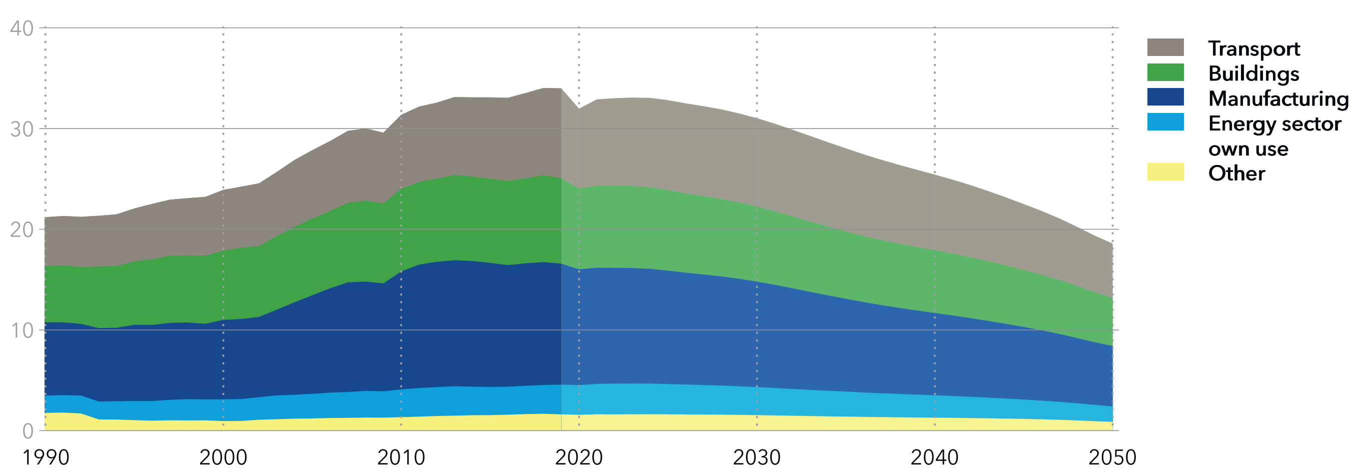
Non-energy related emissions

In addition to CO_2 emissions from combustion of fossil fuels, there are significant emissions from industrial processes that either consume fossil fuels as raw material for feedstock (e.g. plastics and petrochemical products) or through production processes that produce CO_2 through a chemical reaction (e.g. cement and other industrial processes).

FIGURE 8.2

World energy-related CO_2 emissions by sector

Units: **$GtCO_2$/yr**



Emissions from power and hydrogen generation are allocated to end-use sectors.

These non-energy emissions, together with estimates of the subsequent capture of some of these process emissions, are included in our analysis as part of the manufacturing sector. In 2019 these emissions totaled an estimated 4.1 Gt CO_2, of which approximately 40% were from calcination in the cement-production process. The remainder of the emissions were split between coke ovens and the production of lime or other chemicals (Olivier et al. 2020).

We expect a slight growth in base-material output, which largely drives non-energy emissions, over the next 15 years and then a stabilization. However, while base-material output might stabilize at a higher level than today's, improvements in production and technical efficiencies combined with increasing shares of these emissions being captured means that the resulting emissions level will be almost flat until 2030 and then decline. In 2050, non-energy industrial emissions will be 55% compared with today, a reduction of almost 1.5% per year to 2050.

Land-use emissions

CO_2 emissions from AFOLU (agriculture, forestry, and other land use) are not included in our forecast and modelling, but are substantial and must be factored into any calculation of global emissions. Emissions from land use have been growing slowly over the last 20 years and are currently at an average of 5 Gt CO_2 /yr, but with large annual fluctuations. 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 are losing them at double-digit rates compared to previous years due to deforestation and forest fires (Global Forest Watch, 2021). 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, our best estimate is that CO_2 emissions from land use changes will remain at current levels of 5 Gt CO_2 /yr on average until 2030, and then decline linearly to 2.5Gt/yr in 2050, half of the present level.

Carbon capture

Today, carbon capture and storage (CCS) is almost solely applied as part of enhanced oil recovery, where there is a viable business case. Discussions, research, policies and pilot projects are scaling to develop and implement this important measure to decarbonize fossil fuels use, as discussed in our Chapter 6.

FIGURE 8.3

World carbon intensity by sector

Units: gCO_2/MJ

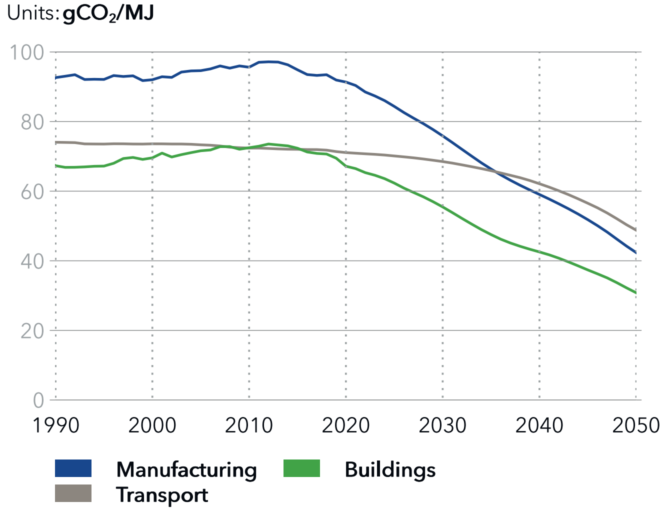
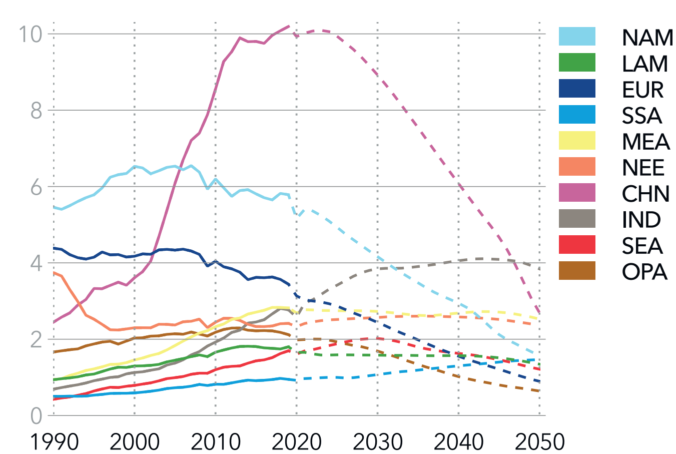


FIGURE 8.4

Energy-related CO_2 emissions by region

Units: $GtCO_2/yr$



Historical data source: IEA WEB (2020)

Going forward, we expect that operators of large point sources in the power and manufacturing sectors will increase the capture of carbon from their processes and waste streams. Additionally, we expect all carbon emissions from hydrogen production as an energy carrier to be captured in the steam-methane reforming (SMR) process; we also expect capture of an increasing share of emissions associated with hydrogen production for the process industry. Some capture is also expected when flaring occurs during natural gas processing.

However, for all the existing and announced policy on CCS, its uptake will be very limited in the near- to medium-term – and effectively too late and minimal in the longer term. 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 find emissions captured by CCS capacity to be 1.3 Gt CO_2. Of these 0.3 Gt CO_2 will be captured from SMR, 0.6 Gt CO_2 is captured from process-based emission from non-energy related activities, and the rest is from point-source capture in power and manufacturing (Figure 8.5). By 2050, the remaining emissions for potential capture in power and manufacturing are in regions with low carbon prices, which to a large extent explains why total carbon captured amounts to only 6% of all CO_2 emissions in 2050.

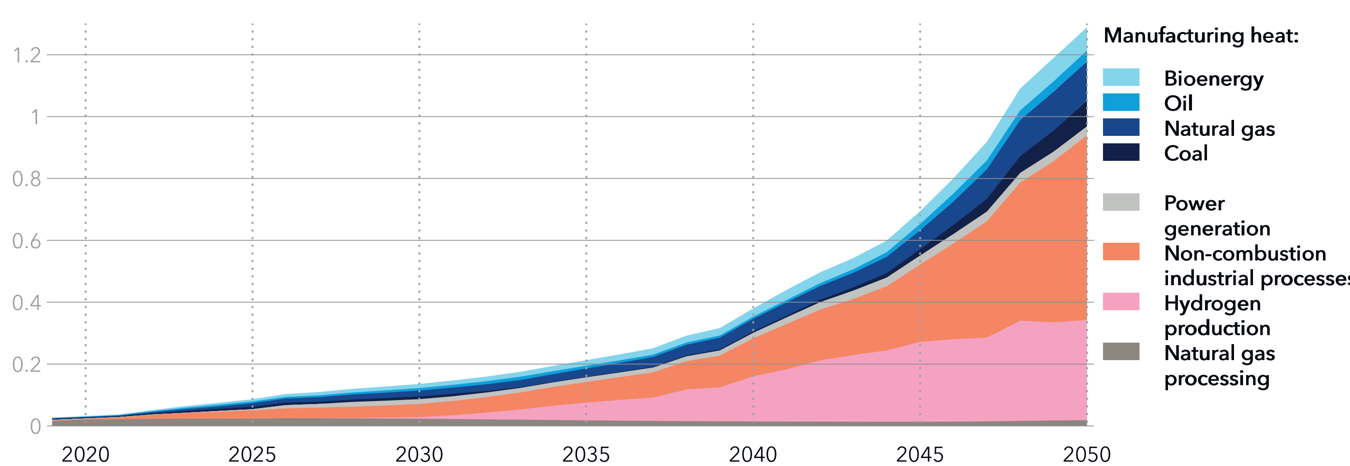
Over 50% of CCS capacity will be in Greater China and North America. Yet both regions will have still-considerable use of fossil fuels in the 2040s and moderate carbon prices. In Europe, the only region with high enough carbon prices to make a viable business case for CCS before 2040, policies are not likely to be geared in favour of CCS as regulations and support mechanisms for non-fossil energy carriers take precedence. Hence, the remaining fossil fuel use and potential for capture is low.

CCS development is thus not happening at sufficient speed or scale to make a significant impact in counteracting temperature increases and associated climate change. 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 dynamics 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.

FIGURE 8.5

World CO_2 emissions captured

Units: $GtCO_2$/yr



8.2 CLIMATE IMPLICATIONS

On the basis of forecast future emission levels, we can determine the corresponding 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, which 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 dealt with in this outlook, which concentrate on the energy transition.

CO_2 concentration

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, 2020), 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 May 2021, was a record level of 416.49 ppm (NOAA GML, 2021). The last time that Earth experienced this level of atmospheric CO_2 concentration was in the Pliocene era about 3 million years ago (Jones, 2017). Over the last 60 years, there has been 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 forecast 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). Thus, with the lengthy persistence of CO_2 in the atmosphere, the cumulative concentration of CO_2 gives a direct indication of long-term global warming. As there is a causal link between concentration and long-term temperature increase (IPCC, 2021), it is possible to calculate the expected temperature increase based on the cumulative net global amount of CO_2 in the atmosphere. Similarly, limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic greenhouse gases and pollution, gives the maximum amount of cumulative net global anthropogenic CO_2 emissions, often referred to as the global carbon budget.

Carbon budget

The carbon budget includes several uncertainties, including accuracy of data on historical emissions, accuracy of the estimated 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

TABLE 8.1

Estimated anthropogenic CO_2 and remaining carbon budget in Gt/yr

Units: Gt/yr

	2020	2030	2040	2050
Energy-related emissions (after CCS)	32	31	25	19
Captured and stored by CCS	0.03	0.1	0.4	1.3
Industrial processes total (after CCS)	4.1	3.9	3.0	1.9
AFOLU	5.0	5.0	3.8	2.5
Total Anthropogenic CO_2 emissions	41.1	39.9	32.2	22.9
Remaining Carbon Budget for 2°C	1150	695	339	64
Remaining Carbon Budget for 1.5°C	400	-55	-411	-686

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 reasonable method to indicate potential future warming levels based on different scenarios for energy-related emissions.

For our temperature estimates, we have used the 'likely' (meaning 67% probability) carbon budgets from the The United Nations' Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (IPCC, 2021). By selecting a 67% chance to stay below the selected temperature threshold, we have chosen to give humanity odds that are better than a 50/50 coin toss of limiting warming to our selected respective temperature thresholds. In order to stay below 1.5°C, IPCC concludes that we have to limit cumulative emissions to 400 Gt CO_2 from the start of 2020 and into the future, and 1150 Gt CO_2 to stay below 2.0°C.

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 or aerosol emissions, can have considerable influence on the size of the carbon budget. We use the IPCC scenarios in line with 'very low' and 'low' non-CO_2 emissions estimates, to follow a similar path as our CO_2 emission trajectory. If emissions from non-CO_2 GHG's are larger, then the carbon budget will be smaller and associated temperature increase larger.

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 2029. To exhaust the budget associated with the 2.0°C threshold it takes another 24 years until 2053. Table 8.1 shows forecast emissions of CO_2 from energy-related activities as well as industrial process and land-use emissions will still be considerable in 2050 and many years thereafter. Thus, the question arises, what temperature increase (to 2100) does our forecast suggest?

Temperature increase

Our energy transition forecast and associated CO_2 emissions ends in 2050, and thus in order to use the overshoot of the carbon budgets to evaluate a likely temperature increase, the emissions for the latter part of this century must be assessed. By 2050, the emissions' trajectory shows a relatively steep decline, with increasing amounts captured by CCS. Eventually there will be some emissions that are increasingly difficult to abate. However, in our analysis we expect that we will arrive at net zero CO_2 emissions before or by the end of this century.

To estimate the CO_2 emissions and global warming by the end of the century, we extrapolate the development of emissions and their capture towards 2100. It is only within the sectors shown in Figure 8.5 that capture occurs, so for sectors such as transport where there is zero or marginal capture, we extrapolate a decline in line with our forecast but ending at net zero by 2100. The approach gives us a cumulative-emissions estimate of 430 Gt CO_2 between 2050 and 2100 (Figure 8.6). This estimate does not include any large-scale negative-emissions technologies that may be able to reduce the atmospheric CO_2 concentrations significantly. With the updated climate response from IPCC AR6 (IPCC, 2021) using the 67% 'likely' overshoot of 370 Gt CO_2 compared to the 2.0 C budget suggests that the world will reach a level of warming of 2.3°C above pre-industrial levels by 2100.

Sensitivites

There are uncertainties associated with this projected increase in temperature. These not only arise from our own work in estimating the future CO_2 emissions trajectory, but also the probabilities associated with keeping temperatures below a certain temperature threshold. If using a 50% probability instead of our selected 67% probability, we would have a larger carbon budget that reduces our 2100 global-warming estimate by 0.17°C.

Other assumptions such as the availability and deployment of large-scale negative-emissions technologies will also affect the outcome. A successful deployment of negative emissions technology, such as BECCS or Direct Air Capture (DAC) could lower our forecast temperature increase. Assuming the technology matures, we could for example start to capture 5 Mn tonnes of CO_2 in 2030, and grow by a 15% CAGR to 2080, by then capturing 5 Gt CO_2 / yr (similar to the emissions of AFOLU today) and continue at this rate until 2100. This would lower our warming estimate in 2100 by 0.1°C. Similarly, if we assume that emissions do not decline at our projected rate, but from 2050 to 2100 we are only able to reduce CO_2 emissions linearly, then the effect would be an increase of almost 0.1°C by 2100.

Future AFOLU emissions continue beyond our forecast but we assume end at net zero in 2100. However such development could be reversed and instead we could assume an increase in sequestered biomass to be used as a carbon sink. If AFOLU emissions are reduced linearly from today to net zero by 2040 and stay there, then this would lower the warming estimate by 0.1°C by 2100, while a further reduction of AFOLU emissions, or even reversal, could result in even lower temperatures.

Other uncertainties, such as climate sensitivity and Earth system feedbacks also contribute towards future warming estimates. We have included the default IPCC values for Earth systems feedbacks, mainly a limited release of methane from thawing permafrost and wetlands. However, we have not considered climate tipping points and other non-linear Earth-system reactions that are beyond the scope of this Outlook. The IPCC Sixth Assessment Report (AR6) has reduced some of these uncertainties compared with previous reports, and therefore have adjusted carbon budgets and a new and narrower range of the climate response.

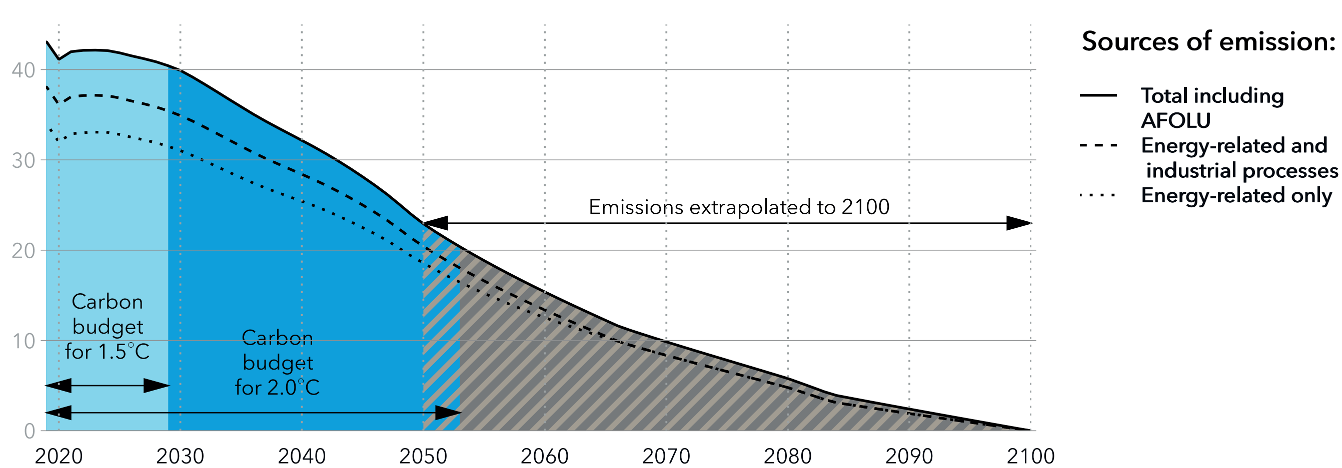
How to lower the global warming forecast significantly is very challenging, and the conclusion that the world is currently not on track to reach meet Paris Agreement goals is robust. As documented by scientists (see opposite), this is a future global warming level that should be avoided, as each tenth of a degree of temperature rise significantly increases the climate impacts. In our forth-coming publication, *Pathway to net zero emissions,* we present our scenario of how to limit global warming to 1.5°C.

The conclusion that the world is currently not on track to meet Paris Agreement goals is robust.

FIGURE 8.6

Carbon emissions and carbon budget

Units: **$GtCO_2$/yr**



IPCC Sixth Assessment Report on climate science

The United Nations' Intergovernmental Panel on Climate Change (IPCC) published the first part of its Sixth Assessment Report (AR6) on August 9th.

The more than 700 authors contributing to the IPCC assessment have reviewed over 14,000 peer-reviewed scientific papers and concluded that it is "unequivocal" that humans have warmed the planet, causing "widespread and rapid" changes to Earth's oceans, ice and land surface. They warn that the changes observed in the climate are "unprecedented over many centuries to many thousands of years".

The Assessment finds that almost all emissions scenarios predict 1.5°C degrees of warming, "in the early 2030s". Without reaching "net zero" CO_2 emissions before 2050, as well as an immediate, sharp reduction in emissions of both CO_2 and other greenhouse gases – the climate system will continue to warm.

"Global average surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades."

A key enhancement in AR6 is that warming projections are based "for the first time" on multiple lines of evidence, including observations of historical and recent warming trends. This is a major shift, as earlier IPCC projections were based entirely on climate models.

The report presents 5 different pathways / trajectories, with associated warmings between 1.4 to 4.4°C. It is only under the single pathway with the lowest emissions that near-term warming (2050) is more likely than not to "reach" 1.5°C, but "with a temporary overshoot of no more than 0.1°C". Moreover, warming would be extremely likely to stay below 2°C.

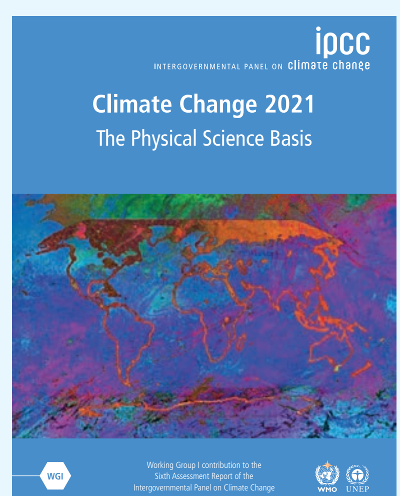
The Assessment also describes significant effects of the climate changing, in areas such as:

- Rainfall patterns
- Sea ice, icesheets and glaciers
- Permafrost and seasonal snow cover
- Oceans (warming and acidifying), sea level rise

The AR6 has a narrower estimate of "transient climate response to cumulative carbon emissions" (TCRE) than in AR5, reducing the uncertainty of climate sensitivity. This indicates progress in scientific knowledge on the climate system response to increasing levels of greenhouse gases in terms of temperature increase.

One of the main authors, Joeri Rogelj, says:

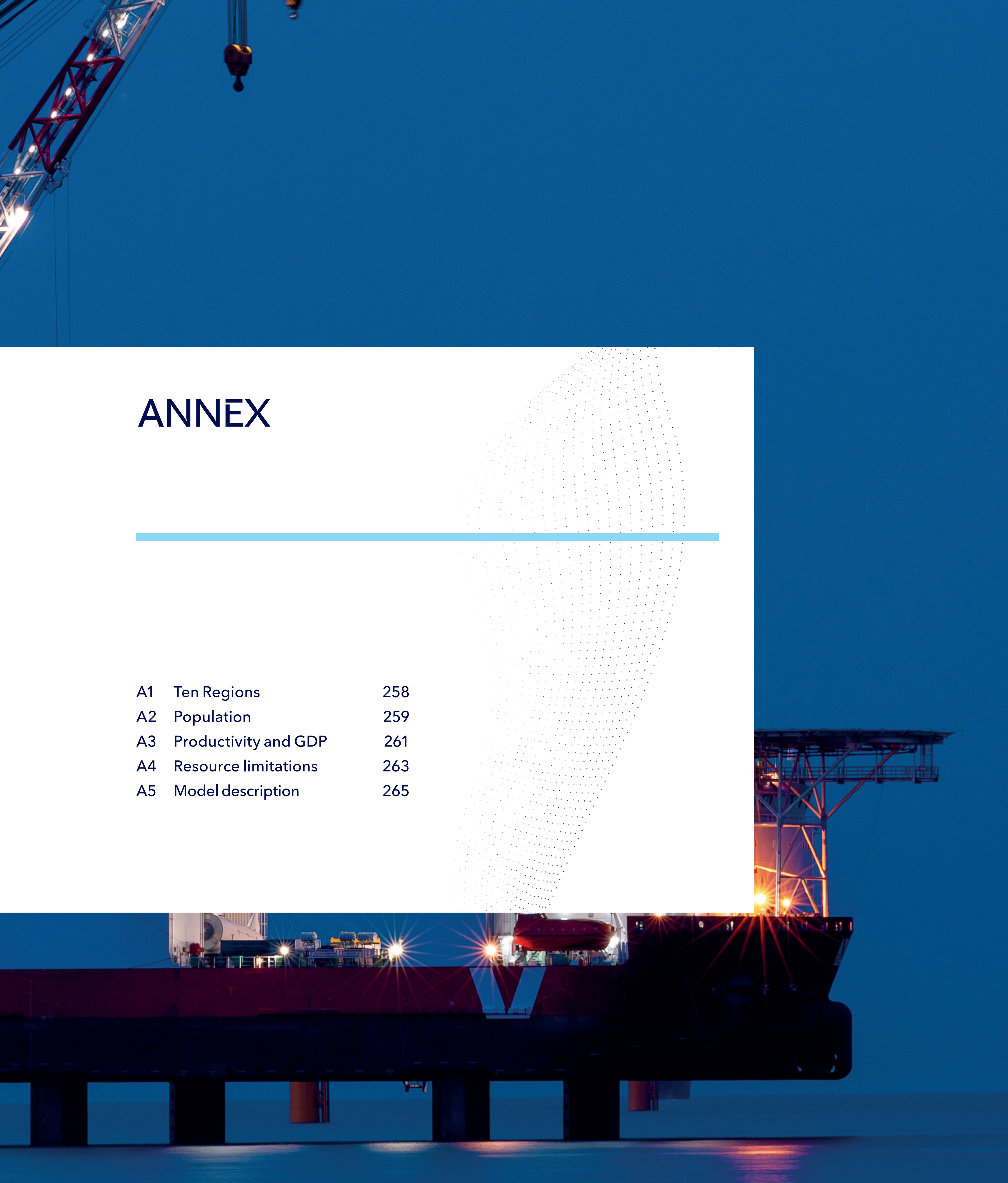
"Our activities have changed the planet, and it will be our activities that decide where we end up over the next centuries. We understand what needs to happen so the message from scientists and this report is hopeful but urgent" (Imperial College, 2021).



Highlights

Our **annexes provide details behind some of the important inputs to our forecast**. We:

- Define the 10 world regions for which we model energy transitions through to 2050.
- Provide background on the population and GDP growth figures used over our 31-year forecast period to 2050.
- Explain our conclusion that the transition is unlikely to be constrained by a lack of availability of either raw materials or land/sea area – although some regions may encounter shortfalls while others will enjoy an abundance.
- Describe our Energy Transition Outlook model – an integrated system-dynamics simulation model that reflects relationships between demand and supply in several interconnected modules. We also list the most significant changes to the model since our 2020 Outlook.



ANNEX

A1. TEN REGIONS

In this Outlook, we have divided the world into 10 geographical regions. These regions are 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 countries in the 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, we refer to "OECD regions"; that comprises the three regions North America, Europe and OECD Pacific.

Detailed discussions, results, and characteristics of the regional energy transitions are included in Chapter 7 of this Outlook, presenting region analysis and forecast energy transitions for all ten world regions.

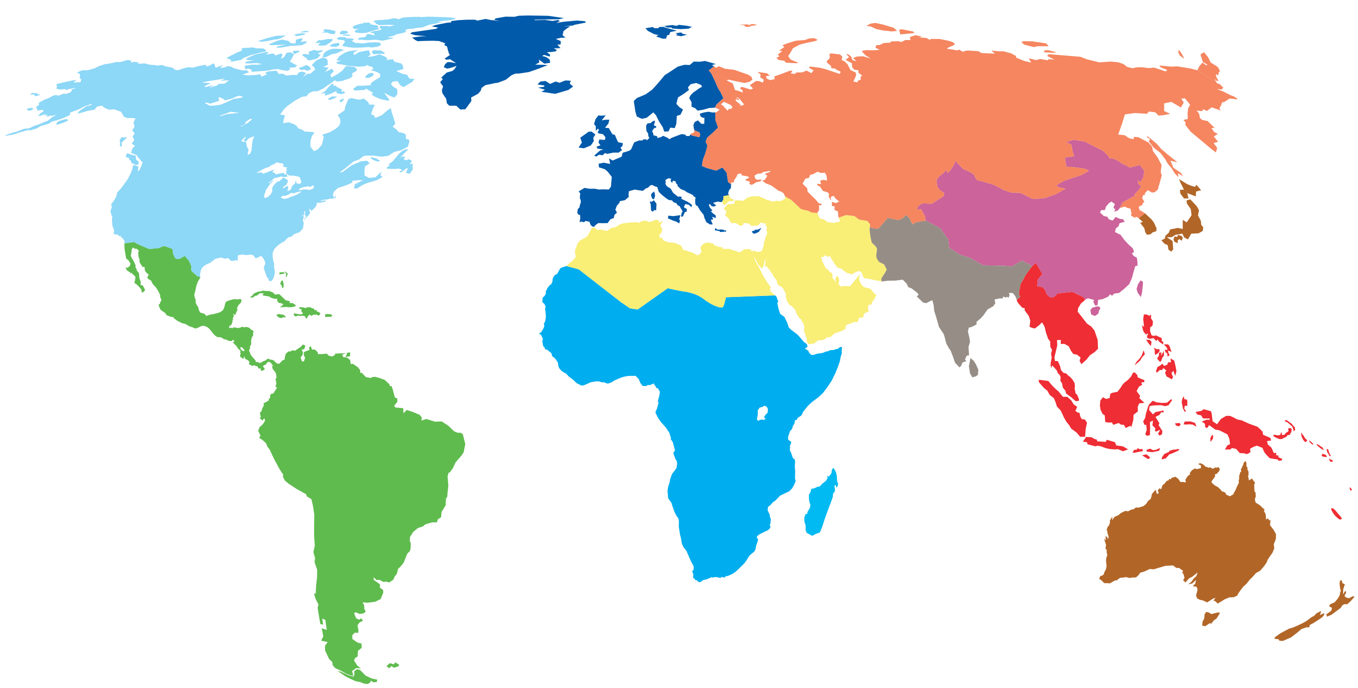


FIGURE A.1

- 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)

A2. 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, 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 Inter-governmental 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.

The pandemic has been influencing fertility figures, and the number of births in most developed countries has fallen. The pandemic has also led to loss of education in many developing countries, with potential higher fertility rates. Research on the long-term impact of these developments will be followed closely, but at the moment, no change in our forecast figures has been included.

Using the Wittgenstein population projections for SSP2, we arrive at our 2050 population forecast of 9.4 billion, which is an increase of 22% from the most recent UN (2019) population estimate of 7.7 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.

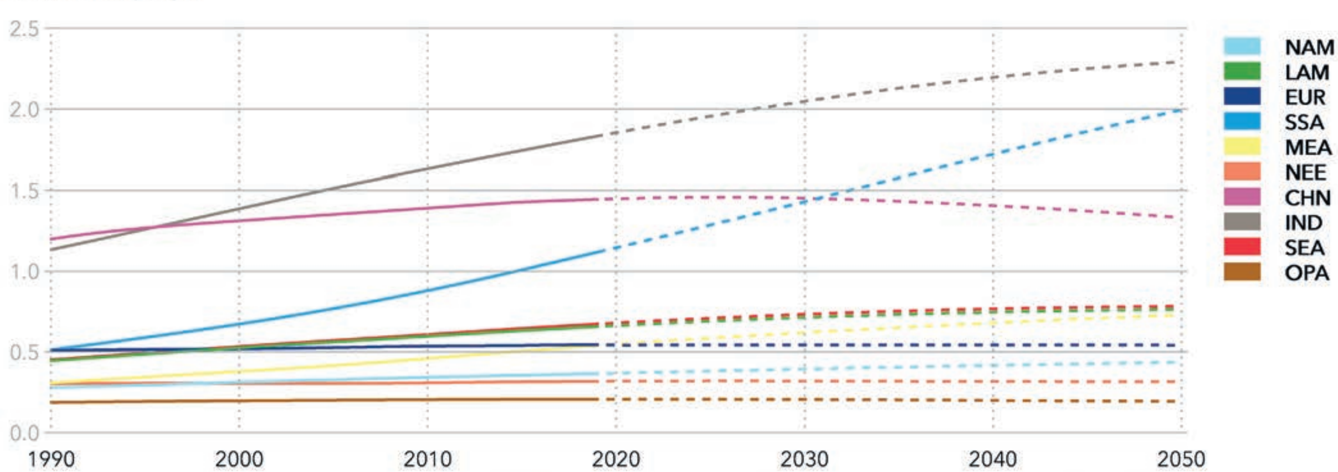
Our 2050 figure of 9.4 billion is 4% lower than the latest UN median estimate of 9.7 billion. Had we used the UN median population projection, most of our energy demand figures would have increased commensurately, but with regional variations.

We forecast a 2050 global population of 9.4 billion, 4% lower than the UN median estimate.

FIGURE A.2

Population by region

Units: **Billion people**



Historical data source: UN (2019), Forecast: Wittgenstein Centre for Demography and Human Capital (2018)

A3. PRODUCTIVITY AND GDP

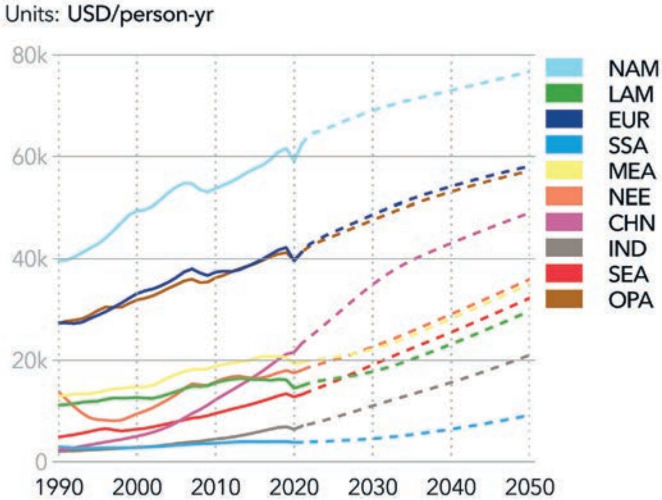
GDP per capita is a measure of the standard of living in a country and is a major driver of energy consumption in our model. From a production point of view, it is also a good proxy for labour productivity, as it reflects the amount of economic output per person.

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.

FIGURE A.3

GDP per capita by region

Units: USD/person-yr



Historical data source: IMF (2021), World Bank (2018), Gapminder (2018)

Measured in purchasing-power-adjusted constant (2017) USD, historical GDP per capita developments from 1990 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 1.2%/yr is estimated in the 2019-2021 period, due to COVID-19. COVID-19 will leave a permanent impact on the economy. In 2023 global economy will be 4.1% smaller compared to the pre-pandemic projections. The post COVID-19 boost in 2023 will result in some regional economies growing slightly faster than they otherwise would have, and in 2050 the loss declines to 3.2%.

The fact box at the start of Chapter 1 describes more fully how we have incorporated the effects of COVID-19 into our forecast.

The fastest growth in GDP per capita, between 2021 and 2030, will be in Asia. The Indian Subcontinent (IND) will have highest growth rate, at an average of 6.2%/yr, followed by South East Asia (SEA) at 4.9%/yr and Greater China (CHN) at 4.6%/yr, as shown in Figure A.3.

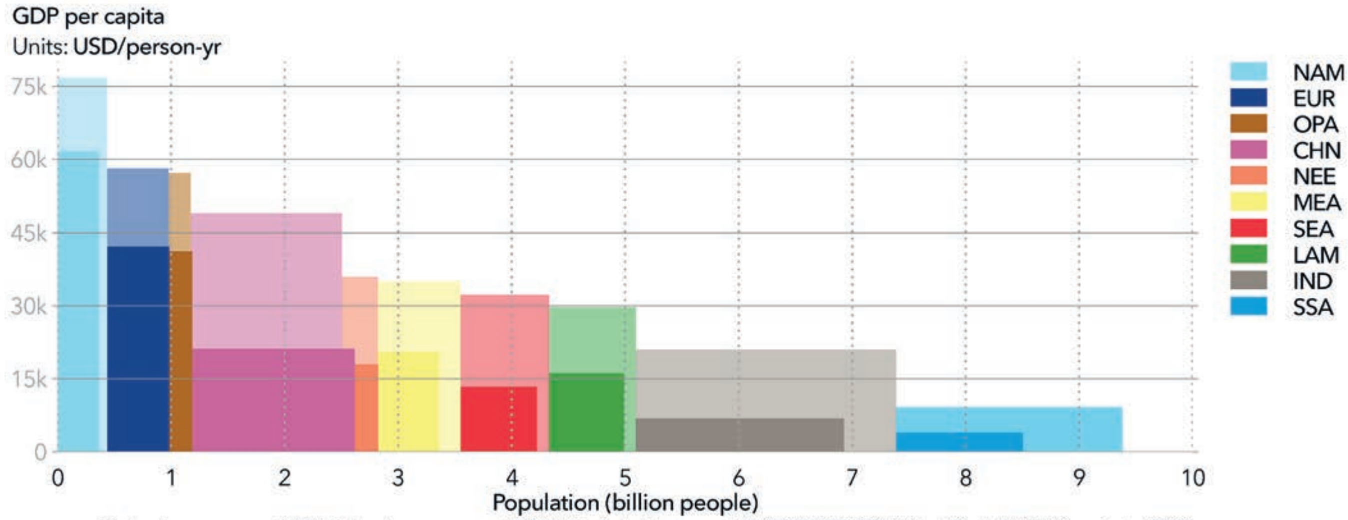
As the Asian economies mature, growth in GDP per capita will slow down after 2030. The period between 2030-2050 will be characterized by a more-even spread of prosperity improvements globally, with highest growth in the least-developed regions. The region with the fastest GDP per capita growth will therefore be SSA, with a CAGR 5.3%/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 138 trn/yr in 2019 to USD 292 trn/yr in 2050. This doubling over the 31-year period is a result of a 22% increase in population and a 74% increase in average GDP per capita, with large regional differences. Figure A.4 illustrates the 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 3.6% compound annual GDP growth from 2000 to 2019. In the 2040s this will gradually slow to 1.9%/yr, combining the effect of slowdown in population growth with the economies of more and more countries becoming 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.

FIGURE A.4

Change in population, GDP per capita and GDP between 2019 and 2050, by region



Darker boxes represent 2019, lighter boxes represent 2050. Historical data source: UN (2019), IMF (2021), World Bank (2018), Gapminder (2018)

TABLE A.1

Compound annual GDP growth rate by region

		2000-2019	2019-2021	2021-2030	2030-2040	2040-2050	2019-2050
NAM	North America	2.0%	1.4%	1.8%	1.1%	1.0%	1.3%
LAM	Latin America	2.5%	–2.9%	2.6%	3.1%	2.7%	2.5%
EUR	Europe	1.5%	–1.2%	1.9%	1.1%	0.7%	1.0%
SSA	Sub-Saharan Africa	4.6%	0.7%	4.2%	5.4%	5.2%	4.7%
MEA	Middle East and North Africa	3.6%	–1.1%	2.6%	3.4%	2.9%	2.7%
NEE	North East Eurasia	3.7%	0.4%	2.5%	2.5%	2.1%	2.2%
CHN	Greater China	8.4%	5.2%	4.6%	1.8%	0.8%	2.5%
IND	Indian Subcontinent	6.4%	2.1%	6.2%	4.3%	3.4%	4.4%
SEA	South East Asia	5.2%	0.5%	4.9%	3.4%	2.6%	3.4%
OPA	OECD Pacific	1.6%	0.2%	1.5%	0.8%	0.4%	0.8%
	World	3.6%	1.2%	3.4%	2.4%	1.9%	2.4%

A4. RESOURCE LIMITATIONS

Our forecast describes the production and use of energy towards 2050. Historically, humanity has mainly used finite fossil energy resources, and in the future, we will increasingly depend on renewable energy resources. This shift will not only impact the structure of the energy system but also the type of raw materials and necessary land to support the transition. Coal mines will increasingly be replaced by nickel and lithium mining and instead of extracting oil and gas from offshore platforms we will have turbines harvesting wind resources for energy.

One central feature of our Outlook is the increasing rate of electrification of the world's energy system. Road transport will increasingly be powered by electricity and energy stored in batteries. In 2050, there will be 1.3bn EVs on the road and transitions on this scale require sufficient raw materials to build the infrastructure and end-use technology and equipment, and enough land for renewable-energy projects. Supply of resources must be capable of expanding at rates that can support demand, both sustainably and cumulatively, between now and 2050. Although we expect 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. Agility, technology and materials choices, and greater recycling and re-use of resources will be important for ensuring that major disruptions are avoided.

Land and sea-areas to support renewable growth

We forecast a 20-fold increase in solar PV capacity by 2050, with sufficient land and building area as 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 of land. In our Outlook, we forecast 20% of all solar to be installed on rooftops and commercial buildings globally. Applying an estimated average 60 MW/ km^2 for non-rooftop solar-PV installations indicates a requirement of less than 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, 1% of agricultural land in Greater China and 1.2% of the Indian Subcontinent agricultural land 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 are also seeing growing interest and developments in floating solar PV where the available land issue is less of a concern.

The overall picture is that there will be enough materials and land to support the transition.

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 area. 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 our analysis, we have reviewed the technical potential and only included areas with sufficient wind speeds, while avoiding densely populated or remote locations. With these limitations and using an estimated area demand of 5 MW/km2, then wind farms cover significant square-km of land mass. Globally 1% of available land, or in comparison about 2% of agricultural land, which is equivalent to 2% of the technical potential. Thus, it is not availability of land that will be the limiting factor, but rather our collective acceptance of visual, noise and other environmental impacts associated with wind power.

In contrast, offshore wind is generally located far from populations and provides plentiful energy in our Outlook. Our analysis and modelling 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 forecast amount of offshore wind. Europe and Greater China will represent almost 60% of global installed offshore wind capacity. Europe and the North-Sea basin are expected to install mostly fixed (90%) but also 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, so also there 90% will be bottom fixed. When considering the technical capacity only a fraction of the installations will be floating offshore wind, but Greater China as well as the Indian Subcontinent will install half of the technical potential of fixed offshore wind by 2050. This would mean that Greater China (including Taiwan) coastal areas would utilize almost 40% of its coastline for installing offshore wind.

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 (DNV GL, 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 further reduce the demand for raw materials. Wind turbines use common building materials, but the vast amounts of steel and cement necessary will put pressure on those hard-to-abate sectors to reduce their embedded carbon footprint during production to ensure low lifecycle emissions from wind. There could be supply-chain challenges for rare earth elements, which usually are abundant but expensive and resource-intensive to extract, especially in the case of neodymium used for permanent magnets in the turbines.

Growth in number of EVs and vehicle battery size will drive a 400-fold increase in global battery capacity. This will spur the demand for minerals (lithium, nickel and cobalt) currently used in Lithium-Ion Batteries unless new battery chemistries are developed. The forecast growth in battery capacity is by far the largest driver of demand for lithium, nickel, and cobalt used in battery anode and cathodes and is where we expect the biggest supply challenges. Battery manufacturing capacity is growing exponentially and there are several initiatives to increase supply for lithium and nickel, while for cobalt the supply chain is less geared for demand surges and therefore we identify cobalt as a critical resource for the energy transition. See our ETO 2020, for a detailed analysis of cobalt supply and demand. Although the price of cobalt has almost doubled in the last year (LME, 2021), there are clear signs that auto manufacturers are diversifying their use of battery chemistries. BYD, a big Chinese manufacturer focuses solely on LFP; 95% of commercial vehicles in China, and many of those exported, use LFP chemistry (Campbell, 2019). For its standard range model 3 vehicle, Tesla has decided to use LFP batteries without cobalt, while for their long range and performance vehicles they use a cobalt based battery but are working on developing a cobalt-free high-performance battery.

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. Considering a more ambitious energy transition focusing on reducing emissions as described in our forthcoming report *Pathway to net zero emissions*, we need to revisit the topic of resource availability and understand the possible limitations a net zero future would entail.

In our view, the energy transition will not be significantly constrained globally by the availability of either raw materials or land/sea area.

A5. MODEL DESCRIPTION

The basis for our forecast is our Energy Transition Outlook Model – 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.5) 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, biomethane production)
- and other relevant developments (economy, grids, pipelines, 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 model are based on academic papers, external databases, commercial reports, and expert judgement from both within and outside DNV. Examples of external databases used include IEA World Energy Balances, IRENA Capacity & Generation Database, GlobalData Power Database, Marklines Automotive Industry Portal, Rystad Upstream Database, UN Comtrade Database, and Clarksons Shipping Intelligence Network. For reliable forecasting, we have run dozens of workshops and discussions with DNV 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 Energy Transition Outlook model 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 model 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 model 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.

Beyond 2050

Our Outlook and model forecasts stop at 2050. Looking 29 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.

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.

Modelling principles

Our main priorities when designing the Energy Transition Outlook model 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, our model is not. Instead, it simply simulates the consequences of its assumed goals, parameters, and interrelationships. The model 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.

We continually update the structure of and input data to our model.

Our Energy Transition Outlook model 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 model 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 that emerge from a complex model 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, 2021e).

Continuous improvement
The structure and input data of the model 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 model since our 2020 Outlook are:

- revision of the CCS sector, allowing us to provide separate estimates on CCS uptake by individual sectors, and more granular CCS cost components;
- revision of the hydrogen supply sector with a revised and more granular estimate of the total cost, a better integration with the power market allowing more reasonable estimates of operating hours of electrolysis, and five types of hydrogen production (grey SMR, blue SMR, coal-gasification, grid-based electrolysis, renewable-based electrolysis) including hydrogen production for refineries and ammonia production. These changes led to higher share of electrolysis, which indirectly help renewables, as electrolysers use the cheap electricity produced by renewables;
- revision of the hydrogen market sector so that the price of hydrogen better reflects the cost of storing and transporting hydrogen;
- introduction of solar + storage as a new power station type;
- introduction of a biomethane sector, that forecasts the fraction of methane provided by biomethane, based on cost and availability;
- revision of the manufacturing sector. There is a new logic to estimating manufacturing demand split into four subsectors (construction and mining is new), and a revised logic for fuel mix and energy efficiencies, which fully takes the fuel prices into account, and hydrogen blending.
- a price-driven buildings energy mix: technology selection is based on convenience-adjusted levelized cost, instead of expert opinion;
- introduction of a gas pipelines sector, that forecasts the capacity and cost of methane and hydrogen pipelines;
- revision of the gas trade and gas market sectors, allowing us to forecast the gas trade and its impact on regional gas prices based on production and transport costs of gas, instead of expert opinion;
- revision of the oil refineries sector;
- revision of the power grids sector so that simulated power line lengths and costs match historical data, which allowed us to better estimate the grid cost component of the electricity price;
- revision of our hourly power market sector so that the behaviour of storage and trade is more realistic.

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 value added in USD, estimated separately for base materials, manufactured goods, and construction and mining. For iron and steel, we measure the output in tonnes. Total manufacturing value added in each of our world regions is driven by the secondary sector GDP. Total value added is split into subsectors using historical shares. 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 buildings, manufacturing and EV uptake. For the energy mix of other end uses, 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 methane, ethane, propane, butane and biomethane), geothermal, bioenergy (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.

Hydrogen is supplied either by electrolysis or from fossil fuels, through steam methane reforming (SMR) or coal gasification. We make a distinction between hydrogen supplied via electrolysis from grid electricity and via off-grid dedicated renewable-based electrolysers. Annual operating hours and expected electricity price for electrolysis are calculated dynamically in the hourly power-market module. The levelized cost of hydrogen from competing technologies determines the investment mix in hydrogen production capacity.

Fossil-fuel extraction

When it comes to the supply of energy from primary sources, the model 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, based on production and transportation costs. 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 model.

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.

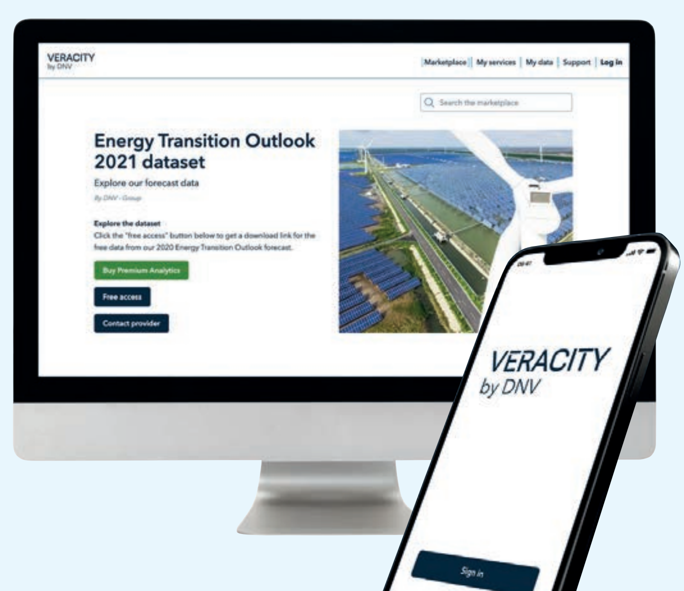
Trade

Trade, especially seaborne trade, of energy carriers, is a vital component of the model. 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 and future changes in gas import costs between trade 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's industry platform, Veracity.com. For details on how to access this material, visit eto.dnv.com.

eto.dnv.com/forecast-data



MODEL DESCRIPTION

Figure A.5 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 feed- back loops in our model is shown opposite (Figure A.6) 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.5

ETO model framework

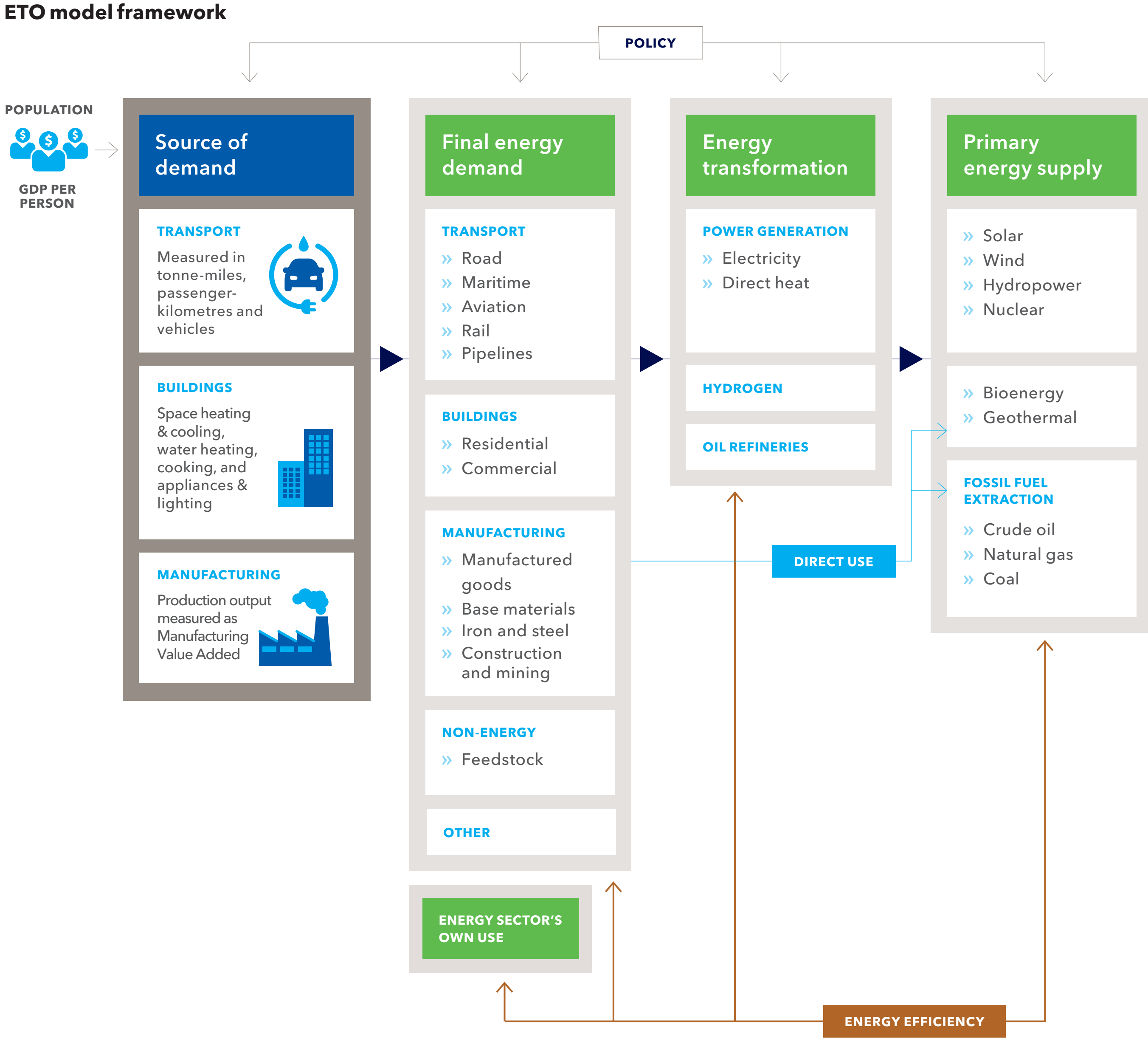
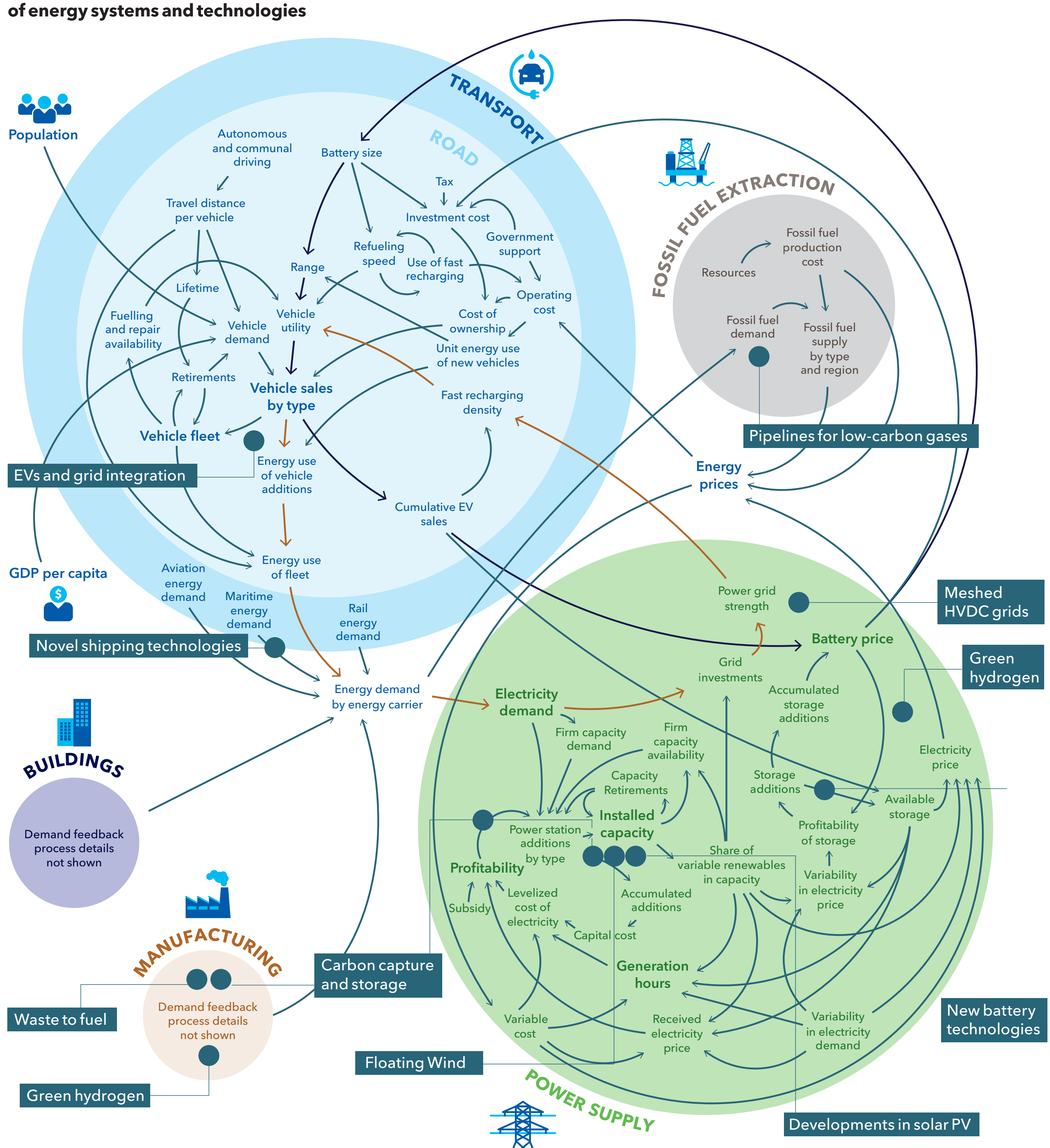


FIGURE A.6

***Energy Transition Outlook* model showing the interconnectivity of energy systems and technologies**



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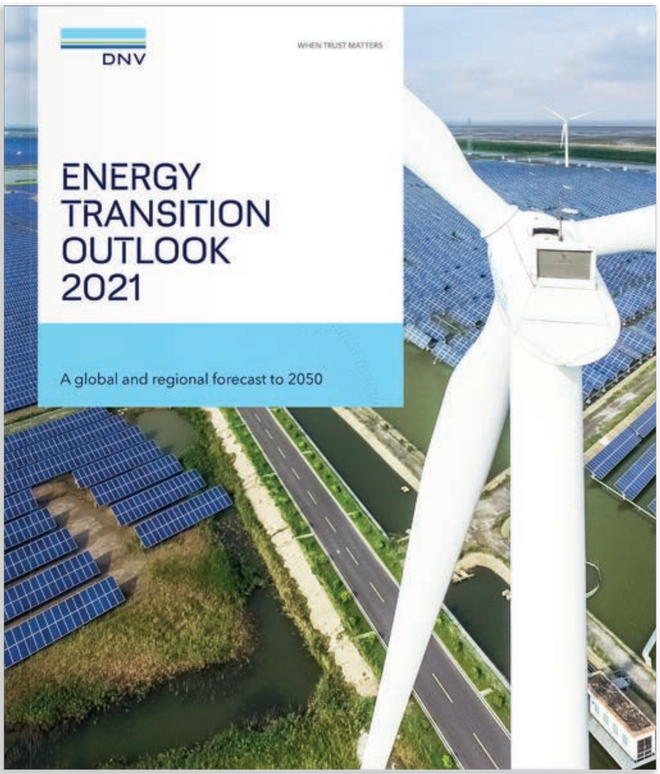
Historical data

This work is partly based on the World Energy Balances database developed by the International Energy Agency © OECD/IEA 2020, but the resulting work has been prepared by DNV and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2018) numerical data is mainly based on IEA data from World Energy Balances © OECD/ IEA 2020, www.iea.org/statistics, License: www.iea. org/t&c; as modified by DNV.

ENERGY TRANSITION OUTLOOK 2021 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 the most likely trajectory of the coming energy transition, and covers:

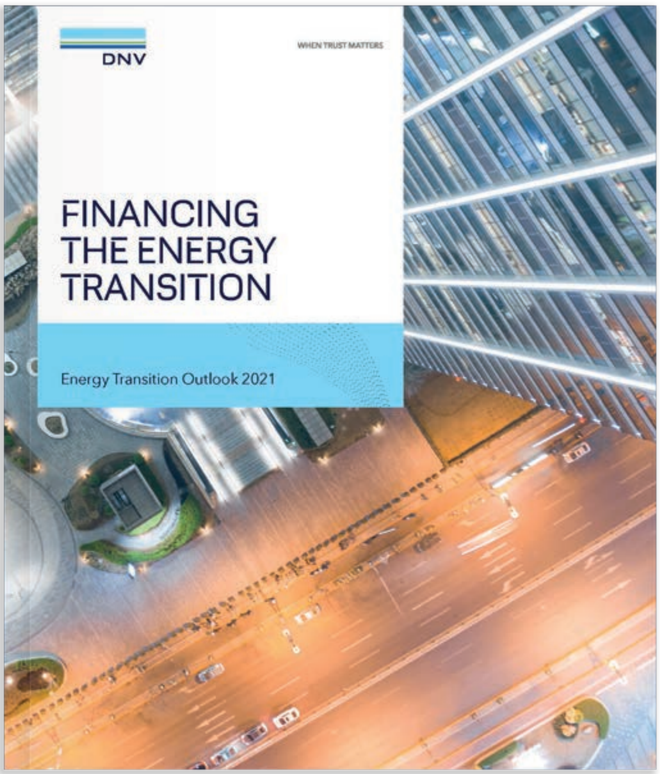
- **The global energy demand** for transport, buildings, and manufacturing
- **The changing energy supply mix**, energy efficiency, and expenditures
- **Detailed energy outlooks** for 10 world regions
- **The climate implications** of our forecast.

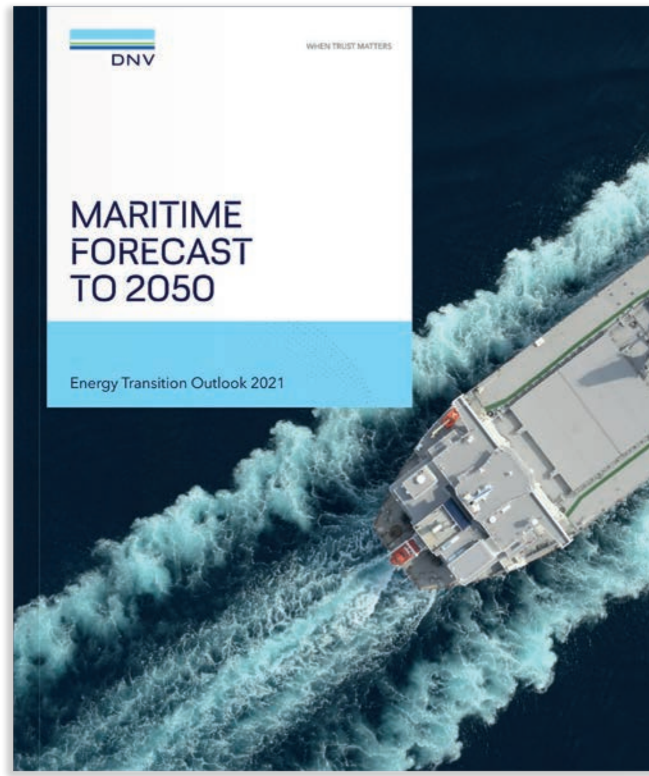
We also provide details on our model and main assumptions (i.e., population, GDP, technology costs and government policy). Our 2021 Outlook explores, inter alia, the impact of COVID-19 and the growing importance of hydrogen as an energy carrier.

Technology progress report
We explore how key energy transition technologies will develop, compete, and interact in the coming 5 years. The ten technologies are:

- **Energy production**: floating wind, solar PV, and waste to fuel and feedstock
- **Energy transport, storage, and distribution**: pipelines for low-carbon gas; meshed HVDC grids, new battery technology
- **Energy conversion and use**: novel shipping technologies, EVs and grid integration, green hydrogen production, CCS.

We attempt to strike a balance between technical details and issues of safety, efficiency, cost, and competitiveness. The interdependencies and linkages between the technologies are a particular area of focus.





Financing the energy transition
Focuses on the financial opportunities and challenges for financiers, policymakers, developers, and energy companies:.

- **An affordable transition** – considering whether a Paris-compliant transition is affordable, and what may be needed to mobilize and redirect capital
- **Accelerating the transition** – examining the role of financial markets, policy, and regulation, and how to get capital to flow to where it can have the most impact on emissions
- **Ensuring a just transition** – exploring the importance of balancing sustainability priorities, ensuring co-benefits, and building climate resilience.

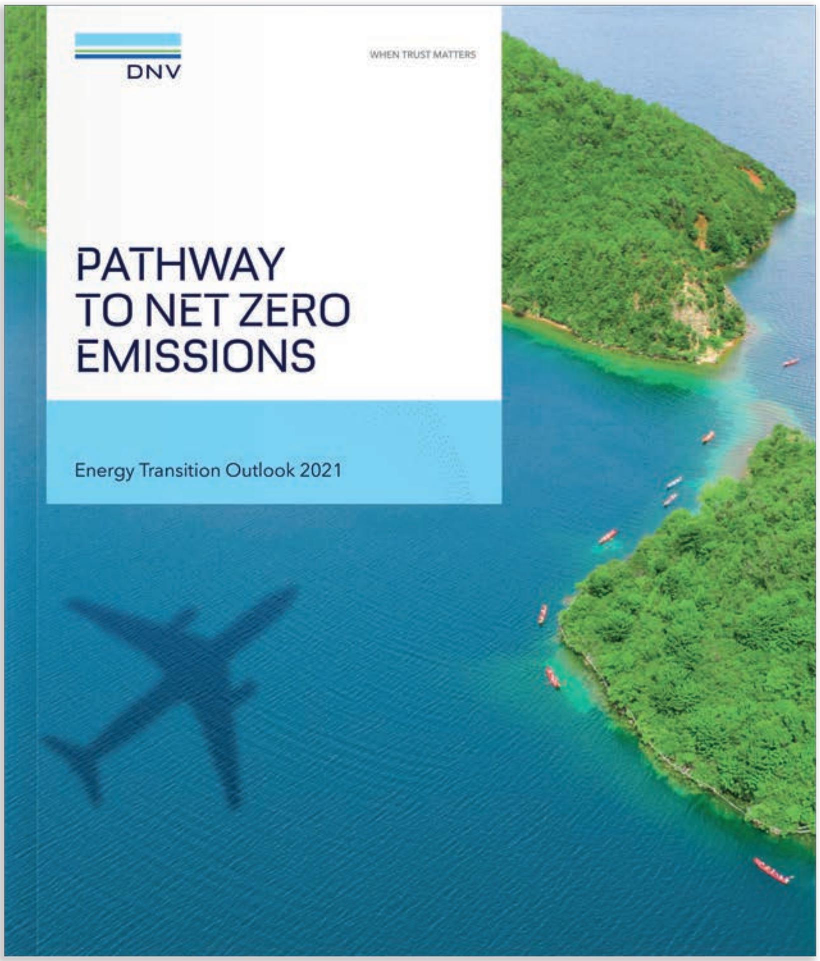
The report combines DNV's independent energy forecast to 2050 with views from a diverse set of leaders in the energy and finance sectors.

Maritime forecast
The Maritime Forecast to 2050 offers shipowners practical advice and solutions as shipping's carbon reduction trajectories rapidly head towards zero.

- **DNV's new carbon risk framework** allows detailed assessments of fuel flexibility and Fuel Ready solutions, the economic robustness of fuel and energy efficiency strategies, and their impact on vessel design.
- **Decarbonization** is leading to increased regulatory requirements, new cargo-owner and consumer expectations, and more rigorous demands from investors and institutions.
- **Investments in energy and fuel production** will be essential to shipping's efforts to decarbonize.

This is the grand challenge for the maritime industry. But by working together as an industry, embracing fuel flexibility, and consulting with expert partners, shipping can reach its destination.

PATHWAY TO NET ZERO EMISSIONS



This year, ahead of COP 26, we are releasing a new companion report to our main *Energy Transition Outlook 2021*. As outlined in the Paris Agreement, and confirmed in the IPCC AR6 WG1 report released in August 2021, there is a dire need for urgent, prioritized action tackling energy-related emissions.

Our new report plots a pathway for how to close the gap between our forecast and net zero CO_2 emissions by 2050 – i.e. actions that are likely to limit global temperature increase to 1.5°C by end of this century. The report covers all energy sectors – including hard-to-abate sectors like aviation, maritime and cement – and each of the ten global regions in our *Energy Transition Outlook*. We look at which technologies will contribute to the required change and the policies needed to achieve that.

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THE PROJECT TEAM

This report has been prepared by DNV as a cross-disciplinary exercise between the DNV Group and our business areas of Energy Systems and Maritime across 15 countries. The core model development and research have been conducted by a dedicated team in our Energy Transition Outlook research unit, part of the Group Technology and Research division, based in Oslo, Norway. In addition, we have been greatly assisted by the external Energy Transition Outlook Collaboration Network, with the experts listed on page 13 this report.

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