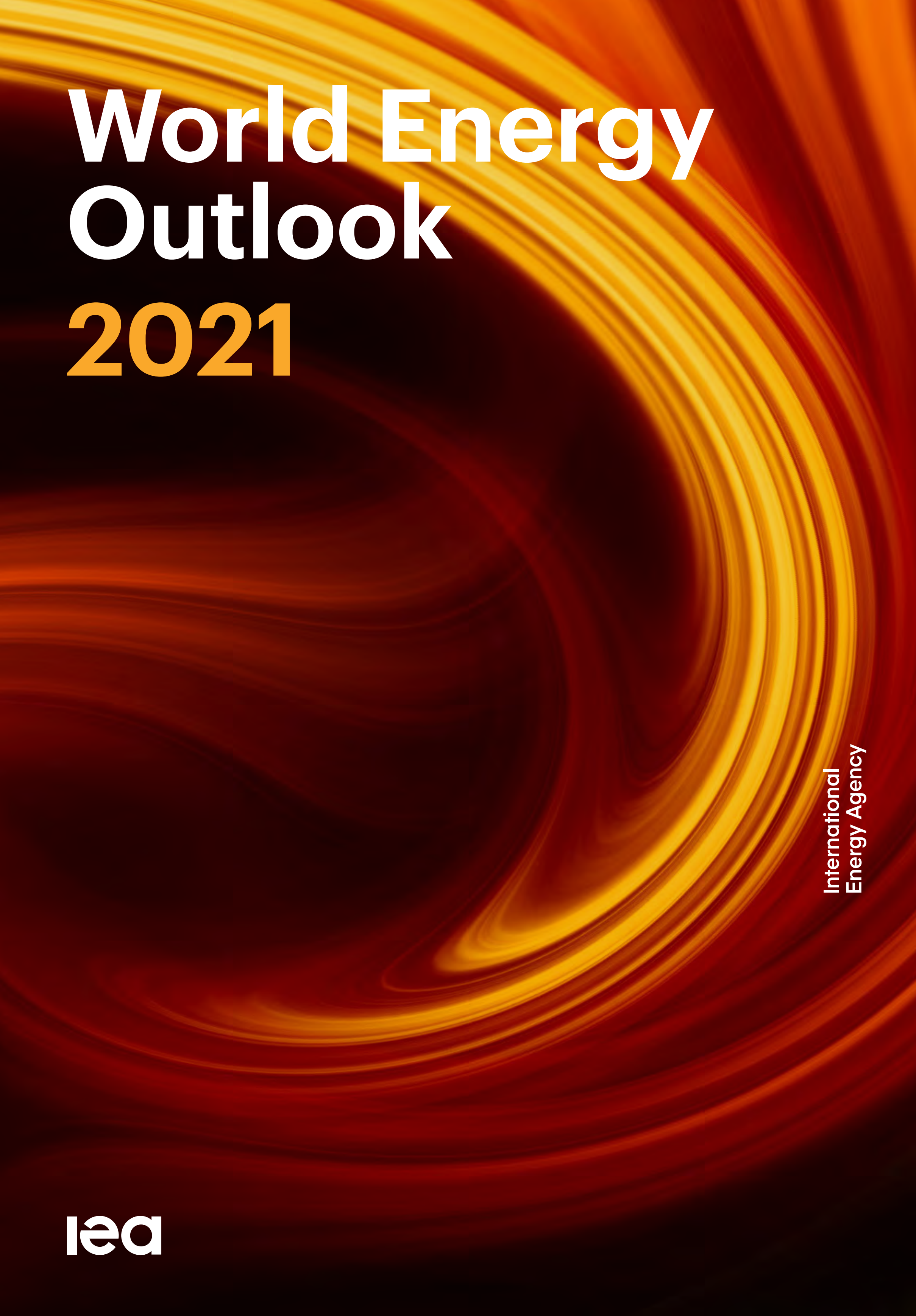

World Energy Outlook

2021

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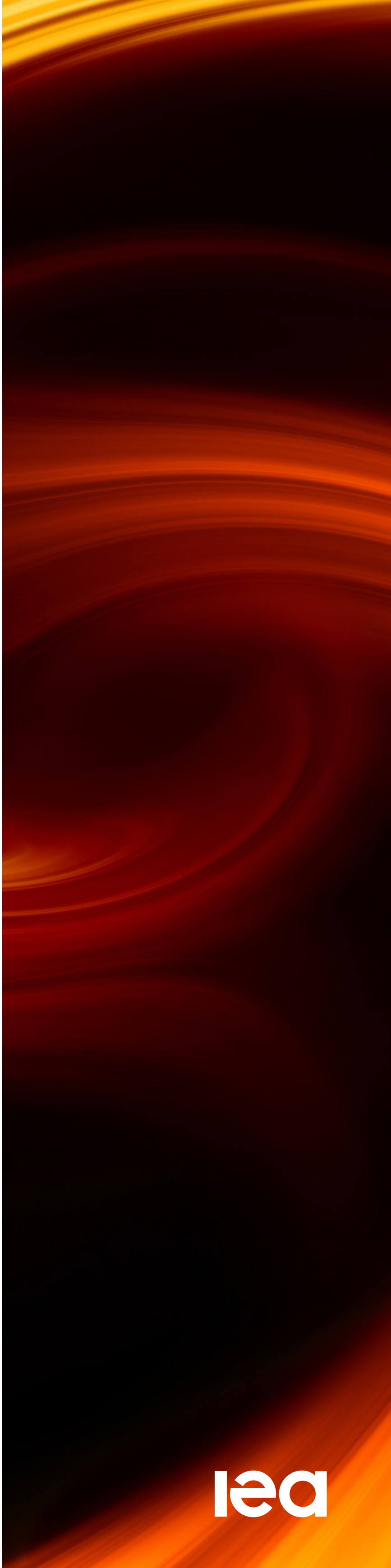

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The *World Energy Outlook (WEO)* is usually published in November. However, for the second year in a row, the International Energy Agency (IEA) is releasing our flagship report a month early, in October. We did this last year because it was an exceptional year defined by the Covid-19 crisis. This year is another exceptional year because of the COP26 Climate Change Conference meeting in Glasgow.

This COP – short for the Conference of the Parties, the main decision-making body of the United Nations Framework Convention on Climate Change – is particularly significant. It is the first test of the readiness of countries to submit new and more ambitious commitments under the 2015 Paris Agreement. It is also an opportunity – as the *WEO-2021* states – to provide an "unmistakeable signal" that accelerates the transition to clean energy worldwide.

This year's edition of the *WEO* has been designed, exceptionally, as a guidebook to COP26. It spells out clearly what is at stake – what the pledges to reduce emissions made by governments so far mean for the energy sector and the climate. And it makes clear what more needs to be done to move beyond these announced pledges towards a pathway that would have a good chance of limiting global warming to 1.5 °C and avoiding the worst effects of climate change.

For this, the analysis in *WEO-2021* relies on our landmark report published earlier this year – *Net Zero by 2050: A Roadmap for the Global Energy Sector* – which is now an integral part of the pioneering energy modelling work that goes into producing the *WEO* each year.

The IEA's work this year has demonstrated our commitment to leading clean energy transitions globally by enabling governments to understand what they need to do to put emissions into rapid and sustained decline. But we have also made very clear that countries' transitions have to be secure, affordable and fair for all citizens. If governments do not ensure that these key elements are at the core of their policy making for the transformation of their energy sectors, then they risk failure.

At the time of publication of this year's *WEO*, governments are getting an advanced warning of this risk, with the prices of natural gas, coal and electricity rising to all-time highs in many regions. The key reasons for these sharp increases in energy prices are not related to efforts to transition to clean energy. They include a rapid economic rebound from last year's pandemic-induced recession, weather-related factors, and some planned and unplanned outages on the supply side.

However, that does not mean clean energy transitions in the years ahead will be free from volatility. The current context underscores the value of the special analysis that we carried out for *WEO-2021* on energy security risks in transitions. This analysis highlights the potential vulnerabilities that need to be on the radar screens of politicians and other decision makers as the world navigates this essential but deeply challenging era of change for our energy systems.

Successful transitions must be secure, or they will not happen fast enough to ward off catastrophic climate change. And they must have people at their centre, as the IEA has emphasised through the work of the Global Commission on People-Centred Clean Energy Transitions, which I convened in early 2021. Headed by Danish Prime Minister Mette Frederiksen, the Global Commission brings together national leaders, government ministers, civil society representatives and other prominent figures to identify how to ensure that the transition to clean energy is fair and inclusive for everyone. It will publish its recommendations ahead of the start of COP26 at the end of October 2021.

As always with the energy sector, investment is critical. The IEA has been warning for years that current investment levels in the global energy sector are inadequate – both to meet near-term energy needs and long-term transition goals. It is hard to understate the dangers inherent in today's shortfall in spending on clean energy transitions, compared with the levels required. If we do not correct it soon, the risks of destabilising volatility will only grow as we move forward.

Reaching the critical but formidable goal of net zero emissions by 2050 will require major efforts from across society – but it also offers major advantages in terms of human health and economic development. What comes through very clearly in this new *WEO* are the huge opportunities that come with clean energy transitions – for manufacturers of wind turbines, batteries, electrolysers and a host of other technologies. A new global energy economy is emerging, with the potential to create millions of decent jobs across a host of new supply chains. To make this a reality, government leaders in Glasgow must play their part by making the 2020s a decade of massive clean energy deployment.

Finally, I would like to thank the truly exceptional work – in extremely challenging times – by the team of IEA colleagues who worked so hard and so effectively on this *WEO* under the outstanding leadership of my colleagues Laura Cozzi and Tim Gould.

Dr Fatih Birol
Executive Director
International Energy Agency

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A new global energy economy is emerging…

In 2020, even while economies bent under the weight of Covid-19 lockdowns, renewable sources of energy such as wind and solar PV continued to grow rapidly, and electric vehicles set new sales records. The new energy economy will be more electrified, efficient, interconnected and clean. Its emergence is the product of a virtuous circle of policy action and technology innovation, and its momentum is now sustained by lower costs. In most markets, solar PV or wind now represents the cheapest available source of new electricity generation. Clean energy technology is becoming a major new area for investment and employment – and a dynamic arena for international collaboration and competition.

…but the transformation still has a long way to go

At the moment, however, every data point showing the speed of change in energy can be countered by another showing the stubbornness of the status quo. The rapid but uneven economic recovery from last year's Covid-induced recession is putting major strains on parts of today's energy system, sparking sharp price rises in natural gas, coal and electricity markets. For all the advances being made by renewables and electric mobility, 2021 is seeing a large rebound in coal and oil use. Largely for this reason, it is also seeing the second-largest annual increase in CO_2 emissions in history. Public spending on sustainable energy in economic recovery packages has only mobilised around one-third of the investment required to jolt the energy system onto a new set of rails, with the largest shortfall in developing economies that continue to face a pressing public health crisis. Progress towards universal energy access has stalled, especially in sub-Saharan Africa. The direction of travel is a long way from alignment with the IEA's landmark **Net Zero Emissions by 2050 Scenario** (NZE), published in May 2021, which charts a narrow but achievable roadmap to a 1.5 °C stabilisation in rising global temperatures and the achievement of other energy-related sustainable development goals.

At a pivotal moment for energy and climate, the WEO-2021 provides an essential guidebook for COP26 and beyond

Pressures on the energy system are not going to relent in the coming decades. The energy sector is responsible for almost three-quarters of the emissions that have already pushed global average temperatures 1.1 °C higher since the pre-industrial age, with visible impacts on weather and climate extremes. The energy sector has to be at the heart of the solution to climate change. At the same time, modern energy is inseparable from the livelihoods and aspirations of a global population that is set to grow by some 2 billion people to 2050, with rising incomes pushing up demand for energy services, and many developing economies navigating what has historically been an energy- and emissions-intensive period of urbanisation and industrialisation. Today's energy system is not capable of meeting these challenges; a low emissions revolution is long overdue.

This special edition of the *World Energy Outlook* has been designed to assist decision makers at the 26th Conference of the Parties (COP26) and beyond by describing the key decision points that can move the energy sector onto safer ground. It provides a detailed stocktake of how far countries have come in their clean energy transitions, how far they still have to go to reach the 1.5 °C goal, and the actions that governments and others can take to seize opportunities and avoid pitfalls along the way. With multiple scenarios and case studies, this *WEO* explains what is at stake, at a time when informed debate on energy and climate is more important than ever.

Announced climate pledges move the needle…

In the run-up to COP26, many countries have put new commitments on the table, detailing their contributions to the global effort to reach climate goals; more than 50 countries, as well as the entire European Union, have pledged to meet net zero emissions targets. If these are implemented in time and in full, as modelled in detail in our new **Announced Pledges Scenario** (APS), they start to bend the global emissions curve down. Over the period to 2030, low emissions sources of power generation account for the vast majority of capacity additions in this scenario, with annual additions of solar PV and wind approaching 500 gigawatts (GW) by 2030. As a result, coal consumption in the power sector in 2030 is 20% below recent highs. Rapid growth in electric vehicle sales and continued improvements in fuel efficiency lead to a peak in oil demand around 2025. Efficiency gains mean that global energy demand plateaus post-2030. The successful pursuit of all announced pledges means that global energy-related CO_2 emissions fall by 40% over the period to 2050. All sectors see a decline, with the electricity sector delivering by far the largest. The global average temperature rise in 2100 is held to around 2.1 °C above pre-industrial levels, although this scenario does not hit net zero emissions, so the temperature trend has still not stabilised.

…but achieving these pledges in full and on time cannot be taken for granted

A lot more needs to be done by governments to fully deliver on their announced pledges. Looking sector-by-sector at what measures governments have actually put in place, as well as specific policy initiatives that are under development, reveals a different picture, which is depicted in our **Stated Policies Scenario** (STEPS). This scenario also sees an accelerating pace of change in the power sector, sufficient to realise a gradual decline in the sector's emissions even as global electricity demand nearly doubles to 2050. However, this is offset by continued growth in emissions from industry, such as the production of cement and steel, and heavy-duty transport, such as freight trucks. This growth largely comes from emerging market and developing economies as they build up their nationwide infrastructure. In the STEPS, almost all of the net growth in energy demand to 2050 is met by low emissions sources, but that leaves annual emissions at around current levels. As a result, global average temperatures are still rising when they hit 2.6 °C above pre-industrial levels in 2100.

Today’s pledges cover less than 20% of the gap in emissions reductions that needs to be closed by 2030 to keep a 1.5 °C path within reach

The APS sees a doubling of clean energy investment and financing over the next decade, but this acceleration is not sufficient to overcome the inertia of today’s energy system. In particular, over the crucial period to 2030, the actions in this scenario fall well short of the emissions reductions that would be required to keep the door open to a Net Zero Emissions by 2050 trajectory. One of the key reasons for this shortfall is that today’s climate commitments, as reflected in the APS, reveal sharp divergences between countries in the pledged speeds of their energy transitions. Alongside its achievements, this scenario also contains the seeds of new divisions and tensions, in the areas of trade in energy-intensive goods, for example, or in international investment and finance. Successful, orderly and broad-based energy transitions depend on finding ways to lessen the tensions in the international system that are highlighted in the APS. All countries will need to do more to align and strengthen their 2030 goals and make this a collaborative global transition in which no one is left behind.

Solutions to close the gap with a 1.5 °C path are available – and many are highly cost-effective

The *WEO-2021* highlights four key measures that can help to close the gap between today’s pledges and a 1.5 °C trajectory over the next ten years – and to underpin further emissions reductions post-2030. More than 40% of the actions required are cost-effective, meaning that they result in overall cost savings to consumers compared with the pathway in the APS. All countries need to do more: those with existing net zero pledges account for about half of the additional reductions, notably China. The four measures are:

- A massive **additional push for clean electrification** that requires a doubling of solar PV and wind deployment relative to the APS; a major expansion of other low-emissions generation, including the use of nuclear power where acceptable; a huge build-out of electricity infrastructure and all forms of system flexibility, including from hydropower; a rapid phase out of coal; and a drive to expand electricity use for transport and heating. Accelerating the decarbonisation of the electricity mix is the single most important lever available to policy makers: it closes more than one-third of the emissions gap between the APS and NZE. With improved power market designs and other enabling conditions, the low costs of wind and solar PV mean that more than half of the additional emissions reductions could be gained at no cost to electricity consumers.
- A relentless **focus on energy efficiency**, together with measures to temper energy service demand through materials efficiency and behavioural change. The energy intensity of the global economy decreases by more than 4% per year between 2020 and 2030 in the NZE – more than double the average rate of the previous decade. Without this improvement in energy intensity, total final energy consumption in the NZE would be about one-third higher in 2030, significantly increasing the cost and difficulty of decarbonising energy supply. We estimate that almost 80% of the additional energy efficiency gains in the NZE over the next decade result in cost savings to consumers.

- A broad **drive to cut methane emissions from fossil fuel operations.** Rapid reductions in methane emissions are a key tool to limit near-term global warming, and the most cost-effective abatement opportunities are in the energy sector, particularly in oil and gas operations. Methane abatement is not addressed quickly or effectively enough by simply reducing fossil fuel use; concerted efforts from governments and industry are vital to secure the emissions cuts that close nearly 15% of the gap to the NZE.
- A big **boost to clean energy innovation**. This is another crucial gap to be filled in the 2020s, even though most of the impacts on emissions are not felt until later. All the technologies needed to achieve deep emissions cuts to 2030 are available. But almost half of the emissions reductions achieved in the NZE in 2050 come from technologies that today are at the demonstration or prototype stage. These are particularly important to address emissions from iron and steel, cement and other energy-intensive industrial sectors – and also from long-distance transport. Today’s announced pledges fall short of key NZE milestones for the deployment of hydrogen-based and other low-carbon fuels, as well as carbon capture, utilisation and storage (CCUS).

Finance is the missing link to accelerate clean energy deployment in developing economies

Getting the world on track for 1.5 °C requires a surge in annual investment in clean energy projects and infrastructure to nearly USD 4 trillion by 2030. Some 70% of the additional spending required to close the gap between the APS and NZE is needed in emerging market and developing economies. There have been some notable examples of developing economies mobilising capital for clean energy projects, such as India’s success in financing a rapid expansion of solar PV in pursuit of its 450 GW target for renewables by 2030. However, there have also been persistent challenges, many of which have been exacerbated by the pandemic. Funds to support sustainable economic recovery are scarce and capital remains up to seven-times more expensive than in advanced economies. In some of the poorest countries in the world, Covid-19 also broke the trend of steady progress towards universal access to electricity and clean cooking. The number of people without access to electricity is set to rise by 2% in 2021, with almost all of the increase in sub-Saharan Africa.

An international catalyst is essential to accelerate flows of capital in support of energy transitions and allow developing economies to chart a new lower emissions path for development. Most transition-related energy investment will need to be carried out by private developers, consumers and financiers responding to market signals and policies set by governments. Alongside the necessary policy and regulatory reforms, public financial institutions – led by international development banks and larger climate finance commitments from advanced economies – play crucial roles to bring forward investment in areas where private players do not yet see the right balance of risk and reward.

Strategies to phase out coal have to effectively deal with impacts on jobs and electricity security

Coal demand declines in all our scenarios, but the difference between the 10% decline to 2030 in APS and the 55% decline in NZE is the speed at which coal is phased out from the power sector. This has four components: halting the approval of new, unabated coal plants; reducing emissions from the 2 100 GW of operating plants, which produced more than one-third of the world's electricity in 2020; investing – at sufficient scale – to reliably meet the demand that would otherwise have been met by coal; and managing the economic and social consequences of change. Approvals of new coal-fired plants have slowed dramatically in recent years, stemmed by lower cost renewable energy alternatives, rising awareness of environmental risks, and increasingly scarce options for financing. Yet some 140 GW of new coal plants are currently under construction and more than 400 GW are at various stages of planning. China's announcement of an end to support for building coal plants abroad is potentially very significant: it could lead to the cancellation of up to 190 GW of coal projects that are built in the APS. This could save some 20 gigatonnes in cumulative CO_2 emissions if these plants are replaced with low emissions generation – an amount comparable to the total emissions savings from the European Union going to net zero by 2050.

Bringing down emissions from the existing global coal fleet requires a broad-based and dedicated policy effort. In our scenarios, coal plants are either retrofitted with CCUS, reconfigured to be co-fired with low emissions fuels such as biomass or ammonia, repurposed to focus on system adequacy, or retired. Retirements in the APS occur at twice the rate seen in the last decade, and the rate nearly doubles again in the NZE to reach almost 100 GW of retirements per year. Policy interventions need to focus on retiring plants that would not otherwise have done so while also supporting measures to bring down emissions from the remaining fleet.

Support must be there for those who lose jobs in declining sectors. Managing the phase-out of coal depends on early and sustained engagement by governments and financial institutions to mitigate the impacts on affected workers and communities, and to allow for the reclamation and repurposing of lands. Energy transitions create dislocations: many more new jobs are created, but not necessarily in the same places where jobs are lost. Skill sets are not automatically transferable, and new skills are needed. This is true both within specific countries and internationally. Governments need to manage the impacts carefully, seeking transition pathways that maximise opportunities for decent, high quality work and for workers to make use of their existing skills – and mobilising long-term support for affected workers and communities.

Liquids and gases are caught between scenarios

Oil demand, for the first time, goes into eventual decline in all the scenarios examined in the *WEO-2021*, although the timing and speed of the drop vary widely. In the STEPS, the high point in demand is reached in the mid-2030s and the decline is very gradual. In the APS, a peak soon after 2025 is followed by a decline towards 75 million barrels per day (mb/d) by

2050. To meet the requirements of the NZE, oil use plummets to 25 mb/d by mid-century. Natural gas demand increases in all scenarios over the next five years, but there are sharp divergences after this. Many factors affect to what extent, and for how long, natural gas retains a place in various sectors as clean energy transitions accelerate. The outlook is far from uniform across different countries and regions. In the NZE, a rapid rise in low emissions fuels is one of the key reasons – alongside greater efficiency and electrification – why no new oil and gas fields are required beyond those already approved for development. Actual deployment of low emissions fuels is well off track. For example, despite the burgeoning interest in low-carbon hydrogen, the pipeline of planned hydrogen projects falls short of the levels of use in 2030 implied by announced pledges, and even further short of the amounts required in the NZE (which are nine-times higher than in the APS).

There is a looming risk of more turbulence ahead for energy markets

The world is not investing enough to meet its future energy needs, and uncertainties over policies and demand trajectories create a strong risk of a volatile period ahead for energy markets. Transition-related spending is gradually picking up, but remains far short of what is required to meet rising demand for energy services in a sustainable way. The deficit is visible across all sectors and regions. At the same time, the amount being spent on oil and natural gas, dragged down by two price collapses in 2014-15 and in 2020, is geared towards a world of stagnant or even falling demand for these fuels. Oil and gas spending today is one of the very few areas that it is reasonably well aligned with the levels seen in the NZE to 2030. IEA analysis has repeatedly highlighted that a surge in spending to boost deployment of clean energy technologies and infrastructure provides the way out of this impasse, but this needs to happen quickly or global energy markets will face a turbulent and volatile period ahead. Clear signals and direction from policy makers are essential. If the road ahead is paved only with good intentions, then it will be a bumpy ride indeed.

Transitions can offer some shelter for consumers against oil and gas price shocks

Energy transitions can provide a cushion from the shock of commodity price spikes, if consumers can get help to manage the upfront costs of change. In a transforming energy system such as the NZE, households are less reliant on oil and gas to meet their energy needs, thanks to efficiency improvements, a switch to electricity for mobility, and a move away from fossil fuel-fired boilers for heating. For these reasons, a large commodity price shock in 2030 is 30% less costly to households in the NZE compared with in the STEPS. Reaching this point will require policies that assist households with the additional upfront costs of efficiency improvements and low emissions equipment such as electric vehicles and heat pumps.

As electricity takes up a progressively larger share of household energy bills, governments have to ensure that electricity markets are resilient by incentivising investments in flexibility, efficiency and demand-side response. Across all scenarios, the share of variable renewables in electricity generation expands to reach 40-70% by 2050 (and even higher in some regions), compared with an average of just under 10% today. In the NZE, there are some 240 million rooftop solar PV systems and 1.6 billion electric cars by 2050. Such a system will need to operate very flexibly, enabled by adequate capacity, robust grids, battery storage and dispatchable low emissions sources of electricity (like hydropower, geothermal and bioenergy, as well as hydrogen and ammonia-fired plants, or small modular nuclear reactors). This kind of system will also require digital technologies that can support demand-side response and securely manage multi-directional flows of data and energy.

Other potential energy security vulnerabilities require close vigilance

Trade patterns, producer policies and geopolitical considerations remain critically important for energy security, even as the world shifts to an electrified, renewables-rich energy system. This relates in part to the way that energy transitions affect oil and gas as supplies become more concentrated in a smaller group of resource-rich countries – even as their economies simultaneously come under strain from lower export revenues. Higher or more volatile prices for critical minerals such as lithium, cobalt, nickel, copper and rare earth elements could slow global progress towards a clean energy future or make it more costly. Price rallies for key minerals in 2021 could increase the costs of solar modules, wind turbines, electric vehicle (EV) batteries and power lines by 5-15%. If maintained over the period to 2030 in the NZE, this would add USD 700 billion to the investment required for these technologies. Critical minerals, together with hydrogen-rich fuels such as ammonia, also become major elements in international energy-related trade; their combined share rises from 13% today to 25% in the APS and to over 80% in the NZE by 2050.

The costs of inaction on climate are immense, and the energy sector is at risk

Extreme weather events over the past year have highlighted the risks of unchecked climate change, and the energy sector will feel the impacts. Today, the world's energy infrastructure is already facing increasing physical risks related to climate change, which emphasizes the urgent need to enhance the resilience of energy systems. We estimate that around one-quarter of global electricity networks currently face a high risk of destructive cyclone winds, while over 10% of dispatchable generation fleets and coastal refineries are prone to severe coastal flooding, and one-third of freshwater-cooled thermal power plants are located in areas of high water stress. In the STEPS, the frequency of extreme heat events would double by 2050 compared with today – and they would be around 120% more intense, affecting the performance of grids and thermal plants while pushing up demand for cooling. A failure to accelerate clean energy transitions would continue to leave people exposed to air pollution. Today, 90% of the world's population breathes polluted air, leading to over 5 million premature deaths a year. The STEPS sees rising numbers of premature deaths from air pollution during the next decade. In the NZE, there are 2.2 million fewer premature deaths per year by 2030, a 40% reduction from today.

The potential prize is huge for those who make the leap to the new energy economy

In the NZE, there is an annual market opportunity that rises well above USD 1 trillion by 2050 for manufacturers of wind turbines, solar panels, lithium-ion batteries, electrolysers and fuel cells. This is comparable in size to the current global oil market. This creates enormous prospects for companies that are well positioned along an expanding set of global supply chains. Even in a much more electrified energy system, there are major openings for fuel suppliers: companies producing and delivering low-carbon gases in 2050 are handling the equivalent of almost half of today's global natural gas market. Employment in clean energy areas is set to become a very dynamic part of labour markets, with growth more than offsetting a decline in traditional fossil fuel supply sectors. As well as creating jobs in renewables and energy network industries, clean energy transitions increase employment in areas such as retrofits and other energy efficiency improvements in buildings, and the manufacturing of efficient appliances and electric and fuel cell vehicles. In total, an additional 13 million workers are employed in clean energy and related sectors by 2030 in the APS – and this figure doubles in the NZE.

Making the 2020s the decade of massive clean energy deployment will require unambiguous direction from COP26

This *WEO-2021* provides stark warnings about the pathway that we are on, but also clear-headed analysis of the actions that can bring the world onto a path towards a 1.5 °C future – with a strong affirmation of the benefits that this yields. Governments are in the driving seat: everyone from local communities to companies and investors needs to be on board, but no one has the same capacity as governments to direct the energy system towards a safer destination. The way ahead is difficult and narrow, especially if investment continues to fall short of what is required, but the core message from the *WEO-2021* is nonetheless a hopeful one. The analysis clearly outlines what more needs to be done over the crucial next decade: a laser-like focus on driving clean electrification, improving efficiency, reducing methane emissions and turbocharging innovation – accompanied by strategies to unlock capital flows in support of clean energy transitions and ensure reliability and affordability. Many of the actions described are cost-effective, and the costs of the remainder are insignificant compared with the immense risks of inaction. Realising the agenda laid out in this *WEO* represents a huge opportunity to change the global energy system in a way that improves people's lives and livelihoods. A wave of investment in a sustainable future must be driven by an unmistakeable signal from Glasgow.

Introduction

The *World Energy Outlook 2021 (WEO-2021)* is a special edition. It is designed to inform the energy and climate debates at the UNFCCC Conference of the Parties (COP26) in November 2021 and beyond. As such, it departs from the usual *WEO* structure in the way it organises and presents the material and analyses. The *WEO-2021* chapters are:

- Chapter 1 provides an overview of key themes, drawing on material from the other chapters and augmented with additional analysis.
- Chapter 2 presents the latest energy data to set the scene and describes the scenarios used in this year's analysis, the assumptions that underpin them, and how and why they differ from each other.
- Chapter 3 focuses on the gap between the announced pledges, made by governments in the run-up to COP26, and the goal to limit the rise of the global average temperature to 1.5 °C, and examines in detail how this gap can be closed.
- Chapter 4 examines what it will take to implement the announced pledges, and looks broadly at the projections for energy demand and electricity across all of our scenarios.
- Chapter 5 continues the multi-scenario approach and explores the outlook for various fuels.
- Chapter 6 presents a cross-cutting thematic discussion of the various energy security hazards that could arise during energy transitions, both in domestic energy systems and internationally.

The chapter structure for future editions of the *Outlook* series remains open, but other new elements in the *WEO-2021* are set to remain as integral parts of the *WEO* approach. The main example is the Net Zero Emissions by 2050 Scenario (NZE), first released as part of the landmark IEA report in May 2021 – *Net Zero Emissions by 2050: A Roadmap for the Global Energy Sector*. The topic covered by this scenario is not new to the *WEO*, as analysis of possible pathways to 1.5 °C has featured in all recent *Outlooks*, but the NZE now joins the stable of core IEA scenarios that will be regulatory updated and featured in the *WEO* series of analyses and publications.

In discussion of fuels, the *WEO* now makes more regular use of the terms "solid, liquid and gaseous" fuels, rather than coal, oil and natural gas. This allows us to take a broader view of the roles of different types of fuel and the energy services that they provide. For example, gaseous fuels can include not only natural gas, but also biogas, hydrogen and synthetic gas. In rapid energy transitions, these low-carbon fuels take a progressively larger share of the market.

In addition, note that the generic energy values in this *WEO* are expressed in exajoules (EJ), whereas they were previously expressed in million tonnes of oil equivalent (Mtoe). One EJ is equivalent to 23.88 Mtoe.

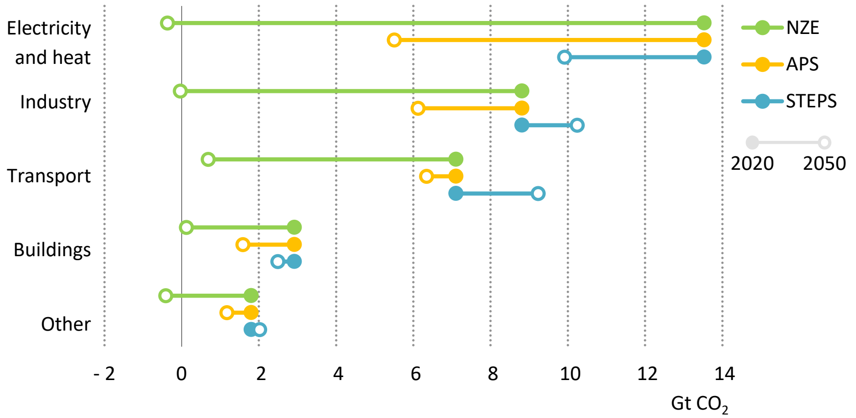
Overview

Key themes of WEO-2021

SUMMARY

- In the run-up to a crucial COP26 meeting in Glasgow, this *World Energy Outlook-2021* (*WEO-2021*) provides a detailed picture of how far countries have come in their clean energy transitions, and how far they still have to go. A new global energy economy is emerging, but will need to take shape much more quickly to avoid severe impacts from a changing climate.
- An outlook based on today's policy settings, the Stated Policies Scenario (STEPS), shows aggregate fossil fuel demand slowing to a plateau in the 2030s and then falling slightly by 2050, the first time this has been projected in this scenario. Almost all of the net growth in energy demand comes from low emissions sources. Nonetheless, the global average temperature rise in this scenario passes the 1.5 degrees Celsius (°C) mark around 2030 and would still be climbing as it reaches 2.6 °C in 2100.

Figure 1.1 ▷ CO_2 emissions by sector and scenario



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Clean electricity can do a lot of the heavy lifting, but it is harder to bend the emissions curve in industry and transport

- Announced net zero pledges and enhanced Nationally Determined Contributions, if implemented in full as in the Announced Pledges Scenario (APS), start to bend the curve and bring the temperature rise in 2100 down to around 2.1 °C. In the APS, oil demand peaks soon after 2025, and a more rapid ramp up in low emissions sources brings emissions down to 21 gigatonnes (Gt) in 2050. However, a much greater global effort will be essential to reach the relative safety of the Net Zero Emissions by 2050 Scenario (NZE). Announced pledges close less than 20% of the emissions gap in 2030 between the STEPS and the NZE.

- Actions in four key areas over the next decade are essential to keep the door to a 1.5 °C stabilisation open: a massive push for clean electrification; a renewed focus on realising the full potential of energy efficiency; concerted efforts to prevent leaks from fossil fuel operations; and a boost to clean energy innovation.
- Many emerging market and developing economies face a continued public health crisis from Covid-19, and the pandemic has set back efforts to improve access to electricity and clean cooking fuels. Funds for sustainable recovery are scarce and capital remains up to seven-times more expensive than in advanced economies, at a moment when their economies are entering what has historically been an energy- and emissions-intensive process of urban expansion and infrastructure development.
- An international catalyst will be essential to accelerate clean energy deployment and to allow developing economies – where per capita emissions are often very low – to chart a new lower emissions path for development; as things stand, emissions from emerging market and developing economies (excluding China) increase more than 5 Gt to 2050 in the STEPS, with the largest growth from industry and transport.
- Transitions are accompanied by marked shifts in energy sector employment, but clean energy jobs expand faster than other sectors fall. The downside risks for jobs are concentrated in the coal sector, where retirements of coal-fired capacity approach 100 gigawatts (GW) per year over the coming decade in the NZE, almost double the figure in the Announced Pledges Scenario (APS). Phasing out coal requires an accelerated scale up of new low emissions generation and infrastructure, as well as a sustained commitment by governments and the international community to manage the impacts on communities, assets, land and the local environment.
- Price volatility is an ever-present feature of commodity markets, but well-managed transitions offer ways to dampen the impacts on household energy bills. Compared with the situation in STEPS, the effect of a large price shock in 2030 in the NZE is reduced by efficiency gains and lower direct consumption of oil and gas.
- Getting the world on track for net zero emissions by 2050 requires transition-related investment to accelerate from current levels to around USD 4 trillion annually by 2030, but only a minority of these investments immediately deliver zero emissions energy or energy services. Ensuring that other investments are financed, for example those that aid transitions in emissions-intensive sectors, is a key challenge for financiers, investors and policy makers.
- If the world gets on track for net zero emissions by 2050, then the cumulative market opportunity for manufacturers of wind turbines, solar panels, lithium-ion batteries, electrolysers and fuel cells amounts to USD 27 trillion. These five elements alone in 2050 would be larger than today’s oil industry and its associated revenues.

Introduction

In a momentous period for the future of energy and emissions, this *World Energy Outlook* uses several long-term scenarios to illustrate the choices that face the world's decision makers in the run-up to the crucial 26th Conference of the Parties (COP26) in November and beyond. A key variable in determining where the world goes from here is action taken by governments. They do not hold all the levers: individuals, communities, civil society, companies and investors can all make a major difference. But none have the same capacity as governments to shape the future of energy by setting the framework conditions that channel investment to energy projects, by supporting innovation, by giving clear signals about their long-term ambitions and by taking the necessary steps to realise them.

This *Outlook* takes into consideration the full diversity of country circumstances, resources, technologies and potential policy choices in its examination of the scenario projections. Countries are not starting this journey from the same place. Many developing economies, in particular, are facing a continued public health crisis and the impacts of the Covid-19 pandemic on their economies and energy sectors will be felt for years to come. By contrast, more rapid progress with mass vaccination campaigns leaves most advanced economies and the People's Republic of China (hereafter China) with a clearer near-term pathway to recovery, though many uncertainties and risks remain.

The main scenarios in this *Outlook* are:

- **Net Zero Emissions by 2050 Scenario** (NZE), which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050.
- **Announced Pledges Scenario** (APS), which assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions (NDCs) and longer term net zero targets, will be met in full and on time.
- **Stated Policies Scenario** (STEPS), which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.

There are also references to the Sustainable Development Scenario (SDS), which, like the NZE, achieves key energy-related United Nations Sustainable Development Goals related to universal energy access and major improvements in air quality, and reaches global net zero emissions by 2070 (with many countries and regions reaching net zero much earlier). The Announced Pledges and New Zero Emissions by 2050 scenarios are introduced for the first time this year. Updates have been incorporated into the STEPS (Box 1.1) and to the SDS since the *WEO*-2020. All the scenarios are described in detail in Chapter 2.

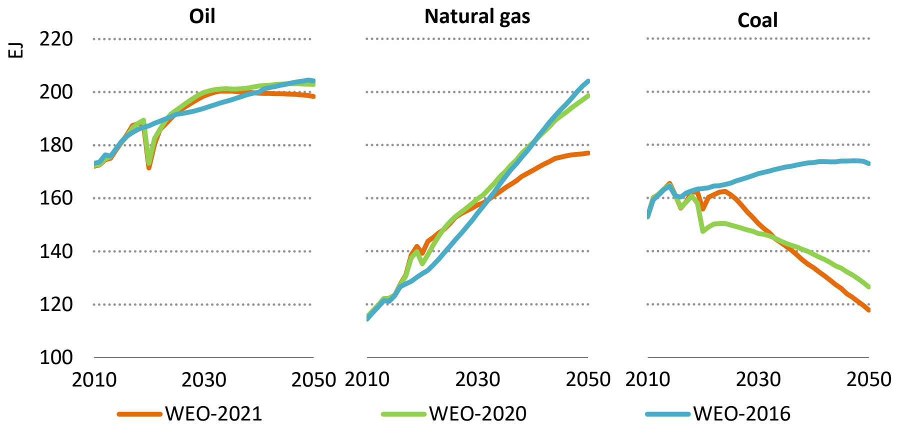
This Overview chapter explores ten key themes covering the risks, trade-offs and benefits of different courses of action. The *Outlook* is based on rigorous modelling and analysis, reflecting the latest energy data, policy announcements, investment trends and technology developments, but it keeps in mind two core tenets: the crucial role of energy in human well-being and social and economic development; and the responsibility of the energy sector for nearly three-quarters of the emissions that are causing climate change.

Box 1.1 ▷ One STEPS beyond…

The Stated Policies Scenario (STEPS) is based on prevailing policy settings and so provides a useful barometer of the strength and impact of these policies over time. Compared with the *WEO-2020*, some of the largest changes in the STEPS in this *Outlook* are:

- Total fossil fuel demand is higher in the near term than in the *WEO-2020* STEPS. However, it is also markedly lower after 2030. For the first time, aggregate fossil fuel demand slows to a plateau in the 2030s and then falls slightly by 2050 (Figure 1.2).
- Natural gas demand is around 600 billion cubic metres (bcm) (or 10%) lower in 2050 than in the *WEO-2020* STEPS, mainly reflecting lower projected consumption in the power and industry sectors in emerging market and developing economies in Asia.
- Oil demand starts to decline in the 2030s for the first time in the STEPS as a result of more muted growth in petrochemicals and faster reductions elsewhere.
- Coal use rebounds more rapidly in the near term and stays above last year's projections until around 2030, but its subsequent decline is faster than projected in 2020 (and much faster than projected five years ago).
- Total CO_2 emissions are around 2 Gt lower in 2050 than in last year's STEPS. Most of the difference is in the power sector, where emissions fall by more than 25% between 2020 and 2050 (compared with a decline of less than 10% in the *WEO-2020*). Generation from solar photovoltaics (PV) and wind in 2050 is around 15% and 20% respectively higher in this *Outlook*.

Figure 1.2 ▷ Oil, natural gas and coal demand in the Stated Policies Scenario in *World* Energy *Outlook 2021, 2020* and *2016*



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Oil demand peaks for the first time in the WEO-2021 STEPS; natural gas has been revised down from the WEO-2020; coal use is a lot lower than projected five years ago

Note: *WEO-2016* numbers are the New Policies Scenario extrapolated to 2050.

1.1 A new energy economy is emerging

There are unmistakeable signs of change. In 2020, even as economies sank under the weight of Covid-19 lockdowns, additions of renewable sources of energy such as wind and solar PV increased at their fastest rate in two decades, and electric vehicle sales set new records. A new energy economy is coming into view, ushered forward by policy action, technology innovation and the increasing urgency of the need to tackle climate change. There is no guarantee that the emergence of this new energy economy will be smooth, and it is not coming forward quickly enough to avoid severe impacts from a changing climate. But it is already clear that tomorrow's energy economy promises to be quite different from the one we have today.

Electricity is taking on an ever-more central role in the lives of consumers and, for an increasing number of households, it promises to become the energy source on which they rely for all their everyday needs: mobility, cooking, lighting, heating and cooling. The reliability and affordability of electricity is set to become even more critical to all aspects of people's lives and well-being.

Electricity's share of the world's final consumption of energy has risen steadily over recent decades, and now stands at 20%. Its rise accelerates in future years as the pace of transitions picks up. In the NZE, electricity accounts for around 50% of final energy use by 2050 (around 30% in the APS). Given that electricity delivers useful energy services with better efficiency than other fuels, the contribution of electricity is even higher than these numbers would suggest.

The rise of electricity requires a parallel increase in its share of energy-related investment. Since 2016, global investment in the power sector has consistently been higher than in oil and gas supply. The faster that clean energy transitions proceed, the wider this gap becomes, and as a result electricity becomes the central arena for energy-related financial transactions. In the NZE, investment in power generation and infrastructure is six-times higher than in oil and gas supply by 2030.

Clean technologies in the power sector and across a range of end-uses have become the first choice for consumers around the world, initially due to policy support but over time because they are simply the most cost-effective. In most regions, solar PV or wind already represents the cheapest available source of new electricity generation. Based on total costs of ownership, the case for electric cars in many markets is already a compelling one.

In the new energy economy, the huge market opportunity for clean technology becomes a major new area for investment and international competition; countries and companies jostle for position in global supply chains. We estimate that, if the world gets on track for net zero emissions by 2050, then the annual market opportunity for manufacturers of wind turbines, solar panels, lithium-ion batteries, electrolysers and fuel cells grows tenfold to USD 1.2 trillion by 2050, around 3.5-times larger than in the STEPS (Spotlight). These five elements alone would be larger than today's oil industry and its associated revenues.

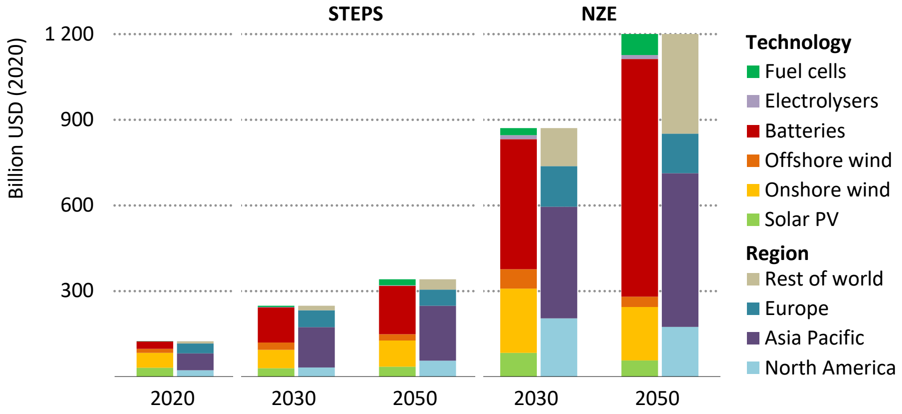
SPOTLIGHT

Sizing the market opportunity for clean energy

Achieving net zero emissions requires an unparalleled increase in clean energy investment. In the NZE, annual investment in clean energy rises to USD 4 trillion by 2030, more than tripling from current levels. Mobilising such a large investment will be challenging, but the investment required to secure clean energy transitions offers an unprecedented level of market opportunities to equipment manufacturers, service providers, developers and engineering, procurement and construction companies along the entire clean energy supply chain.

In the NZE, the combined size of the market for wind turbines, solar panels, lithium-ion batteries, electrolysers and fuel cells represents a cumulative market opportunity to 2050 worth USD 27 trillion. At over 60% of the total, batteries account for the lion's share of the estimated market for clean energy technology equipment in 2050 (Figure 1.3). With over 3 billion electric vehicles (EVs) on the road and 3 terawatt-hours (TWh) of battery storage deployed in the NZE in 2050, batteries play a central part in the new energy economy. They also become the single largest source of demand for various critical minerals such as lithium, nickel and cobalt (IEA, 2021a).

Figure 1.3 ⊳ Estimated market size for selected clean energy technologies by technology and region, 2020-2050



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There is explosive growth in clean energy technologies over the next decade in the NZE, leading to a clean energy market worth a cumulative USD 27 trillion by 2050

Note: Market share estimates are the product of anticipated average market prices and sales of tradeable units of the core technologies: solar PV modules; wind turbines; lithium-ion batteries (for EVs and grid storage); electrolysers and fuel cells. This differs from investment or spending estimates that include, for example, installation costs.

Advanced economies and China have been building up their research and development (R&D) programmes and increasing spending on clean energy innovation, but patterns of spending will change as deployment expands everywhere in the world. In the NZE, the Asia Pacific region is home to 45% of the estimated market for clean energy technologies by 2050, and the share of the market accounted for by North America and Europe is lower than it was earlier in the period.

Many countries are seeking to develop manufacturing expertise and capabilities that would allow them to use some locally produced products to meet domestic demand, and also to participate in global supply chains and to license related intellectual property. Energy start-up companies have an important part to play in this. Despite the pandemic, record-breaking levels of capital have flowed to clean energy technology start-ups, with investment in 2021 expected to surpass the USD 4 billion in early-stage equity raised in 2019, which was the previous peak year. The United States still accounts for around half of the capital being invested, but Europe was the only major region to increase investment in 2020 and China's share of the market has risen from 5% in the 2010-14 period to over 35% in the last three years.

Governments everywhere are also actively seeking to attract additional talent. India and Singapore have launched government initiatives to support international clean energy entrepreneurs. China, Japan and United States have recently made high-level commitments to energy R&D and innovation, framing it as a critical area of technological competition in coming years. In Europe, public initiatives like the European Battery Alliance are actively seeking to create new value chains. There is a momentous opportunity for the best innovators to capture a share of emerging value chains that have huge future potential.

The new energy economy involves varied and often complex interactions between electricity, fuels and storage markets, creating fresh challenges for regulation and market design. A major question is how to manage the potential for **increased variability** on both the demand and supply sides of the energy equation. The variability of electricity supply will be affected by rising shares of wind and solar PV, putting a huge premium on robust grids and other sources of supply flexibility. The variability of demand will be shaped by increasing deployment of heat pumps and air conditioners (the latter especially in developing economies, where current ownership levels are low), and could be exacerbated by poorly sequenced recharging of EV fleets or by cold snaps, heat waves or other extreme weather events. Without effective policies to prepare for and manage these fluctuations, the daily variation of demand could increase on the basis of announced pledges to 270 gigawatts (GW) in the European Union (from 120 GW today) and over 170 GW in India (from 40 GW) by mid-century.

Digital technologies play crucial roles in integrating different aspects of the new energy system. Sectors that have hitherto operated largely independently (such as electricity and transport) become connected in new ways with the rise of electric mobility, and grids need to cope with a much greater diversity and complexity of flows as many new players, including households, enter the arena as producers. Managing the platforms and data required to keep this system operating effectively becomes a central part of the new energy economy, as does mitigating associated cybersecurity and data privacy risks.

Clean electrification is the dominant theme in the early phases of the transformation of the global energy economy together with the quest for improvements in efficiency. Over time, however, continued rapid deployment in these areas needs to be accompanied by **clean energy innovation** and the widespread use of technologies that are not yet readily available on the market. These technologies are vital to decarbonise areas such as heavy industry and long-distance transport that are not readily susceptible to electrification for one reason or another, and they include advanced batteries, hydrogen electrolysers, advanced biofuels, and new technologies for the capture and use of CO_2, including direct air capture. Building these additional pillars of the new energy economy requires early and sustained investment in energy R&D and an accelerated programme of demonstration projects.

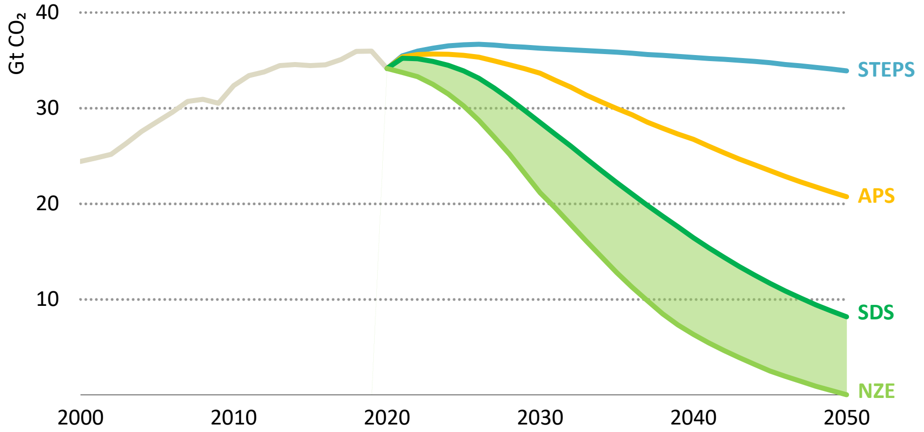
These changes redirect global **flows of trade and capital**. The combined share of hydrogen and critical minerals (such as lithium, cobalt, copper and rare earths elements) in global energy-related trade rises to one-quarter of the total in the APS, and takes a dominant share in the NZE as the value of fossil fuels trade declines significantly (see section 1.9). This completely upends the present dynamics of international energy-related trade, and it is accompanied by a major shift in energy-related financial flows: the decline in the value of trade in fossil fuels causes the dollar-denominated revenues accruing to producer economies from oil and gas exports to decline significantly over time.

The new energy economy depicted in the NZE is a collaborative one in which countries demonstrate a shared focus on securing the necessary reductions in emissions, while minimising and taking precautions against new energy security risks. However, the APS highlights the **possibility of new divisions and fragmentation** as countries proceed at different speeds through energy transitions. By the 2030s, for example, the APS sees the production of "green" steel in economies that have pledged to reach net zero alongside the continuing use of traditional emissions-intensive methods elsewhere, deepening tensions around trade in energy-intensive goods. There could be a gulf too in international investment and finance: increasingly stringent disciplines applicable to financial flows may mean that capital from the "net zero" world does not flow very freely to countries undergoing slower transitions. Successful, orderly and broad-based transitions in which countries enjoy the benefits of global trade will depend on finding ways to lessen and manage the potential tensions in the international system that are highlighted in the APS.

1.2 Scenario trajectories and temperature outcomes

This *World Energy Outlook* provides a detailed stocktake of how far nations have come in their energy transitions, and a sobering picture of how far there still is to go. In the STEPS, global energy-related and industrial process CO_2 emissions rebound quickly in 2021 and rise to 36 gigatonnes (Gt) in 2030. In the APS, emissions peak in the mid-2020s and return to just under 34 Gt in 2030, close to current levels. In the NZE, by contrast, emissions fall to 21 Gt in 2030, marking a decisive change of direction (Figure 1.4).

Figure 1.4 ⊳ **CO_2 emissions in the *WEO-2021* scenarios over time**



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The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050

Note: APS = Announced Pledges Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario.

The 2.6 Gt difference in emissions between the STEPS and the APS in 2030 highlights the "implementation gap" that exists between announced net zero pledges and the policy frameworks and specific measures that they require: pledges need to be underpinned by strong, credible policies and long-term plans to make them a reality. However, realising these pledges in full would fill less than 20% of the total gap between the STEPS and the NZE. This leaves a 12 Gt "ambition gap" between the APS and the NZE in 2030 that requires countries to go beyond existing pledges to be on course to achieve net zero emissions by 2050. In the NZE, methane emissions also reduce far more quickly than in the APS. If methane is also counted, then the ambition gap in 2030 would be around 14 Gt CO_2-eq.[1] If the world is off course in 2030, it will be extremely difficult to make up the lost ground later.

There are large differences in emissions trajectories in the APS: emissions decline by around one-third (or 3.5 Gt) in advanced economies by 2030, but rise by just over 10% (or 2.5 Gt) in emerging market and developing economies. The APS highlights the risk of a two-speed world emerging, in which a narrow focus on achieving national net zero pledges in some countries is coupled with limited efforts to prioritise emissions reductions in others, and little

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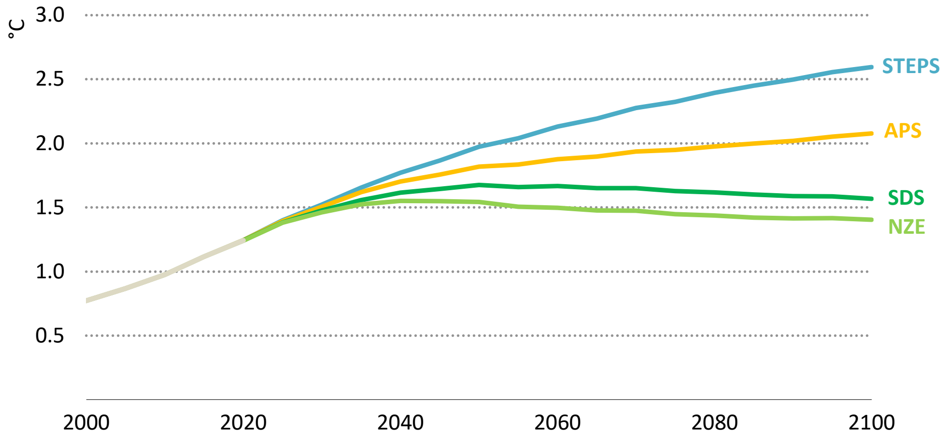
[1] One tonne of methane is considered to be equivalent to 30 tonnes of CO_2 based on the 100-year global warming potential (IPCC, 2021).

attention is given to technological spill-overs or to the scope for working in partnership. That could easily be a recipe for trade and other tensions to emerge, and it would militate against net zero emissions being achieved as cost-effectively as possible. Delivering the NZE is heavily dependent on all governments working together in an effective and mutually beneficial manner.

Figure 1.5 ▹ Global median surface temperature rise over time in the *WEO-2021* scenarios



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The temperature rise is 2.6 °C in the STEPS and 2.1 °C in the APS in 2100 and continues to increase. It peaks at 1.7 °C in the SDS and 1.5 °C in the NZE around 2050 and then declines

Source: IEA analysis based on outputs of MAGICC 7.5.3.

We have carried out new detailed analysis using the Model for the Assessment of Greenhouse Gas Induced Climate Change ("MAGICC") to assess the impacts of these emissions trajectories on the average global surface temperature rise (Figure 1.5).[2] In the STEPS, the global average surface temperature rise would exceed 1.5 degrees Celsius (°C) around 2030.[3] Emissions in 2050 are around 32 Gt CO_2: if emissions continue their trend after 2050, and if there are similar changes in non-energy-related greenhouse gas (GHG) emissions, the rise in temperature in 2100 would be around 2.6 °C (Table 1.1). In the APS,

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[2] MAGICC climate models have been used extensively in assessment reports written by the Intergovernmental Panel on Climate Change. MAGICC 7, the version used in this analysis, is one of the models used for scenario classification in the IPCC's 6th Assessment Report (IPCC, 2021). Emissions of all energy-related GHG from the *WEO-2021* scenarios are supplemented with commensurate changes in non-energy-related emissions based on the scenario database published as part of the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018). All changes in temperatures are relative to 1850-1900 and match the IPCC 6th Assessment Report definition of warming of 0.85 °C between 1995-2014.

[3] Unless otherwise stated, temperature rise estimates quoted in this section refer to the median temperature rise, meaning that there is a 50% probability of remaining below a given temperature rise.

the faster reduction in CO_2 emissions to around 21 Gt in 2050 has little impact on the year in which 1.5 °C is exceeded, but the rise in temperature in 2100 would be restricted to around 2.1 °C. The temperature would continue to rise in both the STEPS and APS after 2100 because total CO_2 emissions are still well above zero in 2100 in these scenarios.

In the NZE, CO_2 emissions are net zero in 2050 globally and there are rapid reductions in all non-CO_2 emissions (such as methane). The rise in temperature reaches a maximum level of just over 1.5 °C around 2050. The temperature then starts to decline slowly as a result of continued reductions in non-CO_2 emissions, and by 2100 the rise in temperature has fallen to around 1.4 °C. In the SDS, CO_2 emissions drop to zero around 2070 and there are rapid reductions in non-CO_2 emissions. The 1.5 °C level is exceeded in the early 2030s and the rise in temperature peaks at just under 1.7 °C around 2050.[4] The SDS is in line with the Paris Agreement objective of "holding the increase in the global average temperature to well below 2 °C", while the NZE goes further to be in line with the Paris Agreement objective of "pursuing efforts to limit the temperature increase to 1.5 °C".

Table 1.1 ⊳ Temperature rise in the *WEO-2021* scenarios (°C)

Scenario	2030		2050		2100	
Confidence level:	50%	33% – 67%	50%	33% – 67%	50%	33% – 67%
Stated Policies	1.5	1.4 – 1.6	2.0	1.8 – 2.1	2.6	2.4 – 2.8
Announced Pledges	1.5	1.4 – 1.6	1.8	1.7 – 2.0	2.1	1.9 – 2.3
Sustainable Development	1.5	1.4 – 1.6	1.7	1.5 – 1.8	1.6	1.4 – 1.7
Net Zero Emissions by 2050	1.5	1.4 – 1.5	1.5	1.4 – 1.7	1.4	1.3 – 1.5

Note: Shows the maximum temperature rises with 33%, 50% and 67% confidence levels.

Source: IEA analysis based on outputs of MAGICC 7.5.3.

The difference in temperature rise between the scenarios has stark consequences for global ecosystems and human well-being. The higher the temperature rise, the greater the risks of severe weather events such as extreme heat, drought, river and coastal flooding and crop failures. Even during the last decade, with an average temperature rise of 1.1 °C above pre-industrial levels, extreme heat events occurred almost three-times more frequently than in pre-industrial times. In the STEPS, around 2050, there would be a 100% increase in the frequency of extreme heat events compared to today and these would be around 120% more intense; there would also be a 40% increase in ecological droughts that would be around 100% more intense. In the NZE, the increase in frequency of extreme heat events would be lower at around 45% and ecological droughts would be less than 20% more frequent.

By 2100, as the temperature trajectories of the scenarios diverge, differences in the frequency and intensity of extreme weather events would become even more stark. There

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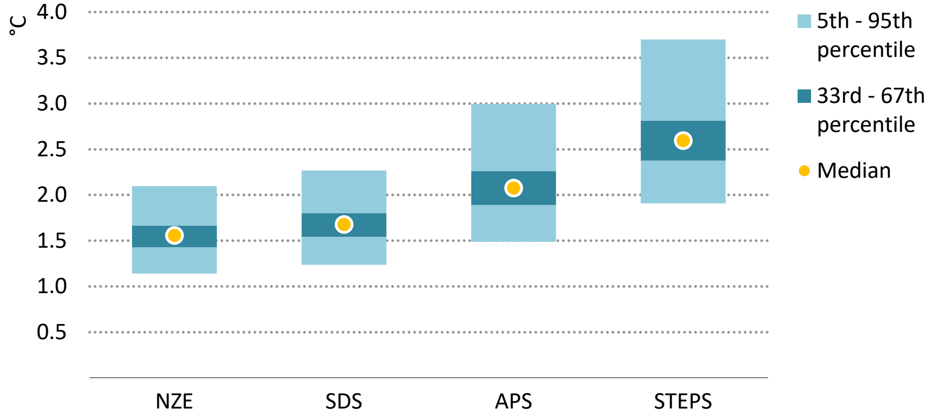
[4] All scenarios in the *WEO-2021* have a similar temperature rise over the 2021-2030 period and a similar year in which 1.5 °C warming is exceeded. This results from a balance between reductions in emissions of gases that have a large near-term warming effect on the climate (such as methane) and reductions in aerosols and gases that have a large near-term cooling effect on the climate (such as sulphur dioxide).

is around a 10% chance that the rise in temperature in the STEPS would exceed 3.5 °C in 2100 (Figure 1.6). This would lead to an 80-130% increase in the frequency of ecological droughts and a two-to-threefold increase in their intensity. Extreme rainfall would happen up to twice as often as today and be three-to-four-times more intense (IPCC, 2021). The risk of ice sheet collapse and disruptions to ocean circulation currents would also be substantially higher.[5] This in turn could precipitate irreversible changes in the permafrost, boreal forests and the Amazon rain forest, potentially accelerating warming.

Figure 1.6 ⊳ **Peak temperature rise in the *WEO-2021* scenarios**



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The NZE limits the maximum median temperature rise to just over 1.5 °C. There is a small chance that the temperature rise in 2100 could exceed 3.5 °C in the STEPS

Note: Shows the temperature rise around 2050 for the NZE and SDS, and in 2100 for the APS and STEPS.

Source: IEA analysis based on outputs of MAGICC 7.5.3.

1.3 Keeping the door to 1.5 °C open

Announced net zero pledges and updated NDCs, reflected in full in the Announced Pledges Scenario, represent an important boost to the world's efforts on climate but, as they stand, they close less than 20% of the gap in 2030 between the STEPS and the NZE. An additional 12 Gt CO_2 emissions need to be abated in 2030 in order to get the world on track for the NZE, and this needs to be accompanied by reductions of almost 90 million tonnes (Mt) in methane emissions from fossil fuel operations (equivalent to another 2.7 Gt of CO_2 emissions). That is the task before the world's decision makers as they assess how to keep a 1.5 °C stabilisation in global average temperatures within reach.

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[5] The uncertainty ranges associated with temperature rises shown in do not take into account the possibility of these low likelihood, high impact events, which could generate feedbacks and cause additional atmospheric warming.

Table 1.2 ▷ Selected indicators in the Net Zero Emissions by 2050 Scenario

	2010	2020	2030	2040	2050
Global indicators					
CO_2 emissions per capita in AE (t CO_2 per capita)	10	8	4	1	0
CO_2 emissions per capita in EMDE (t CO_2 per capita)	3	4	2	1	0
CO_2 emissions intensity (t CO_2 per USD 1 000, PPP)	318	259	114	25	0
Energy intensity (MJ per USD, PPP)	5.4	4.5	3.0	2.2	1.7
Share of electricity in TFC	17%	20%	26%	39%	49%
Share of fossil fuels in TES	81%	79%	62%	35%	22%
Share of population with access to electricity in EMDE	75%	88%	100%	100%	100%
Investment in clean energy (billion USD)	619	974	4 344	4 348	4 210
Total CO_2 captured (Mt CO_2)	14	40	1 665	5 619	7 602
Supply					
Emissions intensity of oil and gas (kg CO_2-eq per boe)	91	93	40	35	31
Methane emissions from fossil fuel operations (Mt CH_4)	104	117	28	14	10
Low-carbon share in total liquids	2%	2%	10%	21%	39%
Low-carbon share in total gases	0%	0%	14%	33%	62%
Low-carbon share in total solids*	18%	21%	39%	55%	72%
Electricity generation					
CO_2 emissions intensity (g CO_2 per kWh)	523	459	138	-1	-5
Share of unabated coal	40%	35%	8%	0%	0%
Share of renewables	20%	28%	61%	84%	88%
Share of wind and solar PV	2%	9%	40%	63%	68%
Buildings					
CO_2 emissions intensity (g CO_2 per MJ)	25	23	18	8	1
Existing buildings retrofitted to be zero-carbon-ready level	< 1%	< 1%	20%	50%	85%
Share of new buildings that are zero-carbon-ready	< 1%	5%	100%	100%	100%
Appliance unit energy consumption (index 2020=100)	106	100	75	64	60
Industry					
CO_2 emissions intensity (g CO_2 per MJ)	56	56	41	21	3
Energy intensity (MJ per USD PPP)	4.8	4.0	3.0	2.3	1.7
Share of electricity in TFC	18%	22%	28%	37%	46%
Transport					
CO_2 emissions intensity of passenger cars (g CO_2 per km)	231	200	106	34	4
CO_2 emissions intensity of heavy trucks (g CO_2 per km)	984	898	589	273	54
Share of low-carbon fuel use in aviation and shipping	0%	0%	17%	51%	81%
Share of PHEV, BEV and FCEV in total passenger car sales	0%	5%	64%	100%	100%
Share of PHEV, BEV and FCEV in total heavy truck sales	0%	0%	30%	84%	99%

*Traditional use of biomass is not considered low-carbon.

Notes: AE = advanced economies; EMDE = emerging market and developing economies; PPP = purchasing power parity; TFC = total final consumption; TES = total energy supply; Mt CO_2 = million tonnes of CO_2; kg CO_2-eq per boe = kilogrammes of CO_2 equivalent per barrel of oil equivalent; Mt CH_4 = million tonnes of methane; g CO_2 per kWh = grammes of CO_2 per kilowatt-hour; g CO_2 per MJ = grammes of CO_2 per megajoule; g CO_2 per km = grammes of CO_2 per kilometre; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle.

The four key priorities for action to close this gap over the next decade, and to prepare the ground for further rapid emissions reduction beyond 2030, are to:

- Deliver a surge in clean electrification.
- Realise the full potential of energy efficiency.
- Prevent methane leaks from fossil fuel operations.
- Boost clean energy innovation.

Figure 1.7 ▷ Four key priorities to keep the door to 1.5 °C open in the Net Zero Emissions by 2050 Scenario

Closing the emissions gap needs efforts to accelerate clean electrification, boost clean energy innovation, minimise methane leaks, and realise the potential of energy efficiency

Notes: MJ per USD PPP = megajoule per US dollar at purchasing power parity. Advanced clean technologies include CCUS, batteries, advanced biofuels, synthetic fuels and direct air capture.

The first three priorities require the application, at massive scale, of technologies and approaches that are mature today, using policies and measures that are tried and tested (Figure 1.7). Boosting clean energy innovation is essential to bring new technologies through the demonstration and prototype stages so that they are ready to scale up dramatically in the 2030s in areas where electrification is difficult to achieve, such as heavy industry and long-distance transport. Ensuring adequate financing for all of these priority areas is a crucial cross-cutting component.

There are strong synergies between all of these efforts. Clean electrification brings major efficiency gains, as well as helping to decarbonise end-use sectors, because many electric technologies are significantly more efficient than their fossil fuel counterparts. For example, today's electric cars use on average 70% less energy to travel one kilometre than a conventional car. In turn, by reducing upward pressure on electricity demand, efficiency measures on appliances and equipment make it easier for cleaner sources of power to gain market share. Clean electrification and efficiency bring down fossil fuel demand and production. This helps to reduce associated methane emissions, although it is not a substitute for concerted policy efforts to reduce emissions as quickly as possible from fossil fuel operations. Innovation has the potential to support more rapid electrification, for example through the development of advanced batteries that are able to bring electricity into heavy-duty segments of the transport sector, and also to bring low emissions electricity indirectly into other sectors via low-carbon hydrogen.

Clean electrification

Cleaning up the electricity mix and extending the electrification of end-uses is a central pillar of transition strategies. It plays a key role in the structural transformation of the energy sector in all our scenarios, and it supports energy-related sustainable development goals, notably access to electricity.

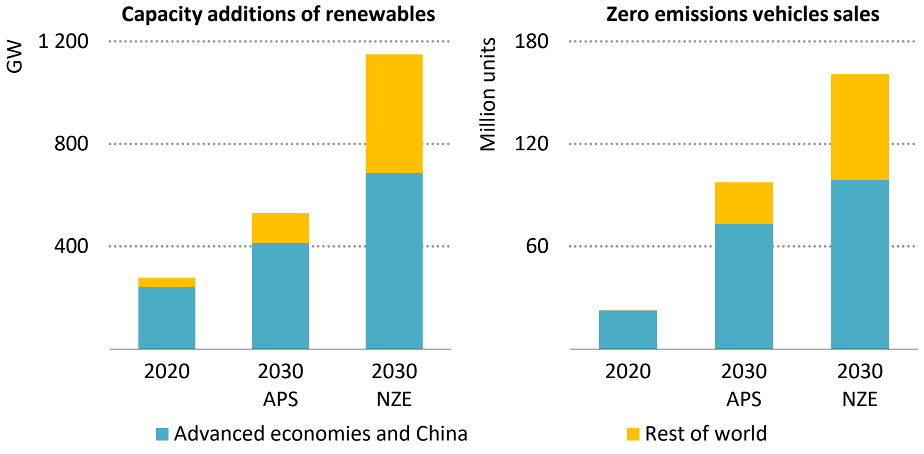
The electricity sector emitted 12.3 Gt CO_2 in 2020 (36% of all energy-related emissions), which is more than any other sector. Coal remains the largest single source of electricity worldwide, and by far the largest source of electricity sector emissions: it contributes just over one-third of electricity supply but is responsible for nearly three-quarters of electricity sector CO_2 emissions. The power sector is already moving away from coal, and it continues to do so in all our scenarios. Accelerating the decarbonisation of the electricity mix is the single most important way to close the 2030 gap between the APS and NZE. In the NZE, faster decarbonisation of electricity cuts emissions by 5 Gt, compared with the APS, and this accounts for 40% of the CO_2 emissions gap between the two scenarios in 2030. We calculate that nearly 60% of this total (about 2.9 Gt) could be cut at no cost to electricity consumers.

Rapid decarbonisation of the electricity sector requires a massive surge in the deployment of low emissions generation. The share of renewables increases from almost 30% of electricity generation globally in 2020 to about 45% in 2030 in the APS, but this is still fifteen percentage points short of the level reached in the NZE. Nuclear power and dispatchable low emissions capacity, such as hydropower, biomass and geothermal are important elements of the picture, but capacity additions are dominated by solar PV and wind. The largest increases in deployment to close the emissions gap take place in emerging market and developing economies.

Decarbonising the global power sector is not only a question of expanding low emissions generation, but also of tackling emissions from existing sources. This requires an end to investment in new unabated coal-fired power plants, as well as strategies to retrofit, repurpose or retire existing ones (see section 1.7). Scaling up grids and all sources of flexibility, including energy storage systems, is also pivotal: investment in electricity infrastructure in the NZE accelerates more quickly than investment in generation. Alongside a rapid expansion and modernisation of grids, utility-scale battery storage capacity increases 18-times from 2020 to 2030 in the APS, and more than 30-times in the NZE.

The transformation of electricity supply goes hand-in-hand with a major increase in electricity use as demand in existing end-uses grows and as new end-uses such as transport and heating are electrified (Figure 1.8). Rapid electrification of passenger mobility in advanced economies and China is already built into the APS, and expanding this to emerging market and developing economies is essential if the gap between the APS and the NZE is to be closed. The challenge is significant: in the NZE, the share of EV cars in total car sales is over 60% in 2030. Faster electrification of transport, together with some deployment of hydrogen-based fuels, would close about 1 Gt of the ambition gap with the NZE.

Figure 1.8 ▻ Selected indicators of clean electrification in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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To close the gap between announced pledges and a net zero pathway, all countries need to do more, with the largest increases in emerging market and developing economies

Notes: Zero emissions vehicles (ZEVs) include battery electric vehicles, plug-in hybrid electric vehicles and fuel cell electric vehicles. This figure shows ZEVs sales of all vehicle types including passenger vehicles, trucks, buses and two/three-wheelers.

Heat pumps are the largest electrification opportunity in the buildings sector, displacing heating from fossil fuel boilers. Although electric heat pumps are an increasingly attractive option, gas-fired boilers remain the dominant form of space heating in the STEPS and in many countries in the APS. Ensuring that new buildings meet zero-carbon-ready standards[6], and providing incentives for householders to install heat pumps when existing heating options breakdown or need to be replaced, both help to close the gap between the APS and the NZE. Electrification is also increasingly used in the NZE to provide low-temperature heat in industry.

Energy efficiency

Improvements in energy efficiency curb demand for electricity and fuels of all kinds. In the STEPS, overall global energy demand continues to climb; in the APS it plateaus after 2030; in the NZE, it is 15% lower than in the APS by 2030. As a result, the energy intensity of the global economy decreases by 4% per year between 2020 and 2030 in the NZE, more than double the average rate of the previous decade. Without this improvement in energy efficiency, total final consumption in the NZE would be about a third higher in 2030, significantly increasing the cost and difficulty of decarbonising energy supply.

Much stronger policies on end-use energy efficiency in the NZE reduce emissions by about 1.3 Gt CO_2 in 2030, compared with the APS, and are of particular importance in the transport and buildings sectors. We estimate that almost 80% of these additional energy efficiency gains in the NZE could be achieved cost-effectively over the next decade. Avoided demand through measures such as digitalisation and materials efficiency reduce emissions in the NZE by a further 1.3 Gt by 2030: much of the potential here is in the industry sector, where opportunities for materials efficiency are substantial and low emissions technologies are less mature than in most other sectors. Behavioural changes contribute around another 1 Gt by 2030 to the additional emissions reductions in the NZE, notably in the transport sector.

Stronger standards for appliances and fuel economy are instrumental in achieving these efficiency gains in the NZE, as is a stronger policy emphasis on materials efficiency in industry. In the buildings sector, the number of building retrofits would need to increase two-and-half-times compared with announced pledges to close the gap; this is particularly important in advanced economies. Energy efficiency measures such as retrofits and appliance standards also save about 0.5 Gt of indirect CO_2 emissions outside the buildings sector, largely by reducing electricity demand.

Methane

Methane has contributed around 30% of the global rise in temperature today and the IPCC 6th Assessment Report highlights that rapid and sustained reductions in methane emissions are key to limit near-term warming and improve air quality. The energy sector is one of the largest sources of methane emissions today: we estimate that fossil fuel operations emitted

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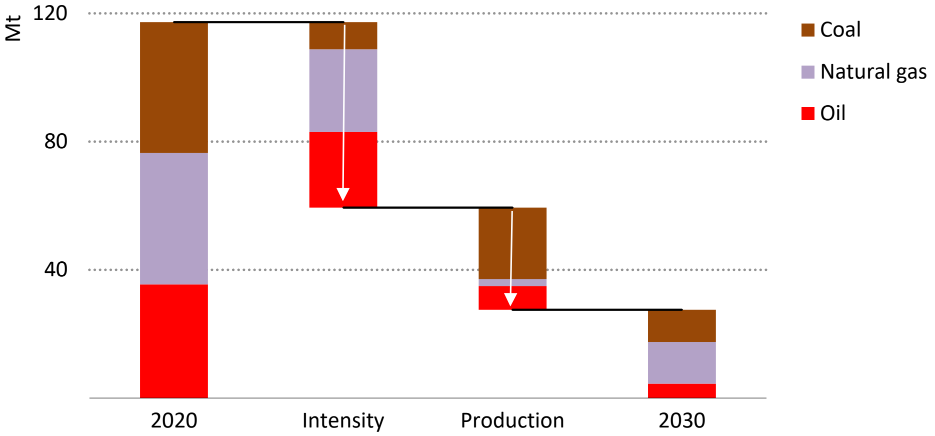
[6] A zero-carbon-ready building is highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonised by 2050 in the NZE (such as electricity or district heat).

around 120 Mt of methane globally in 2020, equivalent to around 3.5 gigatonnes of carbon-dioxide equivalent (Gt CO_2-eq).

We estimate that almost 45% of current oil and gas methane emissions could be avoided at no net cost (based on average natural gas prices from 2017-21) given that the cost of deploying the abatement measures is less than the value of the gas that would be captured. There are a number of well-known technologies and measures that can be deployed to address methane emissions from oil and gas operations. If countries were to implement a set of well-established policy tools – namely leak detection and repair requirements, staple technology standards and a ban on non-emergency flaring and venting – emissions from oil and gas operations could be halved within a short timeframe (IEA, 2021b). Further reductions could be pursued through measures such as performance standards or emission taxes supported by more robust measurement and verification systems. Technology developments, in particular in the field of satellite observation, could help with the development of such systems. Applying a USD 15/t CO_2-eq price to methane from oil and gas operations would be enough to deploy nearly all abatement measures.

There are also opportunities to reduce methane emissions from coal production using existing technologies. However abatement opportunities in the coal sector are often less cost-effective than in the oil and gas sector. This is because methane sources in coal mines tend to be more widely dispersed and to have lower methane concentrations. Plus, often there is inadequate infrastructure to facilitate the use of captured methane. In the NZE, most of the decline in coal-related methane emissions comes from the rapid decline in coal production.

Figure 1.9 ▷ **Methane emissions from fossil fuel operations and reductions to 2030 in the Net Zero Emissions by 2050 Scenario**



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Concerted efforts to reduce leaks drive over 80% of methane emissions reductions in oil and gas; the most effective way to reduce emissions from coal is to produce less

Total methane emissions from all fossil fuel operations fall by around 75% between 2020 and 2030 in the NZE (Figure 1.9). Around one-third of this decline is the result of an overall reduction in fossil fuel consumption. The larger share comes from a rapid deployment of emissions reduction measures and technologies, which leads to the elimination of all technically avoidable methane emissions by 2030.

Innovation

Clean electrification, efficiency and methane emissions reductions do the heavy lifting over the next ten years, but they cannot carry the world all the way to a net zero future. Almost half of the emissions reductions achieved in the NZE in 2050 come from technologies that are at the demonstration or prototype stage today, and that are needed in particular to decarbonise heavy industrial sectors and long-distance transport because these sectors are in general not susceptible to electrification. For this reason, another important "gap" that needs to be closed in the 2020s relates to innovation. Governments need to step up support in key technology areas, such as advanced batteries, low-carbon fuels, hydrogen electrolysers and direct air capture. They also need to collaborate internationally to reduce costs and ease the path of new technologies to market. In the NZE, around USD 90 billion of public money is mobilised to complete a portfolio of demonstration projects before 2030. Currently, only about USD 25 billion is budgeted for that period.

Announced pledges lag on key NZE milestones related to hydrogen-based and other low-carbon fuels, as well as CCUS. For example, by 2030 the APS achieves less than 40% of the level of deployment of clean shipping fuels seen in the NZE, and it is even further behind the NZE on the deployment of hydrogen in industry. Options like industrial CCUS or electric trucks make substantial inroads into emissions in the NZE only after 2030, but early deployment before 2030 is essential to drive down costs and establish enabling infrastructure. Because of long infrastructure lifetimes and relatively slow rates of change in these areas, catching up after 2030 will be particularly challenging if these milestones are missed. It is therefore critical that policy support in the near term is directed towards early deployment of key innovative technologies and the development of supporting infrastructure.

In the NZE, new technologies that have an important future role make vital early progress. Hydrogen-based fuels and fossil fuels with CCUS make up just under 1.5% of total final consumption by 2030, up from almost nothing today. These relatively small inroads into the market prepare the ground for these technologies to ramp up after 2030 and make a bigger contribution towards net zero energy emissions by 2050.

1.4 Energy consumers of tomorrow

Any assessment of the outlook for global energy and emissions has to assign a central place to emerging market and developing economies. There are billions of people on the planet who do not yet have the housing stock and appliances that are taken for granted across most advanced economies, and hundreds of millions of people who lack even the most basic access to modern energy. Emerging market and developing economies excluding China[7] account for two-thirds of the global population today, and they will be home to the vast majority of the two billion people that look set to be added to the world's population by 2050. The population of sub-Saharan Africa is projected to grow especially fast, and is on course to double by 2050.

As China has amply demonstrated over the last two decades, and many advanced economies before it, the process of constructing the infrastructure needed in a modern and rapidly developing economy up till now has been very energy- and emissions-intensive. With many emerging market and developing countries now considering how best to meet their future energy and development needs, the falling costs of key clean energy technologies offer a major opportunity to chart a new, lower emissions path to growth that is centred on clean electrification and efficiency (see section 1.3). However, no country has yet shown a cost-effective way to leapfrog to low-carbon technologies in all areas of energy use, such as steel, cement and freight that are instrumental to the construction and operation of modern economies.

The starting point for this journey is not a propitious one. Most emerging market and developing economies face an ongoing public health crisis with the Covid-19 pandemic, without the means or the opportunity to start mass vaccination campaigns in earnest. The pandemic has been a setback for efforts to improve access to modern energy and has further strained the finances of the utilities that are key investors in grids and off-takers for renewable projects (Box 1.2). Increased borrowing to cope with the effects of the pandemic has left little room for many governments to kick-start investment in sustainable recoveries; the annual boost to clean energy coming from public recovery spending amounts to less than USD 10 billion by 2023. Overall, if China is excluded, emerging market and developing economies account for one-fifth of the amounts being invested worldwide on clean energy.

Across all fuels and technologies, emerging market and developing economies are instrumental in shaping global trends in the coming decades. In the STEPS, oil demand in these economies is 12 million barrels per day (mb/d) higher in 2030 than in 2020 (an increase of nearly 30%), gas demand by 520 bcm (a near-25% increase), and coal demand by 160 million tonnes of coal equivalent (Mtce) (a 4% rise). Demand for fossil fuels in advanced economies falls in the APS, but announced pledges do not bend projected demand trends across much of the developing world.

Nevertheless, there are some indications of structural change. The energy intensity of GDP improves by 2.8% annually in the STEPS in this decade; it is accompanied by a similarly positive outlook for carbon intensity. Progress with energy efficiency and clean electrification helps to underpin these trends. More stringent energy performance standards for air conditioners in India are a case in point, helping to improve the efficient use of energy in a fast-growing segment that could otherwise push up peak demand and exacerbate strains on the power sector.

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[7] China is included in the aggregate numbers for the category *emerging market and developing economies* in this *Outlook*. However, the scale of the country's industrialisation and infrastructure development over the past two decades means that it dominates this aggregate, so China is often considered in a category of its own.

Box 1.2 ▹ Momentum has been lost on access: It needs to be regained fast

Today, 770 million people worldwide still live without access to electricity, mostly in Africa and developing countries in Asia. After decreasing 9% annually on average between 2015 and 2019, preliminary data show that progress stalled between 2019 and 2021 globally, and that the number of people without electricity access actually increased in sub-Saharan Africa. The impact of the pandemic on household incomes has weakened the ability to pay for electricity: in 2020 up to 90 million people with electricity connections in Africa and developing countries in Asia lost the ability to afford an extended bundle of services.[8] Households may be opting for cheaper and smaller systems that provide fewer energy services than would have been the case before the pandemic.

Progress with access to clean cooking has suffered a similar reversal. We estimate that cooking with traditional use of biomass, coal or kerosene causes 2.5 million premature deaths annually, slowing development and entrenching gender inequality. Between 2015 and 2019, the global population without clean cooking access decreased on average by 2% a year, led by efforts in developing countries in Asia. Between 2019 and 2021, however, it increased by 30 million (slightly over 1%). The pandemic diminished the ability of many to pay for modern fuels and to travel to liquefied petroleum gas (LPG) refilling stations during lockdowns, and more time spent at home increased exposure to air pollution and the associated health risks.

Governments and development agencies have provided emergency financial relief to reduce these impacts. Poverty or lifeline electricity tariffs were expanded in some cases, although this element of support is often limited to grid electricity, despite the fact that an increasing number of people are gaining access through off-grid solutions. To maintain access to clean cooking fuels, some governments, notably in India, provided support for free refills of LPG cylinders. Many of these support schemes will need to be extended to offset the continuing impact of Covid-19, and to provide renewed momentum towards access to modern energy for all as economic recoveries accelerate.

China is currently a global leader in renewable energy installations, and this continues in our scenarios, but an increasing number of emerging market and developing economies are following suit. The pace of capacity additions picks up in many countries in the STEPS: these include well-established markets like India and Brazil, where transport biofuels also flourish, as well as more recent ones in the Middle East and Africa. Renewables account for almost two-thirds of all new power capacity additions in emerging market and developing economies (excluding China) in the STEPS by 2030, up from about half today. Increased investment in robust grids and other sources of flexibility is vital to the reliable operation of solar PV and wind-rich systems; it is particularly important in India as it closes in on its target to increase renewable capacity to 450 GW by 2030, from around 150 GW today.

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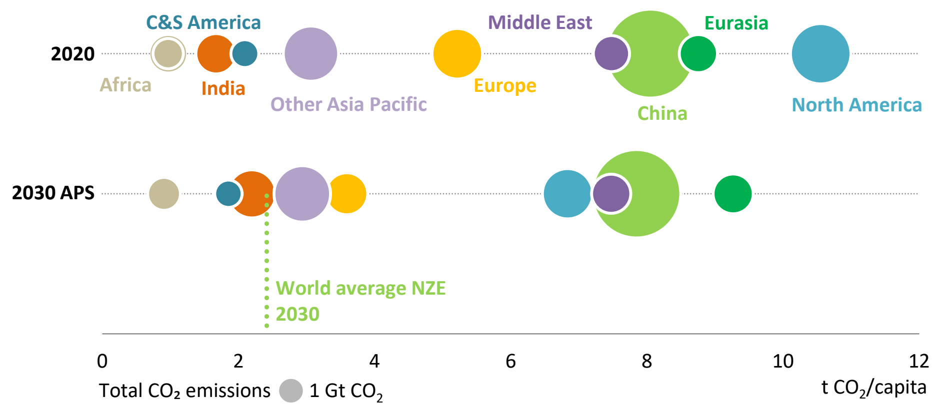
[8] An extended bundle of services includes four lightbulbs operating for four hours per day, a fan for six hours per day, a radio or television for four hours per day and a refrigerator.

Electricity demand grows rapidly in emerging market and developing economies in the STEPS. This reflects increased uptake of industrial electric motors and rising levels of appliance ownership rather than large-scale electrification of new end-uses such as transport. While electric two/three-wheelers gain ground quickly in many countries, passenger EVs face a number of non-economic barriers that are not completely overcome in the STEPS (or in the APS). These include insufficient recharging infrastructure, weak or unreliable grids, and reliance in some countries, especially in Africa, on the second-hand vehicle market where EVs will only become available with a time lag. Despite these barriers, there are some economies within this grouping (for example Singapore and Costa Rica) that already have phase-out policies in place for different categories of conventional vehicles.

Clean electrification cannot answer all the needs of economies undergoing rapid urbanisation and industrialisation. Transitions in fuels and energy-intensive sectors such as construction materials, chemicals and long-distance transport are particularly important. Here the signals in the STEPS are less encouraging, despite continued improvements in efficiency and fuel switching from more polluting fuels to electricity and natural gas. Some new projects are developed for low-carbon liquids and gases, notably for hydrogen in countries either with a large renewable energy resource base or with large natural gas resources (the Middle East is well placed on both counts), but in the STEPS they do not reach the scale that would make hydrogen a mainstream element of industrial strategies and operations.

Figure 1.10 ▷ CO_2 emissions per capita by region in 2020 and the Announced Pledges Scenario in 2030



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CO_2 emissions per capita in emerging market and developing economies remain below the average of advanced economies in 2030, except in Eurasia, China and the Middle East

Notes: C&S America = Central and South America. Bubble size is proportional to total emissions from each region. The world average excludes CO_2 emissions from international aviation and shipping.

Taken together, this means that emerging market and developing economies are set to account for the bulk of CO_2 emissions growth in the coming decades unless much stronger action is taken to transform their energy systems. Emissions from emerging market and developing economies (excluding China) are projected to rise by 5.5 Gt to 2050 in the STEPS, with the largest increase from industry and transport (rather than power). In contrast, emissions are projected to decline by 3.7 Gt in advanced economies and by 3 Gt in China. The divergence in trends is even more significant in the APS.

Only a fraction of emissions from emerging market and developing economies are covered by net zero pledges. Greater ambition is warranted and necessary. However, while tackling climate change is a common cause, responsibilities and capabilities for climate action differ.[9] An international catalyst is essential in the form of stronger financial support, recognising that the average cost of emissions reductions in these economies is much lower than in advanced economies. Moreover, despite limited country-wide emissions reduction pledges, per capita CO_2 emissions in emerging market and developing economies (excluding China) are less than half of the advanced economy average in 2030 in the APS (Figure 1.10). Producer economies across the Middle East and Eurasia are the exception: they are among the highest emitting regions on a per capita basis.

1.5 Mobilising investment and finance

Getting the world on track for net zero emissions by 2050 requires clean energy transition-related investment to accelerate from current levels to around USD 4 trillion annually by 2030. The APS sees progress on this front, but the level of investment required in the NZE is three-quarters higher. This expansion is driven by a USD 1.1 trillion increase, relative to the APS, in annual investment in clean power generation and electricity infrastructure (two-thirds for generation and one-third for networks), a USD 0.5 trillion increase in investment in energy efficiency and end-use decarbonisation in the buildings, industry and transport sectors, as well as a rapid scaling up from a low base of low emissions fuels based on hydrogen or bioenergy. All regions see a surge in clean energy spend, but the required increase is particularly large in emerging market and developing economies.

The large increase in capital investment in the NZE is partly compensated for by the lower operating expenditure that follow the shift away from upstream fuel supply and fossil fuel generation projects towards capital-intensive clean technologies. Keeping upfront financing costs low nevertheless is critical to the speed and affordability of this transformation. In recent years, economy-wide financing costs have tended to come down around the world. However, capital remains up to seven-times more expensive in emerging market and

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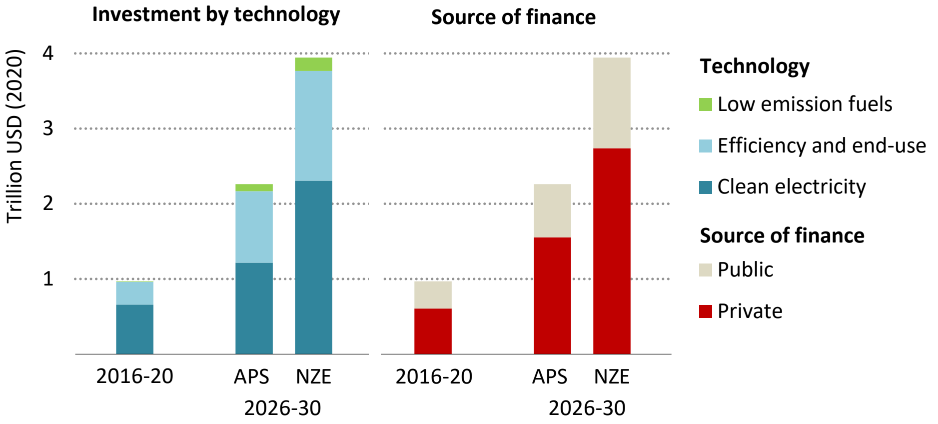
[9] As an illustration, of the eight countries whose targets and actions have been assessed by the Climate Action Tracker as either “compatible” or “almost sufficient” with a 1.5 °C trajectory, seven are emerging market and developing economies. The methodology used for this assessment considers what is the country’s fair level of contribution to the global effort (https://climateactiontracker.org/).

developing economies than in advanced economies, while fiscal expansions and inflationary pressures around the world increase the risk of growing debt burdens and higher borrowing costs in the future.

Achieving rapid clean energy transitions depends on enhancing access to low cost finance for clean energy projects. This means channelling retained earnings from the balance sheets of large energy companies, as well as opening funding from a range of companies and external sources – notably banks and the enormous pools of capital in financial markets. We estimate that around 70% of clean energy investment will need to be carried out by private developers, consumers and financiers responding to market signals and policies set by governments (Figure 1.11). But an expansion of public sources of finance is also required. Public actors, including state-owned enterprises (SOEs), often have a key part to play in funding network infrastructure and clean energy transitions in emissions-intensive sectors. Public finance institutions will need to catalyse private capital, and their role is especially important in the NZE, where their investment more than doubles compared with the APS.

Figure 1.11 ▻ Average annual clean energy investment and financing in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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Annual clean energy investment in the NZE is 75% higher than in the APS and is mostly met by private actors, although public finance plays a critical role in mobilising capital

Note: Public finance includes state-owned enterprises and public finance institutions.

Mobilising clean energy investment will depend on obtaining finance from both local and international sources. International capital providers may find it easiest to invest in large, bankable assets, such as renewable power with long-term contracts, but action is also needed to better connect financial markets with projects for end-use decarbonisation and to build capacity for local currency fundraising, particularly in emerging market and developing economies. While clean energy transitions rely on much higher levels of both equity and debt, capital structures are likely to hinge on the mobilisation of more debt, including through expanded use of project finance and third-party arrangements, and it is used to finance over half of all investment by 2030.

While many actions are needed to mobilise the necessary capital for clean energy transitions, two cross-cutting themes in particular need urgent consideration by public and private decision makers.

Redoubling international support

An international catalyst is needed to boost clean energy investment. Fulfilling the commitment by advanced economies to mobilise USD 100 billion per year in climate finance is necessary, but not sufficient. Development finance institutions (DFIs) have a central part to play, and will need to focus on financing emissions reductions across a broad range of sectors and activities, as well as stepping up delivery efforts. In 2020, climate finance commitments reported by the multilateral development banks (MDBs) topped USD 65 billion, more than double the amount five years ago, and comprised nearly 30% of their total financing. Some MDBs aim to boost climate investments from 30% to over 50% of their portfolio by 2025. Meeting net zero goals will depend on ensuring the delivery and reinforcement of such commitments over time.

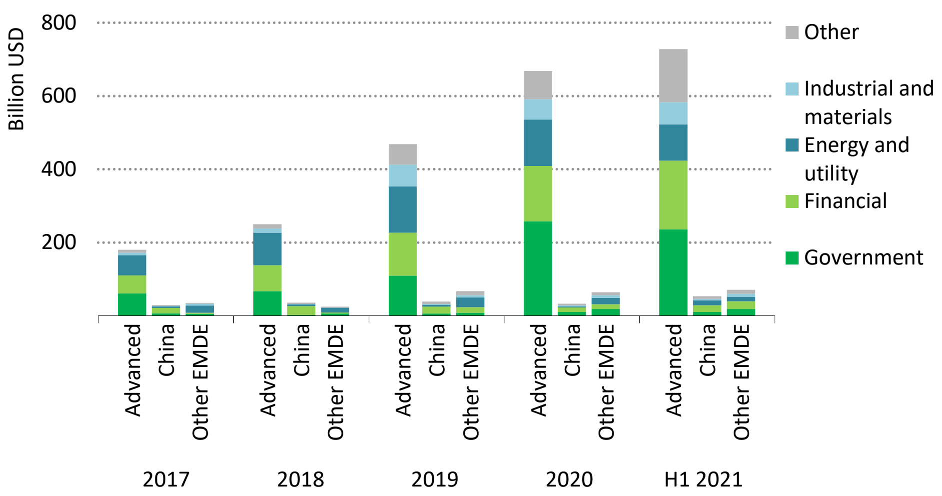
Mobilising additional private capital on the back of these commitments will rely in particular on the enhanced deployment of blended finance to catalyse project development. This will need to include the packaging of a range of instruments and approaches ranging from guarantees to concessional loans to first-loss equity. Such packages are critical to improving the risk profiles of some market-ready investments (e.g. renewables-based power in many sub-Saharan Africa countries) and to support development of small-scale projects that lack a track record with banks (e.g. building retrofits or EV charging infrastructure). It will also be important to deploy risk capital in sectors at early stages of readiness to support, for example, industrial decarbonisation, which currently accounts for a small share of DFIs climate finance commitments, and to help in cases where risks are hard to mitigate, such as energy access projects for vulnerable communities or in remote areas.

All of these actions require DFIs to find ways to manage the tensions that can emerge between the objectives of providing risk capital to those areas most in need, promoting private sector development, fulfilling their role as banks with robust systems of financial management and accountability, and maintaining strong environmental and social safeguards. Maximising the effectiveness of scarce public capital may be best done by pairing funding with technical assistance and capacity building for local actors, especially in emerging market and developing economies, and by collaborations with domestic intermediaries. A multipronged effort will also be needed to manage the financial and human consequences of phasing out emissions-intensive assets such as coal plants (see section 1.7).

Mobilising wider pools of private capital

If clean energy transitions are to be successful, then private developers and financiers need to increase the amount of capital they allocate to energy transitions and to emerging market and developing economies. The growing emphasis on sustainable finance should encourage both shifts. There is no shortage of institutional investor appetite, as the continued surge of sustainable debt issuance shows: over USD 850 billion was issued over the first-half of 2021, which is more than the total for the whole of 2020 (Figure 1.12).

Figure 1.12 ▹ Historical levels of sustainable debt issuance



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The availability of sustainable finance has surged but efforts are needed to improve metrics and to step up engagement with emerging economies and emissions-intensive companies

Notes: Advanced = advanced economies; Other EMDE = emerging market and developing economies excluding China; H1 2021 = first-half of 2021. Sustainable debt includes green bond and loans, sustainability-linked bonds and loans, sustainability bonds and social bonds.

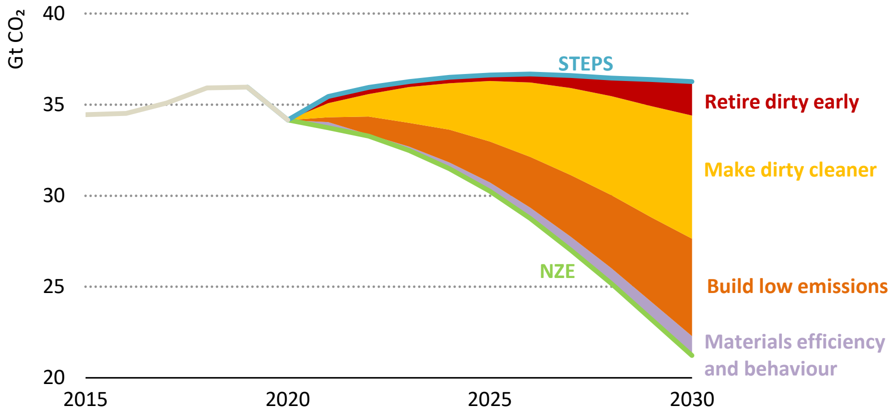
However, a major challenge stems from the fragmented and complex state of reporting and assessment within sustainability frameworks. In order to better incentivise capital markets to fund sustainability in a reliable way, improvements are needed in the quality, quantity and comparability of metrics, corporate disclosures and risk assessments based on clear benchmarks.

As things stand, the alignment of investment portfolios with NZE goals risks excluding countries with high carbon footprints or sectors with more challenging pathways. Sustainable finance approaches are needed that encourage engagement – by both equity and debt investors – with emissions-intensive companies and economies on the development of credible transition plans (Box 1.3). Initiatives by the financial community should also focus on working with regulators and issuers to create sustainability fundraising opportunities in markets that currently lack them.

Box 1.3 ⊳ The complex middle ground of transition investment

Measuring the performance and targeting of capital flows against the investment needs of long-term net zero emissions goals is a complex task. Some investments will unequivocally help to reduce emissions; others are sure to increase them. But the idea that all energy sector investments divide neatly into "clean" and "dirty" does not survive contact with the realities of energy transitions. Our scenarios reveal a large number of gradations: a large portion of investments go towards sectors, technologies and infrastructure that do not immediately deliver zero emissions energy or energy services, but do enable such investments or provide incremental emissions reductions; some of these investments can also help to deliver zero emissions energy over time, but are contingent on actions elsewhere in the system, notably those concerned with decarbonising the power sector. In practice, this middle ground of actions that "make dirty cleaner" is crucial in determining the speed and scope of energy transitions, and delivers the largest share of emissions reductions in getting from the STEPS trajectory to a net zero one (Figure 1.13).

Figure 1.13 ⊳ **Emissions reductions in the Net Zero Emissions by 2050 Scenario relative to the Stated Policies Scenario**



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Delivering net zero requires more than retiring dirty and building low emissions projects; there is a large middle ground that defines the speed and scope of change

To illustrate, we have divided the total energy investment requirement in our scenarios into four categories:

- **Low emissions:** Investments that provide zero emissions (or very low emissions) energy or energy services, regardless of how the energy system evolves. Examples include renewables, low emissions fuels, CCUS and direct air capture.

- **Contingent:** Investments that could provide or enable zero emissions energy or energy services but only with changes elsewhere in the energy system. Examples include electricity networks, electrification of end-use equipment or improvements in the efficiency of electrical appliances, and EVs, that rely on the eventual decarbonisation of power generation.
- **Transition:** Investments that provide emissions reductions but do not themselves deliver zero emissions energy or energy services. Examples include efficiency or flexibility measures that reduce fossil fuel use, investments that support fuel switching away from coal or oil to less polluting alternatives (e.g. new gas boilers that replace coal-fired ones, refurbishments of power plants to support co-firing with low emissions fuels), and gas-fired plants that enable higher penetration of variable renewables.
- **Unabated fossil fuels that do not enable emissions reductions:** Investments in coal, oil and natural gas that do not provide any emissions reductions from today.[10] Examples include investment in coal mines and in unabated coal-fired power plants.

The allocation of investment in certain assets or technologies varies across countries/regions and over time: for example, a new gas-fired power plant may help to reduce emissions in one area, but not in another; investment in a coal-fired power plant may shift from one category to another if it is repurposed or retrofitted with CCUS or to co-fire with low-carbon fuels; and investments in electricity grids, appliance efficiency and EVs shift from being contingent to low emissions as power systems move towards near full decarbonisation. The results show that in the NZE around half of investment over the next decade falls in the complex middle ground of spending (Figure 1.14).

The results highlight challenges for environmental, social and governance (ESG) regulation and sustainable finance taxonomies, as well as for companies in their corporate planning and decision making. The key challenge is how to ensure that adequate financial channels remain open to support these “contingent” and “transition” investments without this becoming a loophole for investments that are not aligned with the Paris Agreement, or that allow for greenwashing.

One of the most important ways for companies to send appropriate signals about investment in these categories is by setting credible (science-based) targets that include measures to reduce emissions, and to complement this by improving the quality and quantity of metrics, governance and key performance indicators that allow the financial community to assess their progress towards these targets. A number of companies around the world have set ambitious targets, but their potential impact remains uneven.

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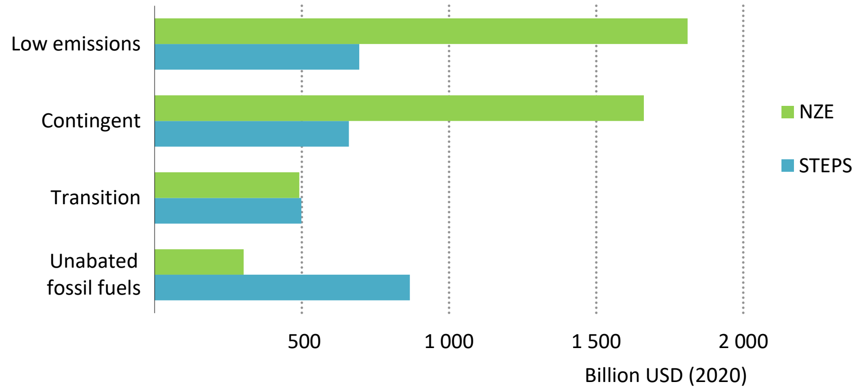
[10] Upstream fossil fuel investments are allocated according to how much of the energy produced is used within each category. For example, investment in a natural gas field is apportioned based on how much of the gas produced is used with CCUS (assigned to low emissions), used for coal-to-gas switching (assigned to transition), and used without providing any emissions reductions (assigned to unabated fossil fuels). In considering investment in fossil fuels, we assume that emissions from the production and processing of fossil fuels is minimised (as is the case in the NZE).

The Scope 1 and Scope 2 emissions reduction targets for the largest oil and gas, and industrial end-use companies account for less than 5% of the required emissions reductions in those sectors in the NZE by 2030.

It will also be important for the financial community to engage with emissions-intensive companies and countries to develop credible transition pathways and properly account for these contingent and transition investments in sustainable finance taxonomies. This should be accompanied by work to develop better and more consistent reporting and assessment standards and improved ways to translate climate performance data into investment.

Figure 1.14 ▷ Average annual energy investment by emissions reduction potential, 2022-30



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A large share of investment in sectors and assets that do not immediately deliver zero emissions energy nevertheless are critical for net zero emissions goals

1.6 People-centred transitions

The purpose of the transformation of the energy sector is to improve lives and livelihoods. Alongside the benefits of avoiding the worst of climate change, this means enabling citizens to seize the opportunities and navigate the disruptions caused by the shift to clean energy technologies. It means eradicating energy poverty: no system is sustainable if it continues to exclude large parts of the global population from access to modern energy.[11] And it means putting considerations of employment, equity, inclusion, affordability, access and sustainable economic development at the centre of the process.

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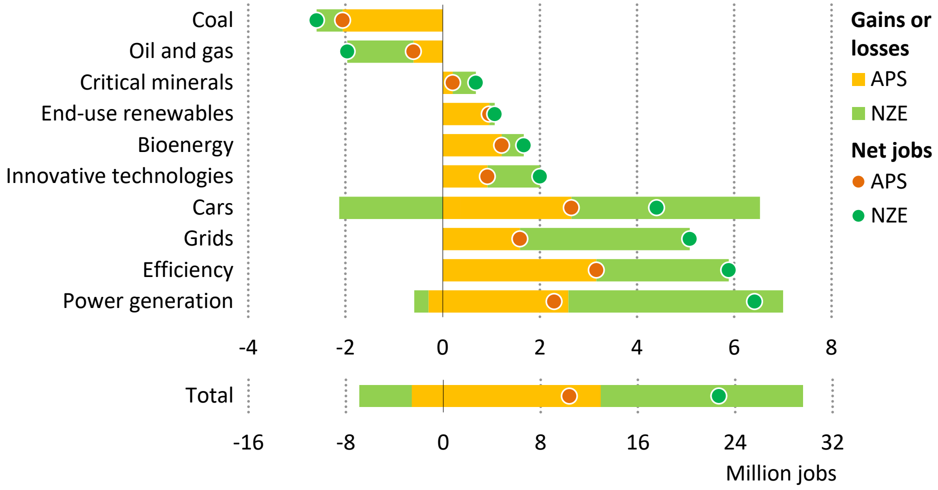
[11] This section draws on *WEO* modelling and analysis to illustrate themes that are also central to the work of the IEA's Global Commission on People-Centred Clean Energy Transitions: https://www.iea.org/programmes/our-inclusive-energy-future.

Employment in clean energy areas is set to become a very dynamic part of labour markets, with growth more than offsetting a decline in traditional fossil fuel supply sectors. As well as creating jobs in renewables and energy network industries, transitions increase employment in related sectors such as construction (retrofits and energy-efficient buildings) and manufacturing (efficient appliances and EVs). In total, we estimate that an additional 13 million workers are employed in clean energy and related sectors by 2030 in the APS, and this figure doubles in the NZE (Figure 1.15).

The transition also comes with dislocation: new jobs are not necessarily created in the same places where jobs are lost. Skill sets are not automatically transferable, and new skills are needed. This is true both within specific countries and internationally. Governments need to manage the impacts in a co-ordinated way, seeking transition pathways that maximise opportunities for decent, high quality work and for workers to make use of existing skills, and mobilising long-term support for workers and communities where jobs are lost.

Figure 1.15 ⊳ Employment growth in clean energy and related areas to 2030



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Clean energy job gains outpace losses in fossil fuels jobs in the APS and job growth in clean energy and related segments doubles in the NZE

Notes: Efficiency considers buildings and industry efficiency measures. Cars reflect job losses in manufacturing ICE-specific components, and job gains from producing electric and hybrid cars, as well as jobs created from increased car sales globally. Critical mineral job estimates assume highly mechanised mining practices, which modestly estimate job growth when compared to labour productivity in some developing regions today. Innovative technologies include batteries, hydrogen and CCUS.

Quantifying the employment effects of various transition pathways facilitates proper planning of support measures, including training and education programmes. Many countries have designed programmes that seek to use existing strengths in the oil and gas sector in emerging areas such as offshore wind, CCUS, geothermal and hydrogen: the United

Kingdom's North Sea Transition Deal is a case in point. Other countries, including South Africa, have instituted broad social dialogues on people-centred transitions, encompassing companies, trade unions, regional and local governments, civil society and the financial sector.

As transitions gain pace, there will be increased competition for clean energy supply chains and related jobs. Most clean energy jobs are created close to the location of a project, whether it is a wind farm or construction of energy-efficient housing. However, we estimate that a quarter of energy employment is tied to supply chains that may be located in other countries, particularly in the case of solar PV, wind, batteries, grid components and vehicle components. Some governments are looking to onshore these elements, or using economic recovery funding to make strategic investments in emerging segments such as CCUS, advanced battery technologies and low-carbon fuels. These industries, although nascent today, grow to employ nearly 1 million workers worldwide by 2030 in the APS. Favouring domestic manufacturing capacity could lead to more secure supply chains in some instances, as well as additional jobs. But, it could also drive up clean energy technology costs if it erects barriers to trade and reduces economies of scale.

Changes in the energy sector must support **social and economic development** and improve quality of life. A starting point is to bring modern energy to those that lack access. We estimate that providing universal access to electricity and clean cooking by 2030 would require investments of USD 43 billion per year, closing an important gap in the global energy system at a fraction of the overall cost of transitions. The affordability and security of energy supply are also vital considerations when it comes to quality of life.

The co-benefits of well-managed transitions include health and productivity gains. Over 90% of the world's population breathe polluted air on a daily basis, which we estimate leads to over 5 million premature deaths a year. Air pollution also leads to multiple serious diseases, placing an extra burden on healthcare systems currently struggling to deal with the Covid-19 pandemic. While the STEPS and the APS see a rising number of premature deaths during the next decade, the NZE leads to dramatic reductions: by 2030 there are 1.9 million fewer premature deaths from household air pollution per year than in 2020, with over 95% of the reduction occurring in emerging market and developing economies.

The average person spends the vast majority of their time indoors, which means that the way transition policies affect buildings is an important element of well-being. In the NZE, immediate action is taken to ensure that, by the end of this decade, all new buildings meet zero-carbon-ready standards and around one-in-five existing buildings are retrofitted to those standards. Shifting to zero-carbon-ready buildings improves thermal comfort through major upgrades to building envelopes, e.g. improved insulation, glazing, weatherproofing and optimised ventilation. Remaining heating and cooling needs are met by the most efficient equipment such as heat pumps, often facilitated by automated controls. Managed well, these improvements can foster good physical and mental health by creating indoor living environments with healthy air temperatures, humidity levels, noise levels and improved air quality (IEA, 2017). Energy efficiency retrofit programmes for low-income housing deliver the greatest benefits, while highly energy-efficient workplaces and schools have also demonstrated positive impacts on productivity.

Good policy design takes into account issues of **equity and inclusion** as well. There are many ways to address these issues. For example, action can take the form of recycling revenues from carbon pricing schemes to relieve distributional impacts; introducing initiatives to bring young generations into the energy and climate policy debate as they have an essential stake in the consequences of the course that is set; and finding better ways to assess the gender impacts of policy choices and to advance the participation of women in the energy sector.

Far-reaching energy transitions require **support and engagement across society.** A number of changes depend on broad social acceptance. In the NZE, at least half of emissions reductions over the next decade require some kind of consumer buy-in, e.g. a decision to switch to an EV or a heat pump. Around 4% of emissions reductions require behavioural changes, e.g. cycling rather than driving to work.

Box 1.4 ▷ Incorporating gender in energy transition policies

Despite compelling evidence of the social and economic benefits of equal opportunities and diversity in the labour force, many sectors of the global economy perform poorly in terms of gender balance; the energy sector is one of the worst. Women represent a small portion of the labour force and few are in senior positions. At a global level, women occupy only one-in-five jobs in the oil and gas sector and one-in-three jobs in the renewable energy sector (IRENA, 2019). In addition, according to data from almost 2 500 publicly listed energy firms, women make up just under 14% of senior managers (representation is strongest in utilities), compared with 16% in 30 000 non-energy firms (IEA, 2021c).

Transitions present an opportunity to mainstream policies and measures to address issues of gender equality in energy and related sectors. This will require tailored policy support, with solutions designed to take into account the specific dynamics of the various sectors and sub-sectors, and the channels through which gender equality can be improved as energy transitions progress.

The transport sector provides a good example of the opportunities. At present, there are large differences between the ways in which men and women use transport services. Research shows that mobility patterns of women are much more for care work and housekeeping than is the case for men. The average distances travelled also differ as do the number of trips and the time of day. In many countries, women have less access to private cars than men, and so represent a majority of public transport users (ITF, 2019). The exposure of women to different forms of gender-based violence, such as harassment on public transport, adds an additional layer of risk. Women sometimes have to take longer trips to ensure safety, especially at night, adding monthly costs that can amount to USD 25-50 (Kaufman et al., 2018). Plans to get more women engaged in the transport sector need to be designed with these differences in mind.

Positive examples include the City of Guadalajara in Mexico, which employed the results from a comprehensive survey on the transport patterns of women and girls over a large corridor and incorporated its findings into their policy planning (contrary to the traditional approach based on gender-blind origin-destination surveys). Many governments have also incorporated gender-related approaches in their government programmes or public procurement processes. These include demanding a minimum share of women in manufacturing or installation processes, or incorporating a gender assessment when evaluating bids. Effective policies across the energy sector require a much greater push to support the collection of disaggregated gender data, which is still relatively rare.

Societal support is about more than consumer buy-in and behavioural change, important though they are, and gaining broad public support for change involves some difficult trade-offs. For example, creating economic incentives for a shift towards heat pumps could make natural gas more expensive (and push up household heating bills in the interim). Similarly, introducing carbon prices to generate changes in energy consumption patterns could provoke a backlash from lower income and/or rural households, in the absence of effective ways to manage the distributional consequences. Acceptance of a changing energy sector is also critical for the siting and permitting of new infrastructure. Energy transitions do not mean an end to large infrastructure projects, successful transitions need them. Such projects do not only include technologies such as CCUS or nuclear, but also wind, solar and grid investments, all which can face opposition from local communities. Ways need to be found to engage those concerned and assuage their concerns. A clear and engaged social debate on the case for change is vital.

1.7 Phasing out coal

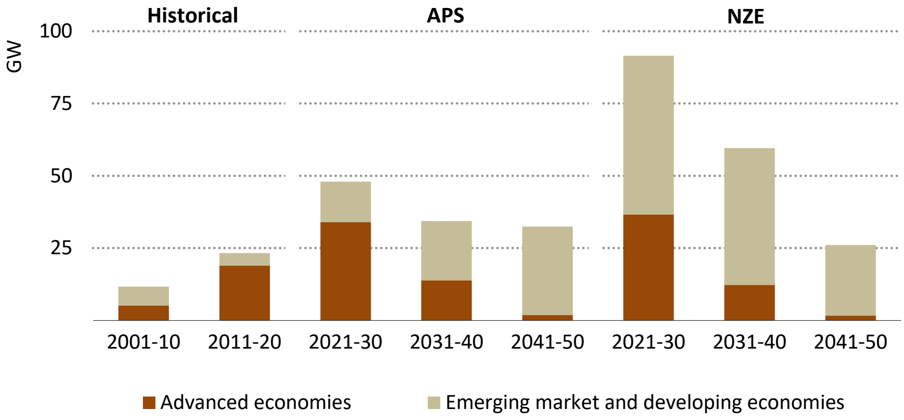
All scenarios that meet climate goals feature a rapid decline in coal use. It is the most carbon-intensive fuel, predominantly used in a sector – electricity generation – where renewable energy options are the most cost-effective new sources in most markets. Global unabated coal use in the energy system falls by around 5% to 2030 in the STEPS, by 10% in the APS, and by 55% in the NZE. However, managing the move away from coal is not simple, especially when it proceeds at the speed required in the NZE where all unabated coal power generation stops by 2040.

There are two aspects to the phase-out of coal in the power sector: halting the construction of new plants and managing the decline in emissions from existing assets. The first is the easier to achieve. There are no new investment decisions for the construction of coal-fired power in the NZE, but as much as 200 GW receive the go-ahead and are completed by 2030 in the APS, mainly in China, India and Southeast Asia, and over 215 GW are approved and built by 2030 in the STEPS, and more go ahead after 2030 in both scenarios. There is a powerful economic and environmental case for countries to proceed instead with low emissions sources of electricity, as well as pressure to do so from financial markets and major international players: all G7 countries have committed to ending new support for unabated coal-fired power and China has pledged to end support for building new coal plants abroad. China's announcement is potentially very significant: it could lead to the cancellation of up to 190 GW of coal projects that are built in the APS to 2050, saving about 20 Gt in cumulative emissions if they are replaced with low-emissions generation.

We estimate that an even larger amount of 350 GW of coal-fired capacity would not be needed in 2030 if policy makers establish the enabling conditions and all of the cost-effective deployment of low emissions sources of electricity is realised (see Chapter 3). This would effectively halt all new investment decisions in the APS and facilitate the retirement of an extra 150 GW of coal-fired capacity by 2030.

Delivering emissions reductions from the existing fleet of coal-fired plants is an even more crucial component of climate action, but a much trickier challenge for public policy. Given the dependence of a number of countries and regions on coal, the closure or repurposing of coal mines and power plants could have significant economic and social consequences. Coal-dependent regions are often highly specialised "mono-industry" areas, where the economy and the local identity are closely tied to the coal value chain. Managing closures appropriately and successfully depends on planning for the impacts on affected workers and communities, and on the repurposing and reclamation of affected land. This is likely to entail long-term engagement by many different parts of government, as well as local businesses.

Figure 1.16 ▷ Annual average coal power plant retirements in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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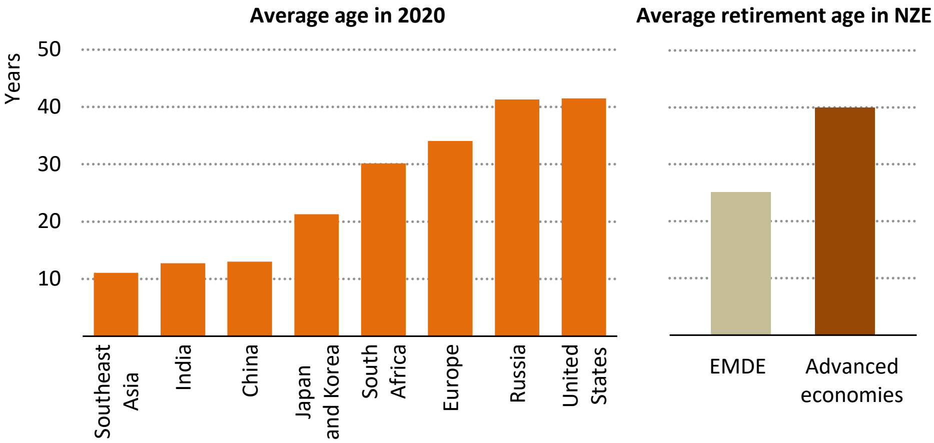
Coal power plant retirements increase fourfold over the next decade in the net zero pathway, notably in emerging market and developing economies

The NZE employs a three-pronged approach to tackle emissions cost-effectively while maintaining reliable electricity supply. In total, 2030 emissions from existing coal-fired power plants are three-quarters below the level in 2020, a reduction of over 7 Gt. Existing plants are either retrofitted with CCUS or co-fired with low emissions fuels such as biomass or ammonia; repurposed to focus on system adequacy or flexibility; or retired. The retrofit and repurpose options limit the impact on workers and local communities, but there is nonetheless a steep increase in plant retirements. Since 2010, coal power plant retirements have averaged around 25 GW each year, largely reflecting the closure of ageing plants in Europe and the United States (Figure 1.16). In the APS, annual closures more than double by 2030. Meeting the goals of the NZE requires annual retirements averaging over 90 GW over the next decade, removing around 40% of the existing coal power fleet by 2030.[12]

Figure 1.17 ▷ Average age of existing coal power plants in 2020 in selected regions and average age at retirement in the Net Zero Scenario



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Existing coal-fired power plants in emerging market and developing economies are relatively young, and in the NZE they retire when they are less than 25 years old

Note: EMDE = emerging market and developing economies.

While the priority is to phase out the oldest and least efficient plants, more than USD 1 trillion of capital has yet to be recovered in younger plants in the existing coal fleet (mostly in Asia, which accounts for two-thirds of global capacity). A rapid phase out risks creating stranded assets. Existing coal-fired power plants in emerging market and developing economies are relatively young: for example, plants in Asia are on average 13 years old (Figure 1.17). In the APS, coal-fired plants in these countries are retired on average when

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[12] In addition to the 480 GW of coal-fired capacity retired in the APS to 2030, we estimate that another 100 GW could be permanently closed without raising electricity bills for consumers.

they are 35 years old, and in the NZE they are retired when they are around 25 years old. In advanced economies, the average age of coal power plant fleet is already almost 35 years, and they are retired on average in eight years in the APS and in five years in the NZE.

Approaches to phase out coal around the world

Phasing out coal at the scale and speed needed in the NZE will require a comprehensive and sustained commitment by national and local governments and the international community to manage transitions for people, communities, assets, land and local environmental quality. Governments have an opportunity to initiate phase outs as part of a broad, coherent and ambitious climate strategy, but other factors – such as changing market fundamentals for coal and local air quality concerns – also provide strong impetus for change. As such, any use of public funds to compensate owners and secure early retirements on climate grounds needs to be carefully assessed so as to ensure that funding is focused on assets that are unlikely to be retired on their own.

In all cases, early planning and social dialogue with affected stakeholders is critical. The multiplicity of government actors involved in local economic development, energy and environmental management makes planning challenging, especially in emerging market and developing economies, and the establishment of special purpose entities might be necessary to pool various funding sources and manage disbursements on the ground. There is an important role for blended finance, along with carbon pricing, in accelerating the closure of coal power plants and increasing investment in clean energy. The early involvement of banks and other investors is critical to deal with potential external financial exposures. Managing social and environmental impacts calls for dedicated and long-term local focus and financing, especially in the most challenging instances where whole towns and communities have been heavily reliant on the coal industry for employment and income.

There is no single blueprint for managing the phase-out of coal-fired generation because a great deal inevitably depends on local circumstances and priorities. Transitions require a range of financial mechanisms that are tailored to coal plants of different types and age, as well as to the varied market structures within which they operate.

The 21 markets that have committed to phase out coal-fired power – nearly all are advanced economies in Europe – represent less than 5% of the global coal generation fleet, and only seven have domestic mining industries that supply coal for power generation. They tend to have well-developed financial systems and market structures characterised by high degrees of private participation. Advanced economies also tend to have slow electricity demand growth, which enables even modest increases in low emissions sources to displace coal. Their focus has been on system planning, tailored support, regulatory incentives and capital markets.

As part of its Just Transition Mechanism, the European Union has capitalised a fund with over USD 20 billion to support economic diversification and assist affected areas and workers. Germany designed a similar regional support programme offering compensation for losses faced by workers and companies, and also has a mechanism that provides tenders that compensate plant owners in exchange for retiring coal capacity.[13] In the United States, regulators have allowed accelerated depreciation schedules, backed by ratepayers, to support faster cost recovery for some assets; some utilities are now looking to refinance coal plants through asset-backed bond issuance and reinvest the proceeds in renewables. The development of sustainability-linked and transition finance instruments could open additional ways to fund emissions reductions through capital markets, leveraging the appetite of private investors for sustainability.

In emerging market and developing economies, where the bulk of existing coal assets are located, circumstances are often quite different. Rapid growth in low-carbon generation is required just to keep up with rising electricity demand, and this limits the scope to displace existing coal-fired power. Investment frameworks are often characterised by lower levels of financial development and higher levels of state ownership. Coal plants are often shielded from competition via long-term off-take agreements. In some markets there are concerns over the potential exposure of the banking system to stranded assets, which adds another layer of complexity.

There are fewer examples of targeted financial innovation in these economies. In China, 20 GW of coal power was retired over the past decade through administrative orders as authorities sought to improve local air quality and curb inefficient plants, but recent closures have been modest in scale. While China's reliance on state-owned generators complicates the political economy of transition, the lower cost of capital of these companies also creates an opportunity to manage the economic burden of closures. In India, where the presence of over 50 GW of financially stressed coal assets has created strains in the banking system, the government is exploring strategies to manage a transition to clean electricity which include the introduction of market-based economic dispatch and the accelerated closure of the least efficient plants.

Efforts to manage transitions from coal in other emerging market and developing economies are largely being facilitated by DFIs, which are designing targeted packages. For example, Chile has a phase-out strategy that is supported by blended finance. Chile established a phase-out schedule and introduced a carbon tax together with a carbon price floor, supported by a concessional loan from the Inter-American Development Bank; this was instrumental in bringing about the early retirement of two coal-fired units.

International efforts are focusing on ways to separate out coal assets into new financing and ownership structures, while creating economic opportunities for workers and communities. The Asian Development Bank is carrying out a feasibility study with potential host countries in Southeast Asia (initially Indonesia, Philippines and Viet Nam) on the Energy Transition

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[13] Over the course of three auctions, regulators awarded around USD 700 million for the closure of more than 8 GW of hard coal and small lignite capacity in Germany by 2022 (based on publicly available data for the first and third auctions, and on an IEA estimate for the second). The tender mechanism targets hard coal and small lignite power plants. Another mechanism to provide direct compensation for the early closure of lignite-fired power plants currently is subject to a state aid review by the European Commission.

Mechanism, a platform to accelerate the retirement of coal power using blended finance and to support investment in renewables, all in an equitable, scalable and market-based manner. The World Bank is supporting long-term transitions for coal regions through institutional governance reforms, assistance to communities and repurposing of land and assets. The Climate Investment Fund's Accelerating Coal Transition programme aims to support the closure and repurposing of coal plants through blended finance of USD 2.5 billion for each target country, including USD 300 million for regional economic development and retraining.

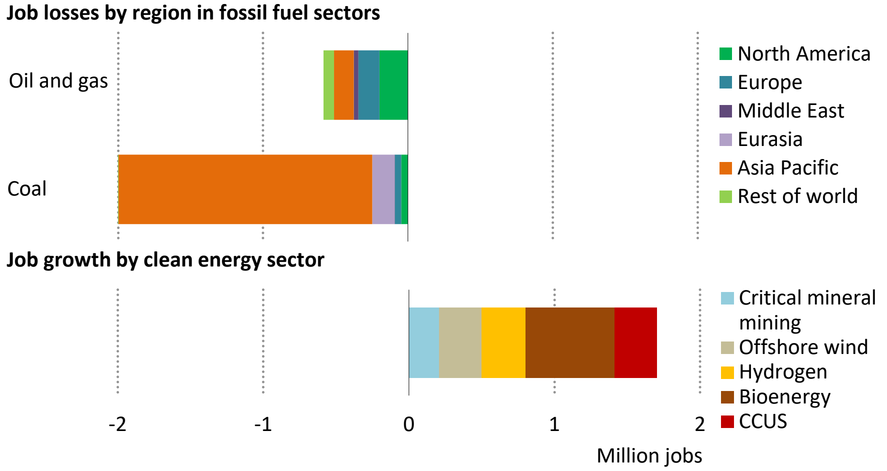
Efforts of this kind will play a particularly vital role in supporting transitions in markets where a strong relationship exists between the energy sector and the government or in those with challenging political economies. In South Africa, for example, domestic and international stakeholders are considering a multi-faceted strategic and financial approach to help Eskom, the state-owned utility, to shift to renewables, reduce its debt load and ensure a just transition for coal miners and plant workers. In Indonesia, PLN, the state-owned utility, has announced it that it aims to retire all (50 GW) coal plants by 2055.

Box 1.5 ▷ Pledges signal a further decline in global coal employment

The APS does not mark the end of coal-fired power generation, but it has clear implications for coal-related employment. Direct coal-related jobs are set to continue the declines seen over the past decade, driven by environmental and demand pressure, especially in advanced economies, as well as by increased productivity, particularly in Asia. By 2030, 30% fewer people work in coal than in 2019, one-third of those declines are associated with productivity gains in coal mining. The drop is most notable in China, although this is mainly the result of continued restructuring in the industry rather than lower demand (Figure 1.18). Coal employment in India, which has the second-largest number of coal workers worldwide, could be bolstered by the policy ambition to increase domestic output, but there are major uncertainties over domestic demand, especially if policies tighten.

Although in aggregate energy transitions create substantial job growth, there is little scope to replace jobs lost in traditional sectors on a one-to-one basis with opportunities in clean energy. Rising demand for critical minerals offers some transfer of employment in the mining sector, but these opportunities are not always located in the same area as coal supply. Miners working at fully modernised mines have skills that could be readily transferred, but over 90% of coal workers are in emerging market and developing economies, and are often unskilled. Most of the scope to re-deploy existing workers to new clean energy projects in practice is in the oil and gas sector. Coal employment is only a small portion of total employment in most countries (less than 0.5% in China and less than 0.1% in India), but it accounts for a high percentage of total earnings and tax revenues in many communities. There is a particular need to help workers and communities where coal plant closures are likely to have cascading effects on communities and supporting businesses.

Figure 1.18 ▷ Changes in fossil fuel employment and energy areas with overlapping skills in the Announced Pledges Scenario to 2030



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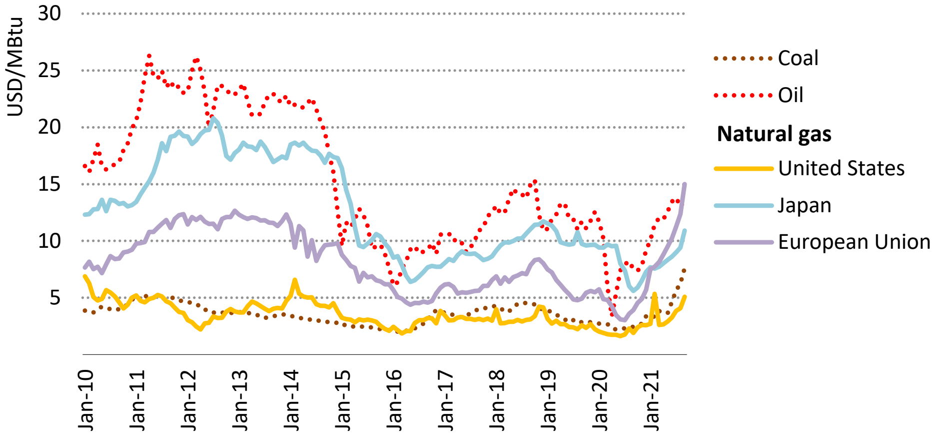
Skilled fossil fuel workers have opportunities to transition to clean energy jobs, though the options are not a direct match for most coal sector jobs lost in Asia

1.8 Prices and affordability

The economic recovery in 2021 has tightened commodity markets and put upward pressure on prices across the board. Crude oil prices whipsawed from USD 20/barrel in the immediate aftermath of the pandemic in mid-2020 to around USD 70/barrel in mid-2021. Spot natural gas prices have been on a relentless upward march around the world, and they reached their highest ever levels in Europe during the second-half of 2021 (more than ten-times the record lows reached in June 2020). Coal prices in 2021 have also seen strong growth on the back of a rebound in demand, especially in Asia (Figure 1.19). High natural gas and coal prices have fed through to higher power prices in many markets, particularly where output from renewables has been relatively low.

Prices for key critical materials, such as lithium and copper, have rebounded strongly and are near or above the highest levels observed in the past decade. This rise in prices may reflect not just the economic recovery but also the commodity market's rising expectation of the widespread use of these critical minerals in clean energy transitions. All else being equal, we estimate that, if current spot prices for key critical minerals were maintained, they would increase clean energy investment costs in the STEPS by over USD 400 billion, and by USD 700 billion in the NZE, by 2030.

Figure 1.19 ▷ Oil, natural gas and coal prices by region, 2010-2021



Gas and coal prices dipped significantly during the pandemic, but have recently risen sharply

Notes: USD/MBtu = US dollar per million British thermal units. Gas prices for the European Union and Japan are weighted average import costs. The United States gas price reflects the wholesale price on the domestic market. Coal prices are an average of steam coal import prices in the European Union and Japan and domestic sales and imports in coastal China.

High prices are a signal that supply is struggling to meet demand. In recent years, investment in oil and gas supply has often appeared to be geared towards a world of stagnant or even falling demand, while purchases of internal combustion engine (ICE) vehicles and expansion of natural gas infrastructure point the other way: towards ever increasing oil and gas consumption. The Covid-19 pandemic, which led to a near-record low in new oil and gas investment in 2020, intensified this trend.

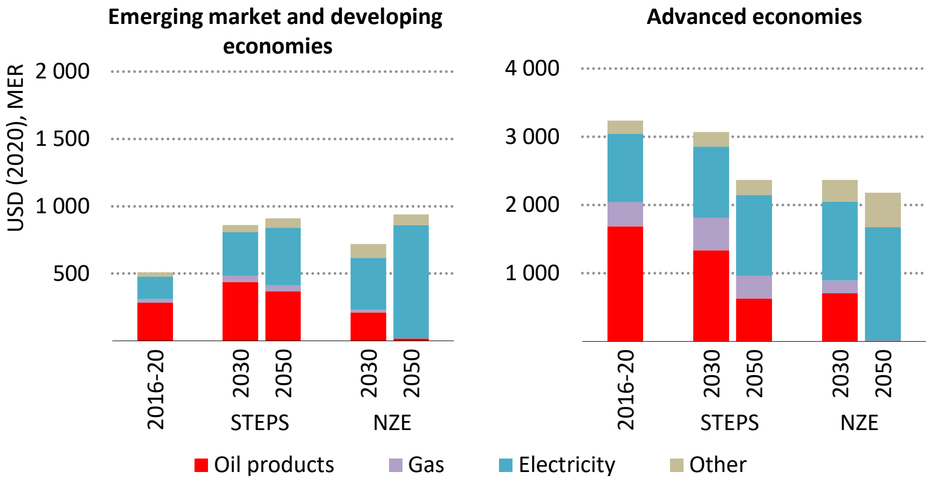
Uncertainty about future levels of demand is reflected in our scenarios. In the STEPS, rising oil and gas demand leads to price levels that incentivise investment in new supply. In the NZE, on the other hand, a rapid drop in oil and gas consumption means that there are no new investments in supply projects beyond those already announced or under construction: prices are set by the operating costs of the marginal project required to meet demand, and this results in significantly lower fossil fuel prices than in recent years. Navigating the uncertainty between these two outlooks will not be easy, and volatility and price shocks cannot be discounted during the transition (see section 1.9).

The effect of high fossil fuel prices on clean energy transitions is not clear cut. High prices narrow the competitiveness gap with lower carbon fuels and technologies such as renewables or bioenergy. They ought to incentivise producers to take action such as reducing methane leaks or gas flaring, and consumers to improve energy efficiency or moderate consumption. But they also send strong signals to invest in new supplies, which would lock in new sources of emissions if companies and investors act on them. Higher cost sources of oil and gas often have a higher level of emissions, and this could exacerbate additional lock in. Rising energy bills for households or industries might also put pressure on governments to raise fossil fuel subsidies, reduce clean energy levies or dilute planned support packages for low-carbon technologies. Equally, it might make them more determined to push ahead as rapidly as possible with efforts move away from fossil fuels. Relative changes in the price of coal, gas and oil could also lead to fuel substitution effects, for example if high natural gas prices were to encourage a switch to coal or fuel oil, or the other way around.

Affordability

The extent to which commodity prices feed through to household and other energy bills is determined by policy and market design, as well as by whatever taxes, subsidies, capital costs and environmental surcharges are reflected in the final bill. In an ideal world, energy bills would be based on cost-reflective energy prices and would encourage efficient and sustainable choices, but without harming low income households or choking off economic activity.

Figure 1.20 ⊳ Average household energy bills by fuel in the Stated Policies and Net Zero Emissions by 2050 scenarios



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Targeted support, efficiency improvements and lower use of oil can help ensure energy affordability during transitions, which is especially important for the developing world

Notes: MER = market exchange rate. Spending related to additional upfront investment is not included in energy bills.

In the STEPS, average household energy bills in advanced economies decline from an average of around USD 3 200 over the last five years to USD 2 400 per household in 2050 (Figure 1.20). In emerging market and developing economies they rise by 80% over this period – more than the growth in average disposable income – as a result of the rapid growth in appliance and vehicle ownership which occurs in parallel with rising electricity, gas and oil prices. Energy efficiency improvements, electrification and switching to low-carbon sources could all help to make energy more affordable. However, they often require upfront investment and, even though such costs are offset over time by energy bill savings, access to finance remains an important hurdle to overcome, especially for low income households. Targeted subsidies for low-carbon energy, particularly electricity, may be necessary to lessen the burden of price increases on low income families as energy systems move towards net zero emissions.

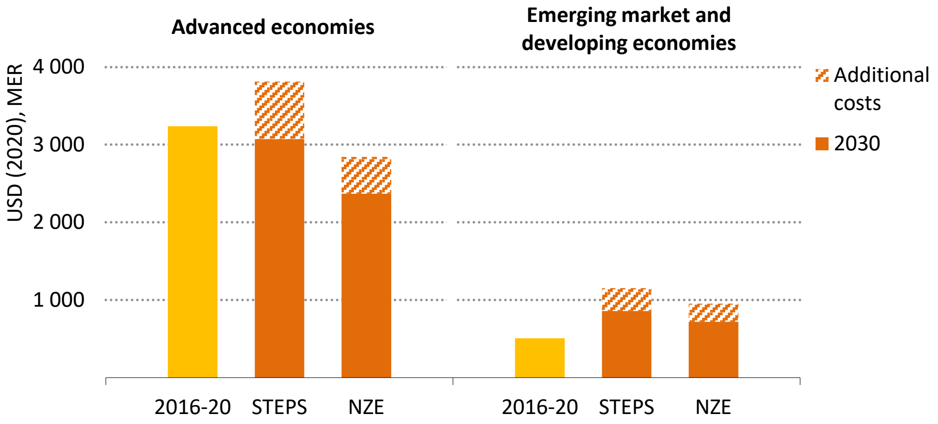
The share of electricity in household energy bills rises in all scenarios. In the NZE, electricity accounts for 90% of household bills in emerging market and developing economies and close to 80% in advanced economies by 2050, compared to a global average of around 30% in 2020.

In advanced economies, household electricity bills in 2050 are higher in the NZE than in the STEPS, however overall energy bills are on average nearly 10% lower because of efficiency gains and because households no longer need to pay for natural gas for heating and oil for cars. In emerging market and developing economies, higher electricity bills are offset for the same reasons, and so the total household energy bill is lower in the NZE than in the STEPS in 2030, and ends up broadly the same in the two scenarios by 2050. This outcome depends strongly on efficiency improvements; without additional improvements relative to the STEPS, average household energy bills globally in the NZE in 2050 would be a third higher.

As events in 2021 show, consumers are vulnerable when prices rise sharply. We have tested this by modelling the impact of a fossil fuel price shock in 2030 on household energy bills in the STEPS and NZE, taking the highest oil, natural gas and coal prices reached in each region over the period from 2010 to 2020 (Figure 1.21). We find that:

- In the STEPS, households in advanced economies would pay 25% extra for their energy, or an additional USD 750, in this sensitivity case. In emerging market and developing economies, households would pay 35% more, primarily because gas, coal and oil make up a larger share of total household energy use in 2030 than in advanced economies. On average across all countries, the price shock raises household electricity bills by 10% in 2030, while the cost of gas-based heating doubles and that of oil-based transport rises by 45%.
- In the NZE, the additional cost to households in advanced economies is USD 470, nearly 40% less than in the STEPS, and in emerging market and developing economies it is 20% less than in the STEPS. The impact of higher commodity prices is dampened by more rapid efficiency gains, by reduced direct use of oil and gas, and by electricity having a higher share in total household energy expenditure (electricity is less affected by the price shock than oil and gas because of the rising role of renewables). In advanced economies, the price shock still leaves total costs to consumers in the NZE below the level of costs in the STEPS without a price shock.

Figure 1.21 ⊳ Impact of a commodity price shock on average household energy bills in 2030 by scenario



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Applying the highest oil, gas and coal prices of the last decade in 2030 raises household energy bills more in the STEPS than in the NZE, and from a higher price base

Notes: MER = market exchange rate. Spending related to additional upfront investment is not included in energy bills.

The reduced exposure to commodity price changes in the NZE is also due to a more capital-intensive energy system, in which the fixed charges for recovering investment in infrastructure become more important drivers of energy bills in the long run. This is especially true for the power sector, which in the NZE becomes dominated by renewables with zero marginal cost, but nonetheless requires a ramp up in grid and battery investments to almost USD 1 trillion by 2050, a more than threefold increase on current levels. The cost of developing critical minerals also becomes more important in setting energy prices in such a capital-intensive world, but these have a less immediate effect on end-user bills than oil, gas or coal prices. Since much of the additional investment in the NZE occurs in end-use sectors themselves, the cost of capital to consumers also forms a crucial part of the energy affordability equation.

Volatile electricity prices cannot be discounted during the transition, however. Fuel costs can still play an outsized role in price formation even though their contribution to overall electricity supply shrink, as in many markets where marginal cost pricing determines wholesale prices based on a merit order where natural gas or coal plants are dispatched according to their short-run costs of generation. Moreover, the weather-dependent nature of electricity supply (from wind and solar) and demand (from air conditioning or heat pumps) can cause significant price volatility, which can contribute to lower or higher consumer bills. Wholesale price volatility is reduced in the NZE by a broad suite of short- and long-duration sources of flexibility (via batteries, hydropower, low emissions thermal generation sources, interconnected grids and demand-side response). Their uptake relies on updated market frameworks to reflect the value of all grid services provided.

In all countries, governments, as far as possible, will want to anticipate and counteract the potential drivers of significant price increases. It will be particularly important to ensure that energy services remain accessible and affordable for all households. Possible actions in support of this include facilitating improvements in energy efficiency and incentivising fuel switching to renewables or electricity, especially for the least well-off households.

1.9 Energy security and the risk of disorderly change

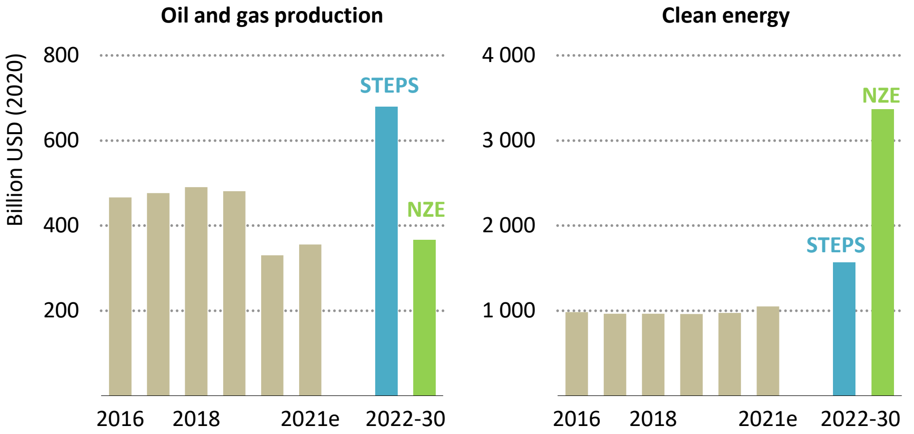
By design, the scenarios in this *Outlook* describe smooth, orderly processes of change. In practice, however, energy transitions can be volatile and disjointed affairs, characterised by competing interests and stop-go policies. As the world makes its much-needed way towards net zero emissions, there is an ever-present risk of mismatches between energy supply and demand as a result of a lack of appropriate investment signals, insufficient technological progress, poorly designed policies or bottlenecks arising from a lack of infrastructure. In the APS, countries undertake clean energy transitions at different speeds, raising the risk of tensions in global trade and constraints on technology transfer. In the NZE, potential new hazards could arise alongside the rise of clean energy.

Investment mismatches

Energy transitions bring about a major shift in the primary energy mix away from carbon-intensive fuels towards low-carbon energy sources. Although the share of fossil fuels in the mix has remained at around 80% over several decades, it declines to around 50% by 2050 in the APS and collapses to just over 20% in the NZE. Lower demand for fossil fuels, and in particular for oil and natural gas, ultimately reduces some traditional energy security hazards, but it cannot be taken for granted that the journey will be a smooth one. Our projections highlight the huge uncertainty over the trajectory for future demand. If there are no further changes in today's policy settings, as in the STEPS, oil demand in 2050 remains above 100 mb/d. By contrast, if the world single-mindedly pursues a 1.5 °C stabilisation objective, then oil demand falls to 24 mb/d in the same year. The comparable range for natural gas is between 5 100 bcm in the STEPS and 1 750 bcm in the NZE.

These variations come with dramatically different implications for investment (Figure 1.22). The declines in oil and gas demand in the NZE are sufficiently steep that no new field developments are required: continued spending to maintain production from existing assets, and reduce the associated emissions, amounts to an annual average of USD 210 billion between 2020 and 2050 in the NZE. In the STEPS, on the other hand, the annual amount required for investment is around USD 680 billion, well above current levels. If companies and investors misread demand trends amid uncertainty about the future, there is a risk of either market tightening or of over investment leading to underutilised and stranded assets.

Figure 1.22 ▹ Investment in oil and gas production and clean energy in the Stated Policies and Net Zero Emissions by 2050 scenarios



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Currently, investment in oil and gas production is closer to the NZE than the STEPS, even while today's spending on clean energy is well below levels reached in both scenarios

Notes: 2021e = estimated values for 2021. See Annex C for definition of clean energy.

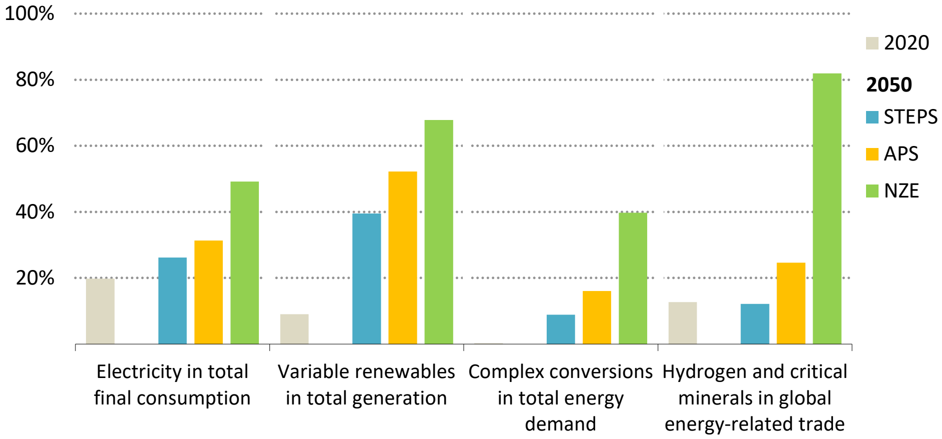
The fact that no new oil and natural gas fields are required in the NZE does not mean that limiting investment in new fields will lead to the energy transition outcomes in this scenario. If demand remains at higher levels, this would result in tight supply in the years ahead, raising the risks of higher and more volatile prices. It is not clear that higher prices would trigger supply responses to the same extent as in the past. A strong policy push to reduce oil and gas demand in line with the trajectory envisaged in the NZE therefore is key to achieving deep reductions in emissions and minimising the risk of market tightening.

Market design and infrastructure in increasingly integrated systems

Many of the new energy security challenges in a decarbonising world arise in the power sector as societies come to depend more on electricity for their energy needs. Across all scenarios the share of variable renewables in electricity generation rises to reach 40-70% by 2050 (and even more in some regions), far above the global average of just under 10% today (Figure 1.23). Wind and solar PV generation varies with the weather as well as with the time of day and year, and this can cause sudden changes to generation patterns on a daily or weekly basis. A large share of seasonal energy demand is also transferred onto the power system through the increasing use of electric heating and cooling equipment. Electricity storage, demand-side response and dispatchable low emissions sources of power are essential to meet flexibility requirements in clean energy transitions.

Managing imbalances between supply and demand, especially over longer timeframes, without resorting to emissions-intensive fuels requires a fundamental transformation of how energy systems operate. Today's energy sector is in essence a series of interlinked but largely independent delivery channels for fuels, heat and electricity to consumers. The energy system of the future consists of a much more complex web of interactions between solid, liquid and gaseous fuels, and electricity. In the NZE by 2050, around 40% of primary energy is converted at least twice before reaching end-users. Energy travels through batteries and electrolysers, undergoes conversions from electricity to heat or fuels, and back again. Such conversion processes are essential to provide the system flexibility needed to match the supply of variable renewables and demand for electricity at least cost. The need for such flexibility in the NZE is considerable: utility-scale battery storage increases from less than 20 GW in 2020 to over 3 000 GW by 2050, and there are millions of behind-the-meter enablers of flexibility, in the form of smart meters, EVs and charging infrastructure.

Figure 1.23 ▷ Key indicators of energy system change by scenario



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New energy security challenges arise in systems increasingly reliant on electricity, low-carbon technologies, higher levels of supply variability and more complex conversions

Note: Complex conversions are a primary energy source that has undergone two or more conversions before being delivered to end-users. It includes roundtrip battery storage.

A more complex energy system, with electrification at its core, raises important questions about the future of natural gas infrastructure, which in many parts of the world plays an important role in meeting seasonal demand for heating as well as short-term peaks in power generation. Current underground gas storage facilities have a capacity of 420 bcm per year – equivalent to more than half of the world's residential space heating demand. This buffer for households relying on gas for heating is not easily replicated by the electricity system. Gas power plants are also a mainstay of today's electricity security because of their ability to flexibly ramp up and down in response to changes in variable renewable output or peaks in demand. In the APS, even though generation on an annual basis declines in the United States and the European Union, the peak of generation from gas-fired power plants in those regions is 10-15% higher in 2030 than in 2020. This underscores the need for market designs that recognise the flexibility value of existing infrastructure even as the focus turns to developing innovative options that can replicate the services that natural gas provides (including low-carbon hydrogen).

Ultimately, secure transitions require careful sequencing to ensure that change in one area is complemented by change elsewhere. A reduction in oil and gas investment requires a surge in capital spending on low emissions fuels and technologies. Bans or limitations on the use of gas boilers or ICE vehicles only work if there are low-carbon alternatives that can deliver the same energy services, ideally at a similar or lower cost to consumers. Minimising the contribution of unabated coal and gas power plants to electricity supply requires lower carbon sources of flexibility in their place. These changes bring opportunities to make use of parts of today's fuel supply system in new ways: for example, there is scope for the supply, transport and storage of hydrogen to piggyback on existing gas pipelines and storage. The key point is that policy makers need to understand not just the value of energy, but also the value of the system's overall capacity to provide it when needed.

The world's energy infrastructure faces increasing physical risks from a changing climate. We estimate that around a quarter of the world's electricity networks face a high risk of destructive cyclone winds, while over 10% of dispatchable generation fleets and coastal refineries are prone to severe coastal flooding and a third of freshwater-cooled thermal power plants are located in high water stress areas. These risks are set to increase over time, highlighting the urgent need to enhance the resilience of energy systems to climate change.

Shifting geopolitics of energy security

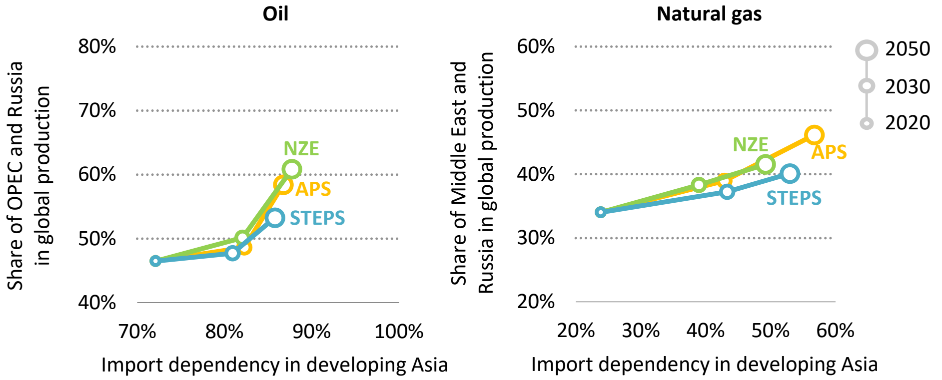
Clean energy transitions are set to bring about a major change in the energy trade patterns that have long been dominated by fossil fuels. The rising importance of critical minerals and low-carbon hydrogen means that their combined share in global energy-related trade doubles to 25% by 2050 in the APS. In the NZE, the share rises further to 80% by 2050 as the value of fossil fuels trade plunges, completely overturning the current dynamics of international energy-related trade.

Energy geopolitics are typically associated with oil and gas. However, clean energy technologies are not immune from geopolitical hazards. The production and trade of critical minerals provide a case in point. Overall mineral requirements for clean energy technologies almost triple between today and 2050 in the STEPS, and up to sixfold in the NZE. However, today's supply and investment plans point to a risk of supply lagging behind projected demand in the NZE. Higher or more volatile prices for critical minerals could make global progress towards a clean energy future slower or more costly. Recent price rallies for critical minerals illustrate the point: all other things being equal, they could make solar panels, wind turbines, EV batteries and grid lines 5-15% more expensive, with ripple effects on the costs of transitions.

The challenges are compounded by a lack of geographical diversity in critical mineral extraction and processing operations. In many cases, the supply of critical minerals is concentrated in a smaller number of countries than is the case for oil and natural gas. This is inevitably a source of concern because it means that supply chains for solar panels, wind turbines and batteries using imported materials could quickly be affected by regulatory changes, trade restrictions or even political instability in a small number of countries. Early attention from policy makers is required to develop a comprehensive approach to mineral security that encompasses measures to scale up investment and promote technology innovation together with a strong focus on recycling, supply chain resilience and sustainability.

The NZE also sees the emergence of inter-regional hydrogen trade (including trade in hydrogen-based fuels such as ammonia), with regions that possess abundant low cost production potential exporting to those with more limited production options. Hydrogen trade grows to around USD 100 billion by 2050 in the APS, higher than the value of current international coal trade, and to USD 300 billion in the NZE. However, there is a question mark over how infrastructure and market norms will develop as demand increases. Hazards could arise from a lack of co-ordination between potential exporters and importers or bottlenecks in infrastructure and equipment manufacturing capacity. Careful co-ordination and dialogue will be essential to bring forward new supply chains in a timely way.

Figure 1.24 ⊳ Import dependency in developing economies in Asia and the level of supply concentration for oil and natural gas by scenario



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Hydrocarbon import dependency in developing economies in Asia rises in all scenarios, while production concentrates in a small number of countries

While new dimensions of energy geopolitics arise, the traditional significance of trade in hydrocarbons does not vanish. Oil and gas supplies in the APS and NZE become increasingly concentrated in a small number of low cost producers. The share of Organization of the Petroleum Exporting Countries (OPEC) members and the Russian Federation (hereafter Russia) in global oil production rises considerably from 47% today to 61% in 2050 in the NZE. Many of the producer economies poised to take a larger share in future supply nevertheless face the prospect of significantly falling hydrocarbon income as overall demand falls. For the moment, these producers remain poorly prepared for transitions, with limited progress on economic and energy diversification, raising the possibility of a bumpy and volatile ride. Meanwhile, import dependency on fossil fuels in developing economies in Asia remains high in all scenarios (Figure 1.24), leading to further concentration of trade flows between the Middle East and Asia. This suggests that Asian importers will continue to be exposed to risks arising from physical or geopolitical events in the Middle East or accidents near trade chokepoints, underscoring the need for vigilance on the security of supply even in a world with contracting fossil fuel demand.

1.10 Fuels: old and new

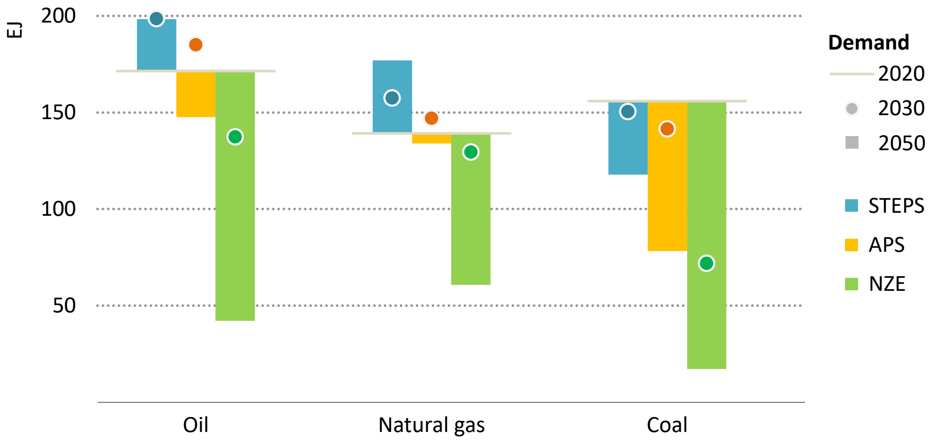
Clean electrification is a central element in all scenarios in this *Outlook*, but it is not possible to electrify everything. Even in the NZE, electricity comprises less than 50% of total final energy consumption in 2050: in the APS and the STEPS the comparable figures are 31% and 26%. Liquid, gaseous and solid fuels of various types will continue to make a major contribution to the global energy mix through to 2050.

Oil demand, for the first time, shows an eventual decline in all scenarios in this *Outlook*, although the timing and sharpness of the drop vary widely. In the STEPS, demand levels off at 104 mb/d in the mid-2030s and then declines very slightly to 2050. Oil use in road transport increases by around 6 mb/d through to 2030, with a particularly sharp rise in 2021, and it increases by close to 8 mb/d in aviation, shipping and petrochemicals. In the APS, global oil demand peaks soon after 2025 at 97 mb/d and declines to 77 mb/d in 2050. Oil use falls by around 4 mb/d in countries with net zero pledges between 2020 and 2030, but that is offset by an 8 mb/d increase in the rest of the world. In the NZE, oil demand falls to 72 mb/d in 2030 and to 24 mb/d by 2050. By 2030, 60% of all passenger cars sold globally are electric, and no new ICE passenger cars are sold anywhere after 2035. Oil use as a petrochemical feedstock is the only area to see an increase in demand; in 2050, 55% of all oil consumed globally is for petrochemicals.

Natural gas demand increases in all scenarios over the next five years, with sharp divergences afterwards. Many factors affect to what extent, and for how long, natural gas can retain a place in the energy mix when clean energy transitions accelerate, and the outlook is far from uniform across different countries and regions. In the STEPS, natural gas demand grows to around 4 500 bcm in 2030 (15% higher than in 2020) and to 5 100 bcm in 2050. Use in industry and in the power sector increases to 2050, and natural gas remains the default option for space heating. In the APS, demand reaches its maximum level soon after 2025 and then declines to 3 850 bcm in 2050: countries with net zero pledges move away from the use of gas in buildings, and see a near 25% decrease in consumption in the power sector to 2030. In the NZE, demand drops sharply from 2025 onwards and falls to 1 750 bcm in 2050. By 2050, more than 50% of natural gas consumed is used to produce low-carbon hydrogen, and 70% of gas use is in facilities equipped with CCUS.

Coal faces structural decline in all scenarios (Figure 1.25). In the STEPS, global coal demand rises slightly to 2025 and then starts a slow decline to 2050 when it is around 25% lower than in 2020. Between 2025 and 2030, total coal demand in China starts to fall and there are large reductions in coal use in advanced economies, mainly as a result of lower demand in the power sector. In the APS, global coal demand in 2030 is only 6% lower than in the STEPS because more than 80% of coal demand today comes from countries that do not have net zero pledges or aim only to reduce emissions after 2030. But it declines rapidly after 2030, notably in China, and global demand in 2050 is only half what it was in 2020. In the NZE, global coal demand drops by 55% to 2030 and by 90% to 2050; in 2050, 80% of the small remaining amount of coal still being used is equipped with CCUS.

Figure 1.25 ▷ Fossil fuel use by scenario



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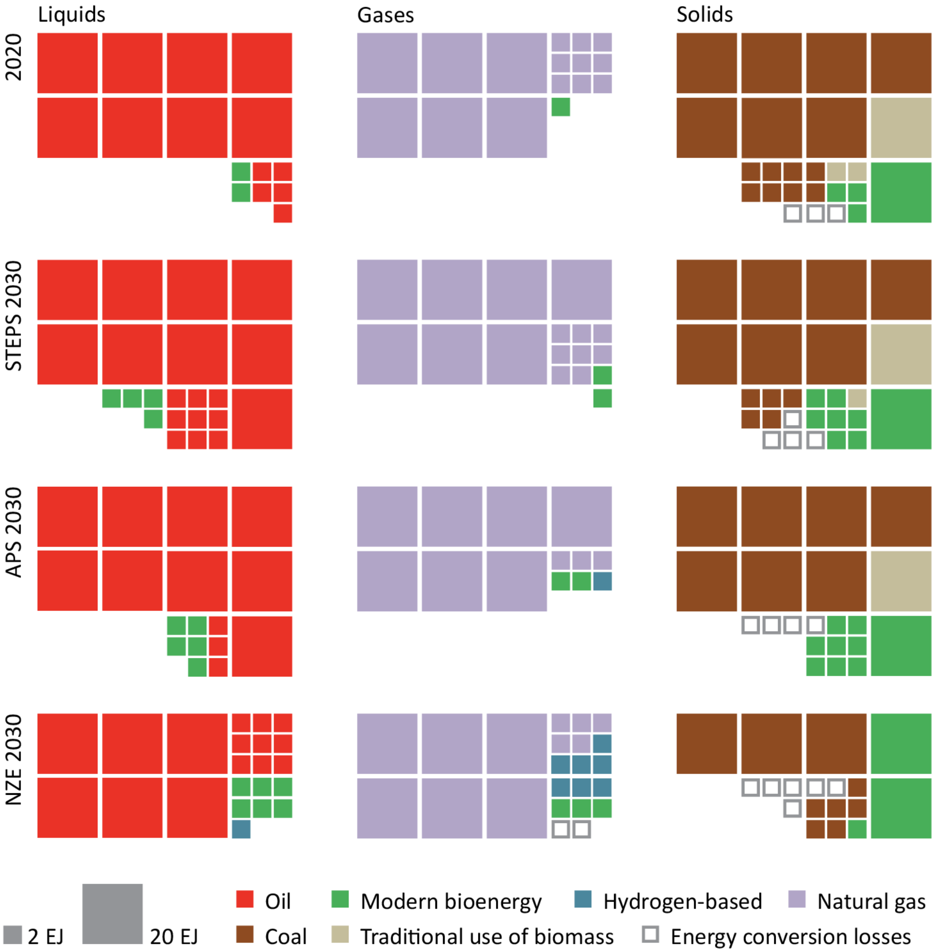
Oil demand peaks in each scenario, but the level and timing vary; natural gas increases to 2025 with sharp divergences thereafter; coal falls in all scenarios

Note: 1 EJ is around 0.5 mb/d of oil, 29 bcm of natural gas or 34 Mtce of coal.

In the STEPS, the increase in oil demand means oil prices rise to around USD 77 per barrel in 2030. Tight oil operators in the United States choose to prioritise returns over production growth, and tight oil satisfies much less of the increase in global oil demand than in the past. OPEC production increases by around 6 mb/d to 2030, and Russian production is maintained: OPEC and Russia together provide 48% of total oil supply in 2030, an increase from 2020 but well below their share during much of the last decade. Internationally traded volumes of natural gas expand by over 240 bcm between 2020 and 2030. Australia remains the largest exporter of coal although exports fall by around 5% to 2030.

In the APS, producer countries with net zero pledges pursue efforts to minimise emissions from oil and gas operations. This increases their production costs relative to other producers as well as their financing costs, but some remain competitive and are able to increase exports of oil and gas when domestic demand declines faster than supply: for example, in 2030 the United States exports 3.5 mb/d of oil and 200 bcm of natural gas in the APS (compared with 2.5 mb/d of oil and 220 bcm of natural gas in the STEPS). This puts downward pressure on prices, and limits export opportunities for a number of new and emerging producers. OPEC and Russia together provide 48% of total oil supply in 2030. Internationally traded natural gas volumes grow by 160 bcm between 2020 and 2030, while the drop in coal demand in countries with net zero pledges mean that coal exports fall from all producers.

Figure 1.26 ▹ The rising share of low emissions fuels in the energy mix



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All low emissions fuels make progress to 2030, but announced pledges are not enough to close the gap with the NZE or to provide the springboard needed for their post-2030 growth

Note: Energy conversion losses = fuel consumed in the transformation process to produce other liquid, gaseous or solid fuels for final consumption.

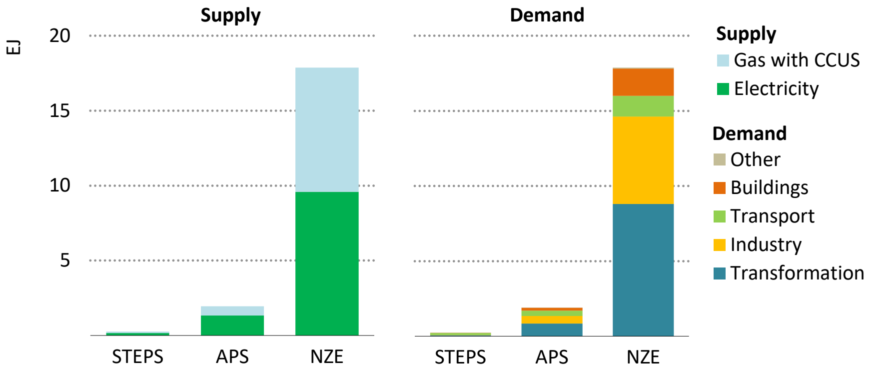
Minimising methane leaks and flaring should be a top priority in the quest to reduce emissions from fossil fuel operations. On average, we estimate that 8% of natural gas and natural gas liquids entering flares are not combusted and leak into the atmosphere. This is more than double previous estimates, and suggests that flaring resulted in more than 500 Mt CO_2-eq GHG emissions in 2020, which is more than the annual CO_2 emissions from all cars in the European Union.

There is a growing role for alternative, low emissions fuels such as modern bioenergy and hydrogen-based fuels in all scenarios (Figure 1.26). These play a key role in the achievement of net zero targets, especially in sectors where direct electrification is most challenging. Policy support for these low emissions fuels varies significantly among countries, with most recent attention paid to low-carbon carbon hydrogen (Box 1.6), but the use of modern bioenergy also grows substantially. Just under 2 mb/d of biofuels were used in 2020, but volumes double to 2030 in the STEPS, increase by two-and-half times in the APS and triple in the NZE. The use of modern forms of solid bioenergy increases by 30-70% across the scenarios to 2030. In the NZE, biogas provides clean cooking access for 400 million people in 2030, and total biogases demand rises to 5.5 EJ.

Box 1.6 ⊳ Is there a pot of hydrogen at the end of the rainbow?

Today, 17 governments have published low-carbon hydrogen strategies and more than 20 countries are developing them. These strategies mainly focus on targets for hydrogen supply, although attention is increasingly being paid to the policies needed to stimulate demand both for low-carbon hydrogen and hydrogen-based liquids, including ammonia, methanol and other synthetic liquid hydrocarbons with a very low emissions intensity.

Figure 1.27 ⊳ Low-carbon hydrogen and hydrogen-based fuel demand and supply by scenario in 2030



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Hydrogen demand increases across the board and is produced by both electrolysis and natural gas with CCUS

Note: Transformation includes electricity and heat, production of hydrogen-based fuels and refineries.

The STEPS sees small increases in the use of low-carbon hydrogen and hydrogen-based fuels to 2030 (Figure 1.27). In the APS and the NZE, demand picks up more rapidly as low-carbon hydrogen and hydrogen-based fuels are used to provide flexibility in the power sector, hydrogen currently used in industry is replaced by low-carbon hydrogen, and new end-uses emerge (including in transport and for heating in buildings in some circumstances). In the NZE, around half of low-carbon hydrogen production in 2030 is from electrolysis and half is from coal and natural gas equipped with CCUS (although this ratio varies considerably among countries).

Progress in the decade to 2030 will be critical to the later success of low-carbon hydrogen and hydrogen-based fuels. Success will depend on major investments in innovation to lower the costs of production and in transport to ensure that new end-user equipment and vehicles quickly become available on the market. There are likely to be large regional variations in production costs for hydrogen and hydrogen-based fuels, and imports could be more economically attractive than domestic production for some countries.

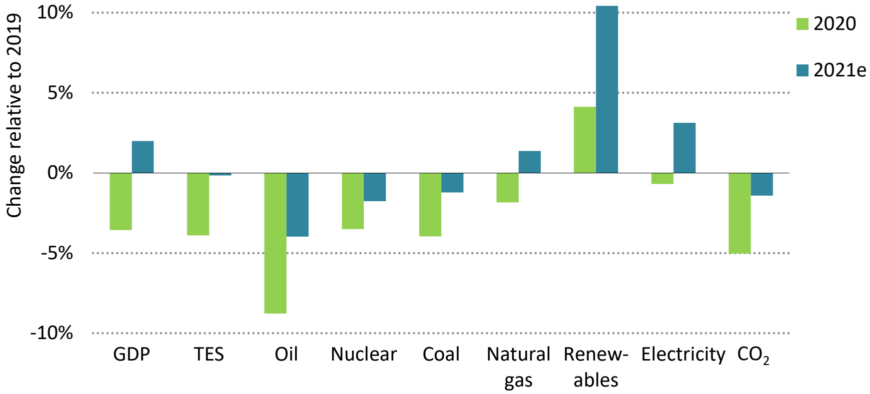
State of play

What sort of recovery?

SUMMARY

- Recovery from the Covid-19 pandemic is underway, but it is uneven, prone to reversals and relatively carbon intensive. The economic impacts appear to have bottomed out in most cases in late 2020 or early 2021, with the exception of China which started its recovery earlier. Countries with fiscal means and access to vaccines are seeing a robust rebound. However, many emerging market and developing economies face continued risks due to low vaccination rates and rising indebtedness.

Figure 2.1 ⊳ **Change in key global indicators for energy demand and emissions, 2020 and 2021**



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Renewables have continued to set records throughout the crisis, but all fuels – and global CO_2 emissions – are set to bounce back strongly in 2021

Note: TES = total energy supply; 2021e = estimated values for 2021.

- Worldwide energy demand in 2021 is set to regain all of the ground lost in 2020 due to the pandemic (Figure 2.1). The resultant upswing in demand for all fuels and technologies has contributed to sharp rises in gas, coal and electricity prices. This is overshadowing signs of more structural changes, such as the continuing rapid rise of renewables and electric vehicles. Global CO_2 emissions in 2021 are on track for their second-largest rise in history.

- Government recovery spending includes some USD 380 billion worldwide for sustainable energy, which is boosting investment in renewables, grids, energy efficiency and areas such as low-carbon hydrogen and carbon capture, utilisation and storage (CCUS). However, the boost that this provides is only around one-third of what would be required to secure an early peak in emissions. There is a major geographical imbalance in spending, with many emerging market and developing economies facing severe constraints on their ability to mobilise capital for recovery and energy transitions.

- After falling by around 1% in 2020, global electricity demand has come roaring back in 2021, outpacing the rise in low-emissions generation even in another record year for renewables. This is leading to increased output from coal-fired plants to meet demand, especially in Asia. The effects of the pandemic are more visible in the transport sector, where oil demand in 2021 is set to remain well below 2019 levels. Natural gas demand is expected to bounce back more quickly, driven mainly by an increase in industrial use.
- Governments, municipalities, companies and financial institutions are making increasingly ambitious pledges to curb emissions in the run-up to the crucial COP26 meeting in Glasgow. As of mid-2021, countries pledging to reach net zero emissions account for 60-70% of today's global GDP and energy-related CO_2 emissions, and around one-third of energy-related methane emissions.
- Our new *Outlook* does not include a forecast for the future of global energy, but offers scenarios that explore the implications of different policy choices, investment trends and technology dynamics.
- The main normative scenario is the **Net Zero Emissions by 2050 Scenario**, which outlines a narrow but achievable pathway to a 1.5 °C stabilisation in global average temperatures. There are also two exploratory scenarios. The **Announced Pledges Scenario** examines where all today's announced energy and climate commitments – including net zero pledges – would take the energy sector if implemented in full and on time. The **Stated Policies Scenario** does not take full implementation of these pledges for granted, but takes a more granular, sector-by-sector look at existing policies and measures as well as those that are under development, and assesses where they lead the energy sector.
- Most global commodity prices have rallied in 2021 as economic activity picked up, underlining that the affordability of energy remains a major concern for households, businesses and policy makers. While we do not, for the moment, anticipate a prolonged pan-commodity upswing in price levels, investment imbalances could well herald a period of greater volatility. Fuel price rises have led to a sharp increase in the estimated value of global fossil fuel consumption subsidies to USD 440 billion in 2021.
- The falling costs of key clean energy technologies offer a huge opportunity for all countries to chart a lower emissions pathway towards growth and prosperity. Renewable power companies have outperformed listed fossil fuel companies and public equity market indices in recent years. Patenting activity for low-carbon energy has likewise outstripped that for fossil fuels since 2000. Nevertheless, a new wave of innovation remains essential to accelerate the pace of transitions.

2.1 Introduction

The warning signs are impossible to ignore. The stark conclusions on the physical science, produced as part of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, are reinforced on a startlingly regular basis by headlines of new extreme weather events from all around the world. Since the energy sector is responsible for almost 75% of global greenhouse gas emissions, it is firmly in the spotlight. There are signs of a response, both in deployment trends for some clean energy technologies and in the increasingly ambitious pledges to curb emissions made by governments, municipalities, companies, investors, financial institutions and others in the run-up to the crucial meeting of the United Nations Framework Convention on Climate Change Conference of the Parties (COP26). However, the latest energy and emissions trends are a reminder that changes in the way that we use and consume energy have a long way to go: the world's partial recovery from the Covid-19 pandemic has been enough to push up demand for all fuels and technologies, leading to a sharp rebound in prices and in carbon dioxide (CO_2) emissions.

The ways in which policy commitments and technological change must drive real changes in energy markets is a central theme of this *World Energy Outlook 2021*. The level of commitment to tackle climate change has never been higher, but there remains a large gap between the data coming from markets and the statements coming from policy makers. In this new *Outlook*, we explore how and when this gap might narrow, as it must if the world is to get serious about addressing climate change, by focusing on:

- **Recovery:** With different rates of vaccination and the spread of more transmissible variants of the virus, how widespread is the recovery from Covid-19? Are the policies and investment coming through going to make it a sustainable recovery?
- **Ambition:** How close do current pledges get the world towards the target of limiting global warming to 1.5 °C while meeting other energy-related sustainable development goals? What more needs to be done and in which parts of the energy system?
- **Implementation:** To what extent are governments and others backing their new commitments with the required actions to stimulate investments?
- **Consequences:** What does this all mean, in various scenarios, for demand for different fuels and technologies, and for capital and trade flows? What are the implications for people and jobs, and for the security and affordability of energy supply? And what does each scenario imply for emissions and for the rise in global temperatures?

This chapter sets the scene. Its first-half examines our starting point in 2021, the continued uncertainties created by the pandemic, the regional differences in outcomes and responses, and what the latest data for energy, investment, prices and emissions tell us about the forces shaping today's energy sector. Its second-half describes the scenarios used in this year's analysis, discusses how and why they differ from each other, looks at the underlying economic and demographic drivers, the outlook for energy and carbon prices, and the dynamic role played by energy technology development and innovation.

2.2 Energy and the Covid-19 pandemic

Last year's edition of the *World Energy Outlook* surveyed the disruption caused to the energy sector by the Covid-19 pandemic and concluded that "it is too soon to say whether today's crisis represents a setback for efforts to bring about a more secure and sustainable energy system or a catalyst that accelerates the pace of change". One year on, many uncertainties remain, but some of the contours of the recovery, in different parts of the world, are more clearly visible.

In the *World Energy Outlook-2020*, we posited three possible ways out of the crisis, based on different assumptions about the severity and duration of the public health emergency, its economic impact and the response from policy makers:

- The Stated Policies Scenario (STEPS) assumed that the pandemic would be brought under control by the end of 2021, bringing a relatively robust economic recovery. This scenario did not assume any dramatic change in policy orientation in favour of a more sustainable recovery, beyond measures already announced.
- The Delayed Recovery Scenario (DRS) assumed more prolonged outbreaks of Covid-19, with deeper economic impacts. Like the STEPS, the DRS did not foresee additional policy changes affecting the nature of the eventual recovery.
- By contrast, the Net Zero Emissions by 2050 (NZE) case and the Sustainable Development Scenario relied on a wholesale shift in policy focus and investment in support of a sustainable recovery, aided by a relatively rapid improvement in public health and the economy.

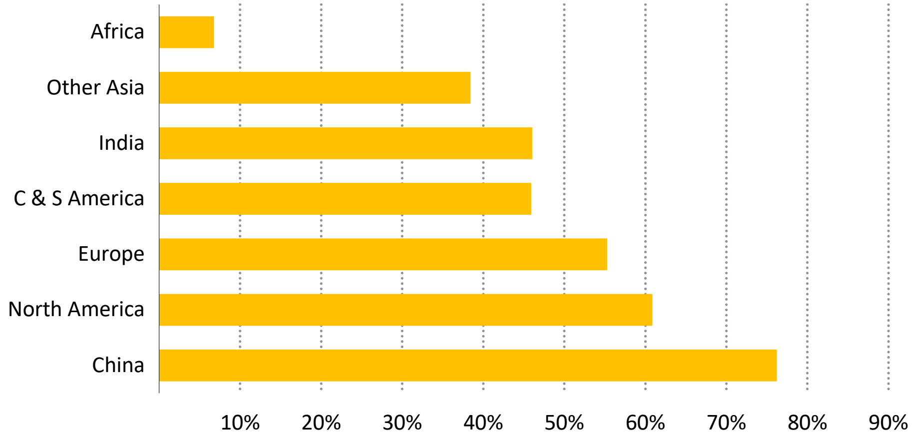
One year on, our assessment of the starting point for this *Outlook* reveals a mixture of these elements. Some parts of the world, notably those with ready access to vaccines, are seeing a robust economic rebound, and some advanced economies are taking steps to promote sustainability in their recovery strategies. However, the picture in many emerging market and developing economies is significantly less encouraging: public health and economic indicators point towards a delayed recovery, and many countries lack both the finance and the policy momentum to mobilise a much-needed increase in clean energy investment. The sharp uptick in commodity prices in the second half of 2021 could cast a shadow over the global economic recovery.

2.2.1 Economy and public health

Public health indicators are still flashing red in many parts of the world. Many countries have experienced multiple waves of infections from Covid-19, and new variants have brought additional challenges. While some countries appear to be on track to get the virus under control over the course of 2021, many others – including most developing economies – are vulnerable to prolonged outbreaks with damaging economic impacts.

Data for infections are incomplete and do not provide a full picture. A more telling indication of country and regional differences is provided by the data on vaccinations (Figure 2.2). Most emerging market and developing economies, especially those in Africa, have not yet had the means or opportunity to start mass vaccination campaigns in earnest and remain very vulnerable to the spread of more transmissible variants of Covid-19.

Figure 2.2 ▹ **Share of population with at least one dose of Covid-19 vaccine**



The pace of vaccination varies widely between countries, and this shapes future downside risks from the pandemic

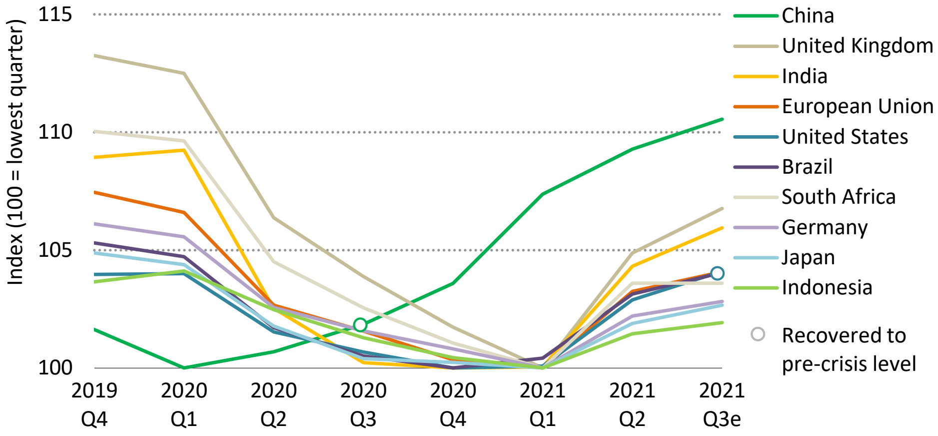
Notes: C & S America = Central and South America. Data for all countries are from 1 October 2021, except China which is from 18 September 2021.

Source: Official data collected by Our World in Data website (2021).

A speedier roll-out of vaccines and continued fiscal support have facilitated the rebound in economic activity in many advanced economies and in China (Figure 2.3). But economic indicators in other emerging market and developing economies have lagged, especially in Eurasia, Latin America, the Middle East and Africa (many developing economies in Asia have fared slightly better).

One of the effects of the pandemic has been a faster increase in levels of debt (Figure 2.4). This is visible across the board, but advanced economies and China have better access to debt finance, at lower cost, than most other countries. Some emerging market and developing economies are starting to experience more difficult borrowing conditions, limiting their ability to mobilise funds for recovery (including for clean energy investments). Financial strains in 2020 were particularly visible among energy exporters, although these have been eased somewhat by a rally in commodity prices in 2021.

Figure 2.3 ▷ **Change in GDP per capita by quarter for selected countries**



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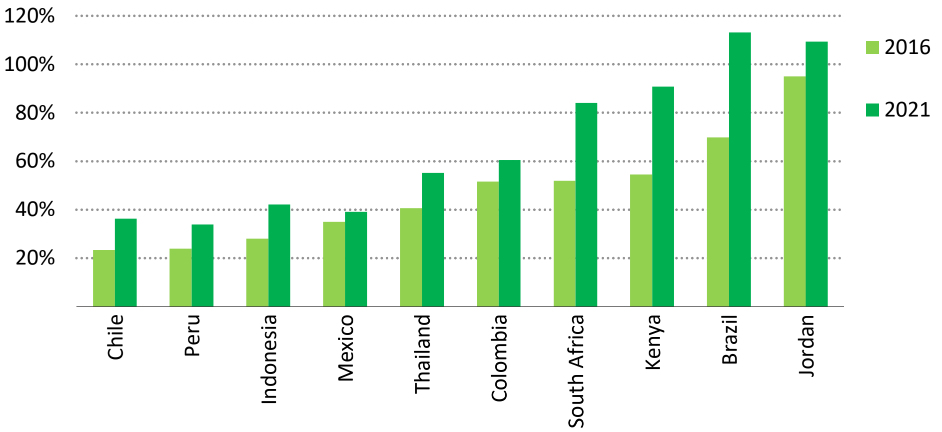
Economic impacts of the pandemic bottomed out in most countries in late 2020 or early 2021, but several months earlier in China

Notes: 2021 Q3e = estimated value for the third quarter of 2021. Change in GDP = annualised year-over-year change by quarter.

Source: IEA analysis based on Oxford Economics (2021).

Figure 2.4 ▷ **Government debt-to-GDP ratios for selected emerging market and developing economies**



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Debts in many emerging market and developing economies have risen significantly, and are expensive to service

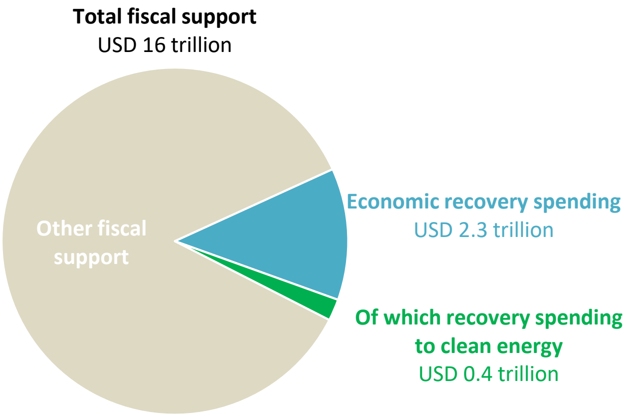
Note: Debt positions in 2021 represent the latest month of available data in the first half of the year.

Source: Calculations based on TheGlobalEconomy.com (2021).

2.2.2 Recovery spending and energy investment

The ability of governments to mobilise fiscal support has helped households and companies to weather the immediate crisis, and will be equally important in shaping the speed and sustainability of the recovery. Most of the cumulative support provided, over USD 16 trillion as of mid-2021, has been aimed at providing near-term emergency and economic relief (IMF, 2021a).[1] Of this, around USD 2.3 trillion has been directed to economic recovery, which is defined as spending that goes to new investments, including spending that could be directed to clean energy infrastructure (Global Recovery Observatory, 2021). As of July 2021, we estimate that USD 380 billion is going to sustainable energy (IEA, 2021a) (Figure 2.5).

Figure 2.5 ▻ **Breakdown of global Covid-19 pandemic-related fiscal support**



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As of mid-2021, governments had spent around USD 380 billion on sustainable recovery measures as part of their response to the pandemic, around 2% of the total fiscal response

Note: Other fiscal support includes non-energy sector fiscal support, including near-term economic relief for companies and households, as well as emergency health measures.

Source: IEA Sustainable Recovery Tracker (2021a).

This funding support for clean energy is set to be delivered over the next few years – 70% of it by 2023 – and along the way it also leverages additional spending from the private sector. Our assessment of the multiplier effects by country and sector suggests that this could mean an additional USD 1 trillion in sustainable recovery investment over the period to 2023.

Some signs of this are already visible in our tracking of energy investment data and anticipated spending in 2021 (Figure 2.6). Overall investment in all parts of the energy sector is expected to rebound in 2021 by some 10% to USD 1.9 trillion, making up most of the decline seen in 2020. Spending on electricity networks is set to rise in 2021 after four years of decline, thanks in part to higher infrastructure spending in China, Europe and United

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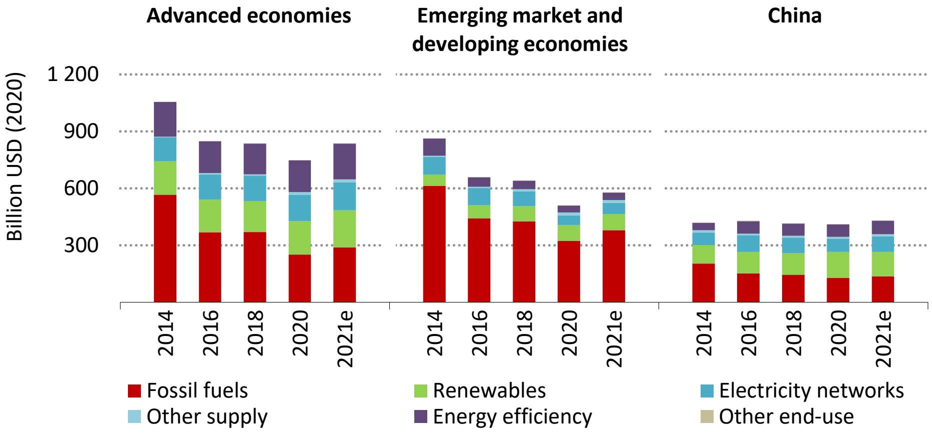
[1] Some of this support has translated into higher savings, especially in advanced economies. When these savings are spent – and what they are spent on – is an important near-term variable for the economic outlook.

States. Spending on energy efficiency improvements is anticipated to increase in 2021 by nearly 10%, in response to renewed economic growth and the initial effects of recovery programmes. Policies and stimulus spending are also spurring projects in new areas such as low-carbon hydrogen and carbon capture, utilisation and storage (CCUS).

However, the amounts that are being dedicated to sustainable recoveries are far from sufficient to jolt the global energy system onto a different track. The additional USD 1 trillion over the period to 2023 is only around one-third of the amount that we estimate would be needed to secure an early peak and rapid subsequent reduction in global emissions (see *Sustainable Recovery* report [IEA, 2020a]). Overall clean energy investment would need to double in the 2020s to be consistent with limiting the rise in global average temperatures to "well below 2 °C" and it would need to more than triple in order to keep the door open to a 1.5 °C stabilisation.

There is a huge geographical imbalance in recovery spending and in clean energy investment. Although advanced economies are only committing around 60% of the global public and private spending envisaged in the *Sustainable Recovery* report (IEA, 2020a), the available funds are much larger than in developing economies, which already face a large infrastructure deficit. This reflects some worrying trends in clean energy investment and finance: if China is excluded, then emerging market and developing economies account for only one-fifth of the amounts being spent worldwide on clean energy, despite needing to find ways to meet the rapidly rising energy needs of two-thirds of the world's population.

Figure 2.6 ⊳ **Energy investment trends by region**



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Emerging market and developing economies need to boost clean energy investment but often have limited fiscal space and constrained access to finance

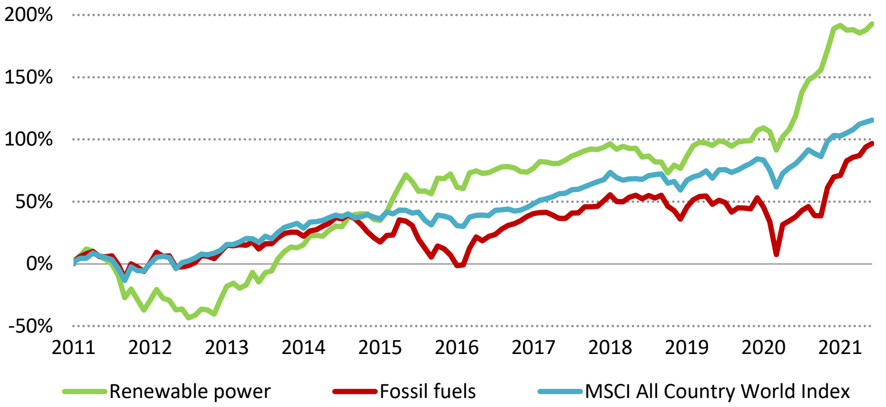
Notes: Emerging market and developing economies aggregate excludes China in this figure. 2021e = estimated values for 2021.

The falling cost of key clean energy technologies offers a huge opportunity for all countries to chart a new, lower emissions pathway towards economic growth and prosperity. Clean energy companies around the world have done well on financial markets, with listed renewable power companies outperforming fossil fuel companies and public equity market indices in recent years. However, clean energy investment still remains far short of what is required to put the energy system on a sustainable track. At the same time, the amount being spent on oil and natural gas is also short of what would be required to maintain current consumption trends. A surge in clean energy spending is the obvious way out of this impasse, but something has to change quickly or global energy markets face a turbulent period ahead.

Box 2.1 ▷ Fossil fuels or renewables: Which energy companies have delivered the strongest financial returns?

Does investing in energy transitions make financial sense? To answer this question, the IEA teamed up with Imperial College in the United Kingdom to examine structural trends in the historical financial performance of energy companies around the world (Figure 2.7). The analysis, updated to June 2021, showed that a publicly traded renewable power portfolio generated generally higher investment returns, higher diversification benefits (meaning that performance was less correlated to the overall market) and lower volatility than a portfolio consisting of fossil fuel suppliers. These findings held in all markets examined, but the overall performance gap was widest within advanced economies and China (IEA, 2021b).

Figure 2.7 ▷ Ten-year returns of a global market benchmark versus publicly traded renewable power and fossil fuel portfolios



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Since late 2014 a renewable power equity portfolio has generated higher investment returns than one consisting of fossil fuel suppliers

Notes: The analysis compiled portfolios of different firms engaged in renewable power and fossil fuel supply and calculated total return and annualised volatility over five- and ten-year periods since 2011. The total return for each company is calculated in the local currency to produce a unit-less return. The portfolio construction methodologies and further analysis on credit conditions and commodity prices are available on the IEA website.

Source: IEA analysis based on Bloomberg (2021).

Renewable power companies have reaped the rewards of huge improvements in cost competitiveness in recent years. They have also benefited from low interest rates, which are an important consideration for companies that are typically two-to-three-times more leveraged than fossil fuel companies. They weathered the initial storm of the pandemic considerably better than their fossil fuel counterparts, with a record-breaking market rally during 2020, though the most recent data for 2021 show a slightly changed picture: indices for fossil fuel are picking up as economic recovery boosts demand and prices.

What are the implications of this analysis for investors? It remains the case that investment opportunities in renewables lack scale and liquidity in most parts of the world, meaning that they are not always readily accessible. But the historical record does show that, with growing policy momentum and cost advantages, renewables have the potential to generate competitive risk-adjusted returns.

2.2.3 Energy demand and supply

Worldwide energy demand in 2021 is set to recover the ground that was lost the previous year, with a 4% increase returning global energy demand to pre-pandemic levels. The pickup in economic activity as countries gradually emerged from lockdowns has meant an upswing in demand for all fuels and technologies. These effects are overshadowing the signs of more structural changes in the energy sector, notably the rise of renewables for power generation and electric vehicles for personal mobility.

The pandemic was a setback for the pace of improvements in energy efficiency: strains on corporate and household budgets, uncertainties about the pace of recovery, and lower fuel prices in 2020 delayed spending on more efficient equipment and vehicles. The amount of energy required to generate a unit of global GDP has been steadily coming down over time, but the rate of improvement has slowed noticeably in recent years and was only 0.5% in 2020. This is well below the 3-4% annual figure needed to achieve global climate and sustainability goals. Investments in energy efficiency are set to pick up in 2021, although growth is likely to be heavily concentrated in markets and sectors with supportive government policies, such as the buildings sector in Europe.

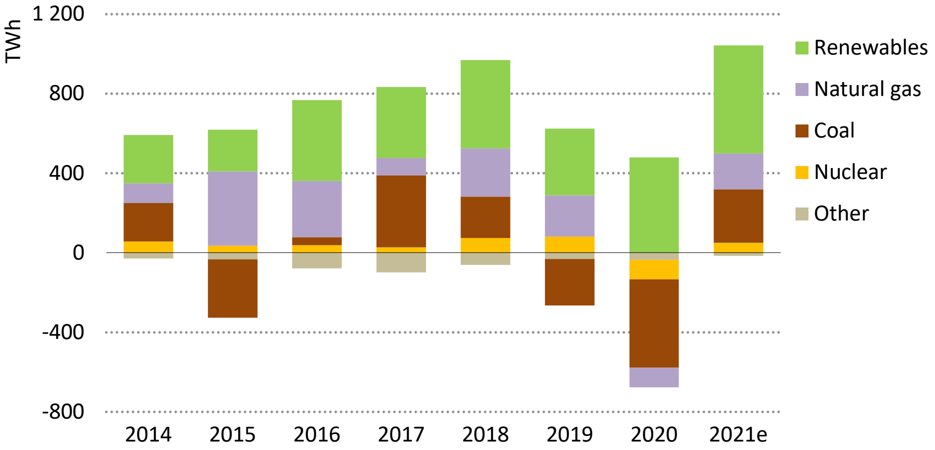
Electricity

After declining in 2020, electricity demand is expected to increase by more than 1 000 terawatt-hours (TWh) in 2021, pushing consumption well above pre-pandemic levels. The increase in China is particularly striking, with demand already around 10% higher than in 2019. The worldwide rise in demand is set to outpace the expansion of low-carbon generation and much of the residual increase is being met by increased output from coal-fired plants in Asia.

In recent years, higher output from renewables has accounted for most of the growth in global electricity generation. Together with coal-to-gas switching, notably in the United

States, this has stemmed the rise in energy-related CO_2 emissions from the power sector. In 2020, record growth in renewables coincided with a fall in electricity demand, resulting in a big jump in the share of renewables in total generation, which rose to 28%, and a squeeze on generation from non-renewable sources. The result was a fall in global power sector emissions of around 3% – the largest relative and absolute decline on record. Another record rise in renewables is in the cards for 2021, but this is set to fall well short of the surge in demand (Figure 2.8).

Figure 2.8 ▷ Change in global electricity generation, 2014-2021



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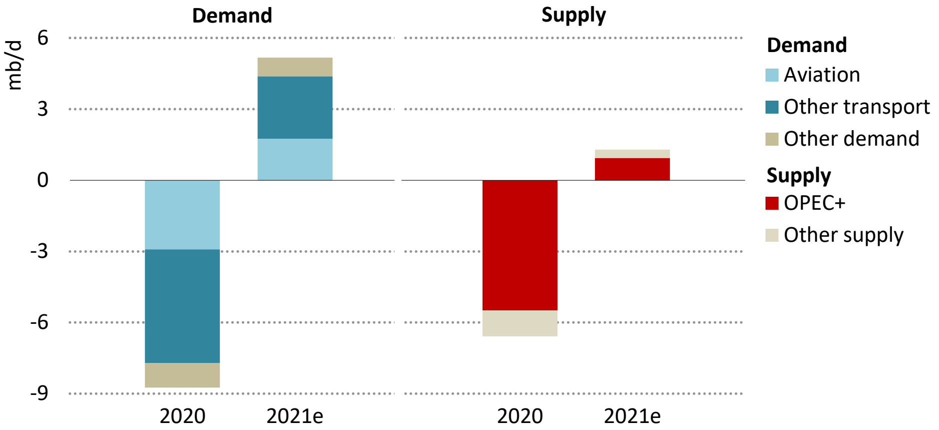
Another record year for renewables in 2021 is not enough to cover the rise in electricity demand, leaving an opening for coal-fired generation – and higher emissions

Note: 2021e = estimated values for 2021.

Liquid fuels

The impacts of the pandemic are lasting longer in the transport sector than they are for electricity. Oil demand in 2021 is set to rise by around 5.2 million barrels per day (mb/d), but this only covers part of the 8.7 mb/d decline from the previous year (Figure 2.9). Consumption of aviation fuels remains well below pre-pandemic levels: most of the immediate reasons are related to restrictions on international travel and limited progress with vaccinations in many developing economies, but the pandemic may also have changed some air travel patterns for good. Road transport demand is rebounding faster, with both diesel and gasoline expected to be back within touching distance of pre-pandemic levels early in 2022, but continued public health risks, teleworking (especially in advanced economies), higher electric vehicle sales and increased efficiencies for new models are all constraining growth.

Figure 2.9 ⊳ Annual change in oil demand and supply, 2020 and 2021



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Oil demand is rebounding in 2021, but remains well below 2019 levels. OPEC+ countries absorbed most of the supply shock in 2020 and are now gradually unwinding these cuts

Notes: 2021e = estimated values for 2021. The differences between supply and demand reflect changes in stocks.

Rising demand and prices make a case for the OPEC+[2] group to unwind some of the cuts in oil supply that they implemented in 2020, but uncertainties concerning demand have not all disappeared, and there are questions about the allocation of output among key producers. Producers outside the OPEC+ group meanwhile are set to get close to pre-crisis levels of production in 2021 and to surpass them in 2022, despite mounting social and environmental pressures on many oil companies and increased scrutiny of their investment plans.

Compared with traditional oil supply, the volumes of low-carbon liquid fuels coming to market are relatively small – around 1.9 million barrels of oil equivalent per day (mboe/d) in 2020. However, policies are giving a boost in some areas: production capacity for hydrotreated vegetable oil (HVO) – a renewable diesel fuel – is expected to nearly double over the next two years, significantly expanding the capacity to produce biofuels from waste and residue feedstocks.

Gaseous fuels

Unlike oil, natural gas demand in 2021 is rising well above pre-pandemic levels and this has created strains in gas markets, contributing to a spike in prices in the third-quarter of 2021 that has fed through into higher wholesale electricity prices in many markets. The broad-based increase in natural gas consumption has been accompanied by a series of planned and unplanned outages on the supply side. Although industrial users have led the recovery,

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[2] The OPEC+ group includes the 13 Organization of the Petroleum Exporting Countries (OPEC) members and ten other oil producing countries including Azerbaijan, Bahrain, Brunei Darussalam, Kazakhstan, Malaysia, Mexico, Oman, Russia, South Sudan and Sudan.

weather-related factors, including an extended heating season and low wind generation in Europe, limited hydropower production in Brazil and heatwaves in Asia, have also played a role in boosting demand from the power and buildings sectors.

On the supply side, exporters in Russia and Central Asia bore the brunt of the demand slump in 2020 and are capturing some of the rebound in 2021, mostly via increased pipeline deliveries. Liquefied natural gas (LNG) supply, by contrast, saw less downside in 2020 and continues to see a steady increase in seaborne gas trade. Asian countries now account for nearly three-quarters of global LNG imports.

As with liquids, low-carbon gases account for only a small share of total supply (currently below 1%), but demand for these gases is growing rapidly. Preliminary data show a double-digit rise in global biomethane production in 2020 to more than 5 billion cubic metres (bcm), largely due to supportive policies in Europe and North America, and a further large increase is anticipated in 2021. Low-carbon hydrogen is another fuel enjoying a surge of interest and investment, although for the moment the vast majority of global production comes from fossil-based hydrogen (including carbon capture without permanent sequestration).

Solid fuels

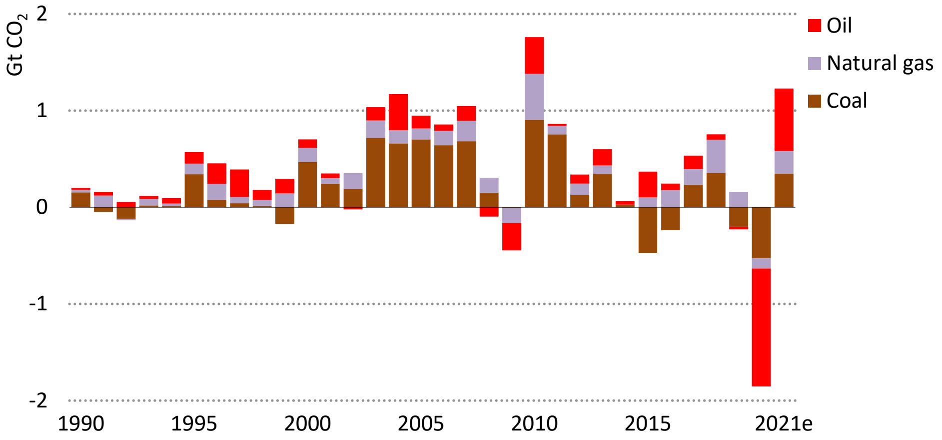
The 4% decline in global coal demand in 2020 was the largest drop in more than 70 years, but growing electricity demand and the pickup in industrial activity are behind the rebound in 2021, around 80% of which is coming from Asia. China is by far the world's largest producer and consumer of coal, and is instrumental in setting the global trend, but is far from alone in seeing higher coal demand in 2021. The increases, for the most part, are a reaction to the upswing in activity, but they are also a strong indication that the pace of structural change in the energy sector is far from sufficient.

Low-carbon solid fuels count for more in the energy mix than their liquid or gaseous counterparts: almost 90% of the bioenergy used today is in solid form. Some of this solid bioenergy is used in modern technologies to provide electricity and heat, while helping to reduce emissions. A larger share of it is for traditional use as a cooking and heating fuel in developing economies – an unsustainable and inefficient form of energy consumption that is a major cause of indoor air pollution and related adverse health impacts.

2.2.4 Emissions

Global energy-related CO_2 emissions are on track to rise by 1.2 billion tonnes in 2021, erasing two-thirds of the pandemic-related reduction seen in 2020 (Figure 2.10). A rise of this size would represent a 4% increase and the second largest absolute rise in history. The spike in electricity demand coupled with an increase in coal use is responsible for nearly 30% of this increase. Emissions from transport are also set to rise substantially in 2021, although continued limitations on air travel prevent them from rising past 2019 levels. Emerging market and developing economies generally have much lower per capita emissions than elsewhere, but overall account for around 60% of global CO_2 emissions. Emissions in advanced economies have been in gradual structural decline, but the rebound in economic activity is set to produce a rise of around 3% in 2021.

Figure 2.10 ⊳ **Annual change in energy-related CO_2 emissions**



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Global CO_2 emissions are set to see one of the largest rises in history in 2021, erasing most of the gains realised during the pandemic

Note: 2021e = estimated values for 2021.

2.3 Where do we go from here?

2.3.1 Climate pledges

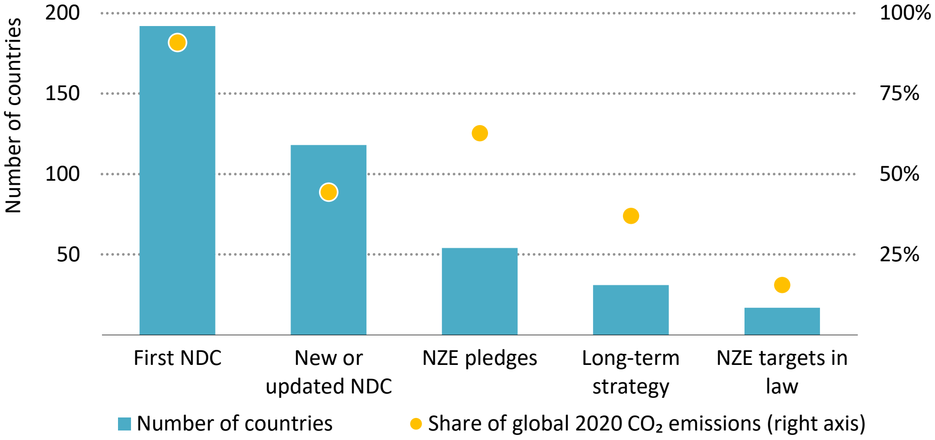
A key variable in determining where we go from here is what governments commit to do, and whether they are successful in realising their ambitions. Pledges made by governments are central to the architecture of the Paris Agreement and the fight against climate change, and the last year has been a particularly busy one for new climate policy announcements. This *World Energy Outlook* considers all pledges and commitments made as of mid-2021, including formal Nationally Determined Contributions (NDCs) as well as other announced ambitions, including longer term net zero targets (Figure 2.11).

In the context of the Paris Agreement, NDCs are meant to be updated every five years, becoming more ambitious over time. Most countries in the world have submitted a first NDC, although only around 60% of that number, so far, have formally submitted new or updated versions. The current crop of NDCs is typically focused on targets for 2030, but an increasing number of countries are putting their actions on emissions in the context of long-term strategies and net zero emissions targets.

If the world is to stem the rise in global average temperatures, it has to bring emissions down to a point where any residual emissions from human activity are balanced by removals of emissions from the atmosphere. That is why net zero targets – and the consistency of interim goals with these targets – have become a central focus of the climate debate. As of September 2021, 53 countries and the European Union have pledged to meet net zero emissions targets; in total they account for 60-70% of today's global GDP and energy-related CO_2 emissions, and around one-third of energy-related methane emissions, the other main greenhouse gas.

The urgency of addressing climate change requires ambition from policy makers, but in practice there is not a single standard against which to judge the adequacy of their pledges. Countries are not starting the journey to net zero from the same place, and they should not be expected to finish it at the same time: there is a strong case for advanced economies to reach net zero before emerging market and developing economies (each of which has its distinctive circumstances) and assist others in getting there. The context for company pledges likewise varies depending on their operations: it is much easier for firms reliant on electricity, such as technology companies, to take on ambitious targets than it is for those in logistics or heavy industrial sectors.

Figure 2.11 ▷ Number of countries with NDCs, long-term strategies and net zero pledges, and their shares of global CO_2 emissions in 2020



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Net zero pledges by countries, sub-national jurisdictions, coalitions and companies have become a keystone of the global push to tackle climate change

Note: Submitted NDCs and their updated or new versions as defined by the United Nations Framework Convention on Climate Change (UNFCCC), as of 24 September 2021.

That said, beyond the headline level of ambition, there are several important questions to ask when assessing pledges:

- What does the pledge cover? Some national commitments focus only on certain sectors and exclude others. Some cover all greenhouse gases and others only CO_2. Company pledges also vary in scope: some include emissions from operations, but not indirect emissions in their value chain.

- Are there conditions attached? If so, what are the conditions that have to be met in order for the commitment (or parts of it) to be realised? In the case of country pledges, the most common conditions relate to financial support. In practice, many commitments are implicitly reliant on measures to strengthen institutional capacity.
- Does the pledge rely on carbon dioxide removal (CDR) or offsets? This is an increasingly important consideration. CDR technologies include natural CO_2 sinks, such as forests and soils, as well as technological solutions, such as direct air capture or bioenergy with carbon capture and storage. Reliance on these solutions can be justified in areas where emissions reductions are extremely difficult to achieve, but broad reliance on offsets is often an indication of a lack of stringency.
- Are there mechanisms in place to track progress and ensure compliance? These are vital to ensure that the emissions reductions are robust, and that governments are held accountable for performance against their targets.

2.3.2 WEO-2021 scenarios

This *World Energy Outlook* (*WEO*) explores various scenarios, each of which is built on a different set of underlying assumptions about how the energy system might evolve. These scenarios are not predictions – the IEA does not have, and has never had, a single view about what the long-term future might hold. Instead, what the scenarios seek to do is to enable readers to compare different possible versions of the future and the levers and actions that produce them, with the aim of stimulating insights about the future of global energy.

These scenarios highlight the importance of government policies in determining the future of the global energy system: decisions made by governments are the main differentiating factor explaining the variations in outcomes across our scenarios. However, we also take into account other elements and influences, notably the economic and demographic context, technology costs and learning, energy prices and affordability, corporate sustainability commitments, and social and behavioural factors.

This *World Energy Outlook 2021* assesses three main scenarios. One is normative, in that it is designed to achieve a specific outcome and shows a pathway to reach it. Two scenarios are exploratory, in that they define a set of starting conditions and then see where they lead. In contrast to the 2020 edition of the *WEO*, we do not vary the assumptions about public health across the scenarios; we assume in each scenario that the pandemic is largely brought under control by the end of 2021 in advanced economies and China, but that this takes longer in many emerging market and developing economies.

The scenarios are:

- The **Net Zero Emissions by 2050 Scenario (NZE).** This is a normative IEA scenario that shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular by achieving universal energy access by 2030 and major improvements in air quality. The NZE does not rely on emissions reductions from outside the energy sector to achieve its goals, but assumes that non-energy emissions will be reduced in the same proportion as energy emissions. It is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability).

- The **Announced Pledges Scenario (APS)** appears for the first time in this *WEO*. It takes account of all of the climate commitments made by governments around the world, including NDCs as well as longer term net zero targets, and assumes that they will be met in full and on time. The global trends in this scenario represent the cumulative extent of the world's ambition to tackle climate change as of mid-2021. The remaining difference in global emissions between the outcome in the APS and the normative goals in the NZE or the Sustainable Development Scenario shows the "ambition gap" that needs to be closed to achieve the goals agreed at Paris in 2015.
- The **Stated Policies Scenario (STEPS)** provides a more conservative benchmark for the future, because it does not take it for granted that governments will reach all announced goals. Instead, it takes a more granular, sector-by-sector look at what has actually been put in place to reach these and other energy-related objectives, taking account not just of existing policies and measures but also of those that are under development. For example, the new Fit for 55 package of measures announced by the European Commission in July 2021 provides the detailed underpinnings for the European Union to reach its new 2030 emissions reduction target (a 55% reduction in emissions by 2030 compared with 1990 levels), and this is sufficient to bring the near-term EU trajectory in the STEPS close to that in the APS. The STEPS explores where the energy system might go without a major additional steer from policy makers. As with the APS, it is not designed to achieve a particular outcome.

An additional scenario referenced in the text is the **Sustainable Development Scenario (SDS)**. As a "well below 2 °C" pathway, the SDS represents a gateway to the outcomes targeted by the Paris Agreement. Like the NZE, the SDS is based on a surge in clean energy policies and investment that puts the energy system on track for key SDGs. In this scenario, all current net zero pledges are achieved in full and there are extensive efforts to realise near-term emissions reductions; advanced economies reach net zero emissions by 2050, China around 2060, and all other countries by 2070 at the latest. Without assuming any net negative emissions, this scenario is consistent with limiting the global temperature rise to 1.65 °C (with a 50% probability). With some level of net negative emissions after 2070, the temperature rise could be reduced to 1.5 °C in 2100.

2.4 Inputs to the scenarios

2.4.1 Economic and population assumptions

The global **economy** is assumed to grow by around 3% per year on average over the period to 2050, with large variations by country, by region and over time (Table 2.1). The assumed rates of economic growth are held constant across the scenarios, which allows for a comparison of the effects of different energy and climate choices against a common backdrop. We recognise that the pace and nature of change in the energy system will have economic repercussions, both positive and negative: these impacts have been assessed in other reports, including the *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA, 2021d). Joint analysis with the International Monetary Fund (IMF) which was featured in the *Roadmap* suggests that the surge in energy investment needed to get the world on track in the NZE would add 0.4 percentage points to yearly global growth over the next decade.

Table 2.1 ▷ Real GDP average growth assumptions by region

	Compound average annual growth rate			
	2010-2020	2020-2030	2030-2050	2020-2050
North America	1.6%	2.4%	2.0%	2.1%
United States	1.7%	2.3%	1.9%	2.1%
Central and South America	0.3%	2.8%	2.6%	2.7%
Brazil	0.3%	2.3%	2.7%	2.5%
Europe	1.1%	2.3%	1.5%	1.8%
European Union	0.8%	2.1%	1.3%	1.5%
Africa	2.5%	4.2%	4.2%	4.2%
Middle East	1.7%	2.6%	3.1%	2.9%
Eurasia	1.8%	2.5%	1.6%	1.9%
Russia	1.3%	2.2%	1.1%	1.4%
Asia Pacific	4.7%	4.9%	3.1%	3.7%
China	6.7%	5.2%	2.9%	3.6%
India	5.1%	7.1%	4.4%	5.3%
Japan	0.4%	1.1%	0.7%	0.8%
Southeast Asia	4.2%	4.9%	3.2%	3.8%
World	**2.6%**	**3.6%**	**2.7%**	**3.0%**

Note: Calculated based on GDP expressed in year-2020 US dollars in purchasing power parity terms.

Sources: IEA analysis based on Oxford Economics (2021); IMF (2021b).

Experience thus far indicates that – when Covid-19 is brought under control and the restrictions are removed – the trajectory for economic recovery is relatively rapid, especially in countries that have mobilised strong fiscal support. Recoveries have been led by industry and retail, while other sectors such as tourism and transport have lagged. However, some major near-term uncertainties remain. As noted, there are continued downside risks from a prolonged pandemic, with the spread of variants posing particular threats to emerging market and developing countries with low vaccination rates. There are also questions about the extent and duration of government support, with rising debt burdens limiting fiscal leeway in many countries; developing economies are again more vulnerable in this respect. In addition, there are uncertainties about the near-term impact on the broader economy following the sharp increases seen in energy prices in 2021.

Over the longer term, emerging market and developing economies are the main drivers of an expanding global economy, although a steady slowdown in population growth, the possibility of a further retreat from globalisation and a gradual moderation in growth in China all dampen the advance of global GDP over time. Higher public debt arising from the pandemic may be managed in practice by central bank tolerance for slightly higher inflation. The main energy-related uncertainties for the economic outlook relate to the impact of price volatility, the size of any near-term surge in clean energy investment, the extent of productivity gains associated with the deployment of new energy technologies, and the pressure exerted by energy transitions on major hydrocarbon-rich economies.

The global **population** is assumed to rise from just under 8 billion today to 8.5 billion in 2030 and 9.7 billion in 2050, an increase of just over 25% in 30 years.[3] The rate of growth continues to slow over time, despite a near doubling of the population in sub-Saharan Africa. Although its effects are likely to be transient, the pandemic appears to have slightly slowed population growth, with China and many advanced economies registering fewer births during the pandemic. Other short-term impacts of the pandemic include a fall in life expectancy in a number of advanced economies and a significant fall in international migration: the number of new visas and residence permits issued by Organisation for Economic Co-operation and Development (OECD) countries fell by 46% in the first-half of 2020 compared with the same period in 2019.

A rising share of older people in the global population is an increasingly important demographic trend. This has not been a major issue at global level: the share of the global population aged 65 and above increased from about 5% in 1960 to 9% in 2019. However, it is already a noticeable trend in high income countries, and becomes increasingly relevant over time in China and other middle income economies. Aside from the economic implications, older populations also affect patterns of energy use, with higher residential consumption offset by a lower propensity to travel.

Urbanisation is a key driver of our energy projections. Some 56% of the global population lived in cities and towns in 2020, and they accounted for two-thirds of global energy consumption and over 70% of CO_2 emissions, despite the fact that approximately one-in-three urban inhabitants dwell in informal settlements and slum households without adequate access to basic services (Ritchie and Roser, 2019). The share of the global population living in towns and cities is expected to rise to almost 70% in 2050, and to grow especially fast in sub-Saharan Africa and South Asia.

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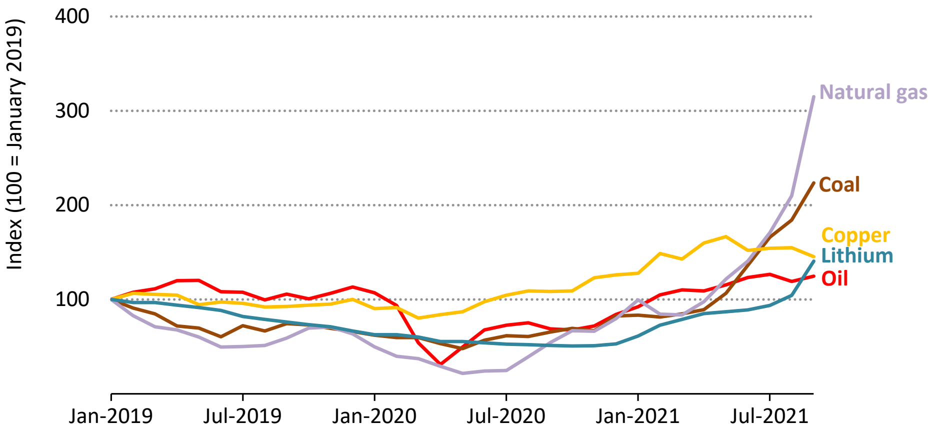
[3] This is in line with the median variant of the United Nations projections (United Nations Department of Economic and Social Affairs, 2019).

The model of urban development that is followed will have major consequences for the energy outlook, in particular the demand for energy-intensive construction materials such as steel and cement. In some advanced economies, the pandemic led to major cities such as London, Paris, Madrid, Milan and Berlin experiencing population declines as inhabitants sought easier living conditions further afield during lockdowns. It is an open question whether the experience of remote working will affect the balance between urban and rural populations in the future.

2.4.2 Energy prices

The economic recovery in 2021 has tightened commodity markets and put sharp upward pressure on prices (Figure 2.12). Looking beyond the immediate factors that have contributed to market tightness, some analysts have posited that the world may be entering a new super cycle, i.e. a prolonged period during which strong demand and some constraints on supply lead to high prices for energy and other commodities. The readiness of governments to spend on new infrastructure, a pickup in broader business investment and the increased mineral intensity of clean energy transitions could all support such a thesis. Indeed, the IEA has highlighted the importance of copper, lithium, nickel, cobalt and rare earth elements to a secure and rapid transformation of the global energy sector, and pointed to a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realising those ambitions (IEA, 2021d).

Figure 2.12 ⊳ Monthly price indicators for selected commodities



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Most global commodity prices rallied in 2021 as economic activity picked up, but this does not necessarily mean a prolonged upswing in price levels

Note: Natural gas = Netherlands TTF natural gas forward one month; oil = Europe Brent spot price FOB; coal = Northwest Europe (ARA) CIF; copper = LME-Copper grade A; lithium = lithium carbonate global average.

Sources: IEA analysis based on Bloomberg (2021), IHS Markit (2021) and S&P Capital IQ (2021).

The scope for a broad-based super cycle that encompasses energy markets as well as other commodities can be overstated. There is no visible equivalent today to the role in the previous upswing played by China, whose breakneck urbanisation and industrialisation drove markets in the early part of the 2000s. There are also trade-offs between different commodity types: to the extent that there is a surge in demand for minerals and metals for solar arrays, wind turbines, power lines and electric motors, this should ultimately ease pressure on traditional fuel markets. In addition, as noted, there are clouds on the economic horizon that could hold back the speed of recovery, especially in emerging market and developing economies. For these reasons, we do not anticipate an extended pan-commodity period of high prices, but there is still ample scope for price volatility and price spikes, given the multiple mismatches between current investment trends and possible patterns of demand.

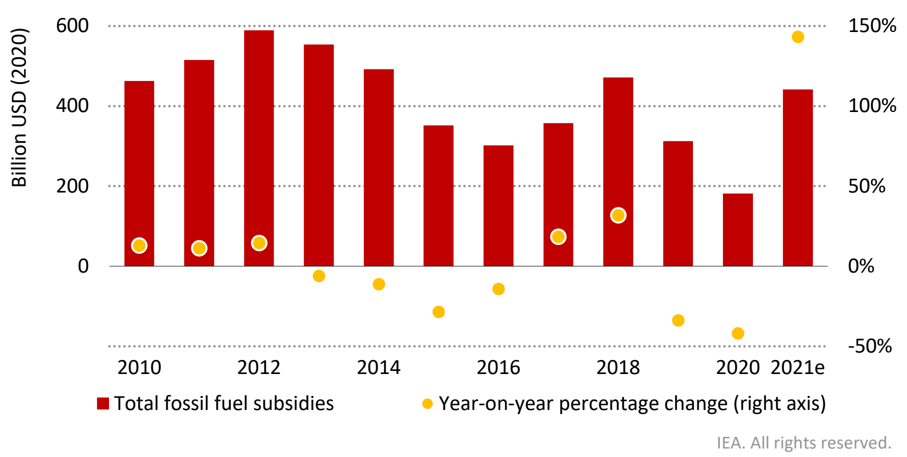
The impact of changes in the energy sector on consumers is naturally a matter of political concern, especially when it comes to lower income households and certain energy-intensive industries. The scope and level of carbon pricing is one aspect of this, but there are also regulatory interventions that push in the other direction by holding the price paid for certain fossil fuels below their market value. After a sharp fall in 2020, the estimated value of these fossil fuel consumption subsidies is set to rise again in 2021 (Box 2.2).

Box 2.2 ⊳ As prices and demand bounce back, so do fossil fuel consumption subsidies

The continued prevalence of taxes and regulated prices that favour fossil fuels makes the journey towards a sustainable energy future considerably more difficult. These market distortions dilute the case for more efficient and cleaner investments. The IEA has been a longstanding supporter of efforts to phase them out. Fossil fuel consumption subsidies are one important element of these market distortions, and occur when prices paid by consumers for fuels or electricity are lower than reference prices reflecting their full market value. These subsidies fell to a record low of USD 180 billion in 2020, but higher fuel prices and energy use, coupled with hesitancy on pricing reforms, are set to push this amount to an estimated USD 440 billion in 2021 (Figure 2.13).

This rebound to well above pre-pandemic levels is worrying at a time when countries need to be redoubling efforts to cut wasteful consumption and accelerate clean energy transitions. Subsidies to oil products remain the largest component of the total, but subsidies to natural gas and electricity have been the fastest rising. The increase in the subsidy burden adds to the fiscal pressures in many emerging market and developing economies, especially where subsidies are a specific incurred cost (typically where the fuel in question is imported) rather than foregone revenue (from potential sale of domestic output at a market price). Pricing reform is politically challenging but economically and environmentally essential to put the world on track for a more sustainable future.

Figure 2.13 ⊳ Global fossil fuel consumption subsidies, 2010-2021



After their biggest ever percentage fall in 2020, fossil fuel consumption subsidies are set for their highest ever rise in 2021 as fuel prices and consumption rebound

Note: 2021e = estimated values for 2021.

Oil

In the STEPS, oil demand rebounds quite rapidly and reaches pre-pandemic levels by 2023 (Table 2.2). This maintains some support for prices compared with the low levels of 2020. Prices range between USD 60-90 per barrel in the STEPS, rising slowly over time and then plateauing. OPEC members continue to purse market management efforts, while shale producers maintain a more cautious stance on output growth than in the past. This reduces the peak in tight oil production in the STEPS compared with *WEO-2020*, but means the subsequent decline from the peak is also less pronounced.

In the APS, global oil demand peaks sooner than in the STEPS and then starts to decline, as do prices. Net zero pledges implemented by countries in this scenario do not include targets on production, but do imply stringent efforts to minimise emissions from oil and gas operations. This tends to increase slightly the production costs in these countries relative to other producers: since these countries are generally the marginal producers, it also offers some support at the margin for global prices.

In the NZE, the rapid drop in oil and natural gas demand means that no fossil fuel exploration is required and no new oil and natural gas fields are required beyond those that have already been approved for development. Prices are increasingly set by the operating costs of the marginal project required to meet demand. Resource-rich governments are assumed to restrict investment in new fields. If they were to opt to increase production so as to capture a larger share of the market, prices would be much lower.

Natural gas

Natural gas has experienced an even sharper increase in prices in 2021 than oil, driven by a combination of circumstances that included a strong recovery in demand in Asia and Europe (leading to strong LNG demand from Asia), unseasonal weather and planned and unplanned capacity outages. As in the case of oil, the immediate period of higher prices is expected to be temporary, not least because of the planned expansion of LNG export capacity following a record year for project final investment decisions in 2019, but the potential for supply-demand imbalances and price volatility in the coming years remains strong.

Table 2.2▷ Fossil fuel prices by scenario

			Net Zero Emissions by 2050		Sustainable Development		Announced Pledges		Stated Policies	
Real terms (USD 2020)	**2010**	**2020**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
IEA crude oil (USD/barrel)	92	42	36	24	56	50	67	64	77	88
Natural gas (USD/MBtu)										
United States	5.2	2.0	1.9	2.0	1.9	2.0	3.1	2.0	3.6	4.3
European Union	8.8	4.2	3.9	3.6	4.2	4.5	6.5	6.5	7.7	8.3
China	7.9	6.3	5.3	4.7	6.3	6.3	8.5	8.1	8.6	8.9
Japan	13.0	7.9	4.4	4.2	5.4	5.3	7.6	6.8	8.5	8.9
Steam coal (USD/tonne)										
United States	60	43	24	22	24	22	25	25	39	38
European Union	109	50	52	44	58	55	66	56	67	63
Japan	127	69	58	50	67	63	73	63	77	70
Coastal China	137	89	61	51	72	66	77	65	83	74

Notes: MBtu = million British thermal units. The IEA crude oil price is a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. The European Union and China natural gas prices reflect a balance of pipeline and LNG imports, while the Japan gas price is solely LNG imports. The LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. The US steam coal price reflects mine mouth prices plus transport and handling cost. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports.

In the STEPS, higher natural gas demand and the rise in oil prices (for oil-indexed supply contracts) exerts some upward pressure on natural gas prices. Demand growth in China, India and elsewhere in Southeast Asia continues to support prices in those regions through to 2050, giving signals for incremental export capacity growth to established producing regions such as Australia and the Middle East as well as to emerging exporters in East Africa. In Europe, near-term prices are buoyed somewhat by headwinds facing competing sources, with the retirement of coal and nuclear plants.

In the APS, the pursuit of net zero targets translates into a sharper decline in natural gas demand in several major gas importers such as Japan, Korea and the European Union, leading to a flat or declining gas price trajectory in those regions. Henry Hub prices stay in the

USD 2-3 per million British thermal units (MBtu) range as domestic demand in the United States falls sharply, while a small upside from coal-to-gas switching in Europe quickly dissipates as prices settle around USD 6.50/MBtu. The surplus in internationally traded gas that results from lower European import requirements means that prices do not rise as strongly as they otherwise would in places such as China.

In the NZE, no new fields or export projects are developed, and natural gas prices fall to the marginal cost of delivering LNG from existing and under-construction projects, which require ongoing investment to sustain the required output. There is some temporary price support for gas as oil demand falls away more quickly than in the STEPS or APS and reduces the volumes of associated gas reaching the market. Natural gas becomes the largest fossil fuel in the energy mix by the late 2040s, and its discount to oil prices is progressively eroded.

Coal

International coal prices in 2021 reached levels not seen for more than ten years as demand rose in parts of Asia, especially for power generation and industrial uses in China, accompanied by some disruption and logistical issues on the supply side. This is not a harbinger for the future, however, and coal markets balance at lower prices in our scenarios. The difficulty of obtaining funding for new coal supply projects and infrastructure gives some support to prices in the STEPS. In the much more constrained demand environment of the APS and even more so the NZE (where no new coal mines or mine extensions are required) prices simply gravitate towards the operating costs of existing projects. In contrast to oil and gas, operating costs make up the largest share of coal supply costs.

Critical minerals

Many mineral commodities started 2021 with strong price rallies, with some reaching multi-year highs. Copper prices broke the symbolic USD 10 000/tonne barrier in May 2021, hitting an all-time high, and nickel prices rose by 50% from pre-pandemic levels, reaching their highest level since 2012. Lithium and cobalt prices are also resuming an upward trajectory. The recent price rallies were mainly driven by a combination of demand recovering faster than supply, stock building activities, ultra-loose monetary policies and expectations for strong future demand growth as a result of accelerated energy transitions.

The outlook for prices for many energy transition minerals depends on the pace of economic growth and on supply responses to that growth. It also depends to a large extent on how the world's decarbonisation pathway evolves. In the STEPS, the markets for many mineral resources may not necessarily be in deficit and may not tighten rapidly, given that investment is showing signs of a rebound. In the NZE, however, the projected level of demand growth is unprecedented, and this is bound to put substantial upward pressure on prices. The level of prices in these scenarios will be determined by the extent to which industry and governments ensure adequate investment in new supply well before the imbalances emerge, and also by how far consumers respond to rising prices by reducing demand and switching to substitute materials.

2.4.3 Carbon prices

An increasing range and variety of carbon pricing schemes are coming into operation around the world. The main development since the *WEO-2020* has been the launch of China's national emissions trading system (ETS), which immediately became the world's largest carbon market (by volume) covering over 4 gigatonnes CO_2 emissions. There have been other developments such as various reforms to strengthen the European Union ETS, the launch of national carbon markets in the United Kingdom, and extensions to the scope of the ETS in Korea and Germany. Carbon taxes were also introduced in the Netherlands and Luxembourg.

The STEPS includes only existing and announced initiatives, whereas in the APS, SDS and NZE additional measures of varying stringency and scope are assumed to be introduced. In the NZE, for example, carbon prices are in place in all regions, rising by 2050 to an average of USD 250/tonne CO_2 in advanced economies, to USD 200/tonne CO_2 in other major economies (in China, Brazil, Russia and South Africa), and to lower levels elsewhere. As with other policy measures, CO_2 prices need to be introduced carefully, with a view to the likely consequences and distributional impacts.

The level of CO_2 prices included in the scenarios should be interpreted with caution. The scenarios include a number of other energy policies and accompanying measures designed to reduce emissions, and this means that the CO_2 prices shown are not the marginal costs of abatement as is often the case in other modelling approaches (NGFS, 2021). For example, many emerging market and developing economies in the NZE are assumed to pursue a variety of direct policies to adapt and transform their energy systems and so the level of CO_2 prices is lower there than elsewhere. Nonetheless, CO_2 prices provide an important backstop for fuel switching and for some investment decisions in sectors and countries that have few other policies to reduce emissions. It is also assumed that parallel policies are introduced to avoid differences in CO_2 price levels leading to the relocation of industrial (and other) activities. CO_2 prices are applied to other non-CO_2 emissions, such as methane.

The CO_2 prices used in our World Energy Model are applied at the point where the emissions occur and so are not directly included in the wholesale fossil fuel prices discussed in section 2.4.2. Nonetheless, they could indirectly impact fossil fuel prices via the effects on demand and also due to their application on emissions resulting from the direct activities of the fossil fuel industry, such as the energy required to extract oil and gas from the ground. This additional cost, or the measures adopted to reduce the emissions intensity of production, could raise total production costs.

2.4.4 Technology innovation, deployment and costs

The *World Energy Outlook* includes a very broad and dynamic representation of various energy technologies and their costs. The model which it uses incorporates the latest data on current costs for all technologies, and then builds in the effects on costs of continued research, economies of scale, and improvements in manufacturing and installation from learning-by-doing. As a result, technologies across the energy sector – including key renewable electricity production and storage technologies – get progressively cheaper over time. The pace at which this happens varies by scenario as cost reductions are linked to cumulative deployment: the more a technology is deployed, the larger the assumed reductions in costs. Policies play a crucial role in this process, particularly in determining how quickly new, innovative clean technologies are scaled up in sectors such as shipping, aviation and heavy industry (Box 2.3).

The speed of scaling up is particularly important in the NZE, which relies on a much more rapid pace of technology innovation than has typically been achieved in the past. The time from first prototype to market introduction in the NZE for technologies such as solid-state batteries, small modular nuclear reactors, ammonia-fuelled ships, or direct air capture, on average, is 20% faster than the fastest energy technology developments in the past, and around 40% faster than was the case for solar photovoltaics (PV). The speed at which new technologies are developed is crucial: almost half of the emissions reductions needed in 2050 in the NZE come from technologies that are today at the prototype or demonstration state, i.e. they are not yet readily available on the market.

Box 2.3 ⊳ Energy patents start to pivot towards low-carbon technologies

Energy-related patent applications around the world can provide a good leading indicator of future technology trends. Joint analysis of the historical data by the IEA and the European Patent Office (IEA, 2021e) shows a clear divergence since 2015 between a continued rise in patents for low-carbon technologies and a decline in patenting for fossil fuels.[4] However, the pace of growth in clean energy patenting has slowed compared with a decade ago – a finding that reinforces the IEA's call for a new wave of innovation, accompanied by concerted policy support to accelerate the pace of clean energy transitions (Figure 2.14).

Alongside these headline findings, the composition of patents in the area of clean energy also contains some more granular insights. The market maturity of some low-carbon energy supply technologies, such as solar PV, in reflected in an initial period of heightened patenting activity that has tailed off since 2012. Most patents in recent years have been related to end-use sectors. Transport has been a particularly active sector for innovation. So has industry, with a focus on energy-efficient technologies for industrial production, including in some of the hard-to-abate sub-sectors such as iron and steel. Meanwhile, the overall growth trend since 2017 is being led by invention in cross-cutting technologies that enable higher levels of clean energy, such as batteries, hydrogen, smart grids and CCUS.

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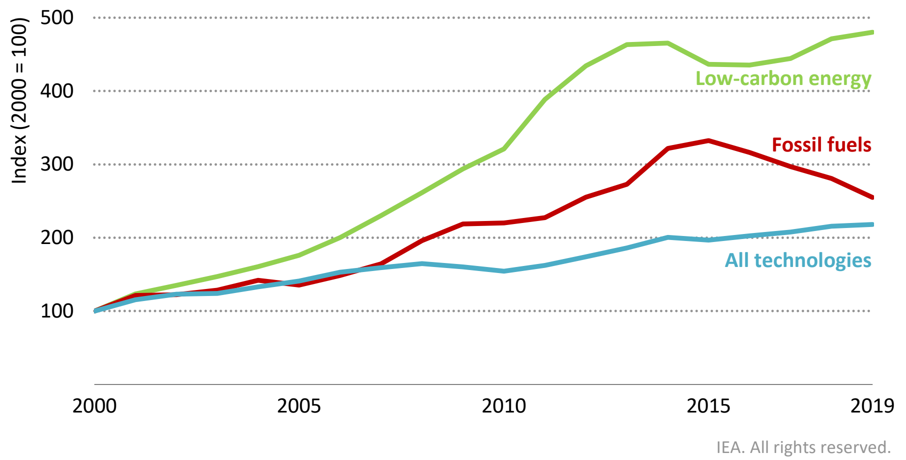
[4] The analysis focuses on international patent families, each representing a high value invention for which patent applications have been filed at a regional patent office or in at least two jurisdictions worldwide.

Figure 2.14 ▷ **Global patenting for low-carbon energy technologies versus fossil fuel and other technologies, 2000-2019**



Patenting activity for low-carbon energy technologies has risen faster than for fossil fuels since 2000, but a new wave of innovation remains essential

Source: Joint analysis by IEA and European Patent Office (2021e).

The very rapid pace of clean energy innovation assumed in the NZE depends on governments putting research, development, demonstration and deployment at the core of their energy and climate policies. There are some positive signs in this respect. Public spending on energy research and development continued to rise in 2020, and low-carbon technologies accounted for 80% of this. Innovation features in many of the stimulus packages announced by governments, with about USD 25 billion already committed to major demonstration projects for large-scale low-carbon energy technologies, including CCUS and other ways to mitigate industrial emissions. This figure could double based on recent announcements. However, this still falls far short of the USD 90 billion of public money that needs to be mobilised to complete a full portfolio of demonstration projects over the coming decade. Moreover, the international collaboration that plays an important part in accelerating knowledge transfer and supporting rapid diffusion of new technologies cannot be taken for granted.

Chapter 3

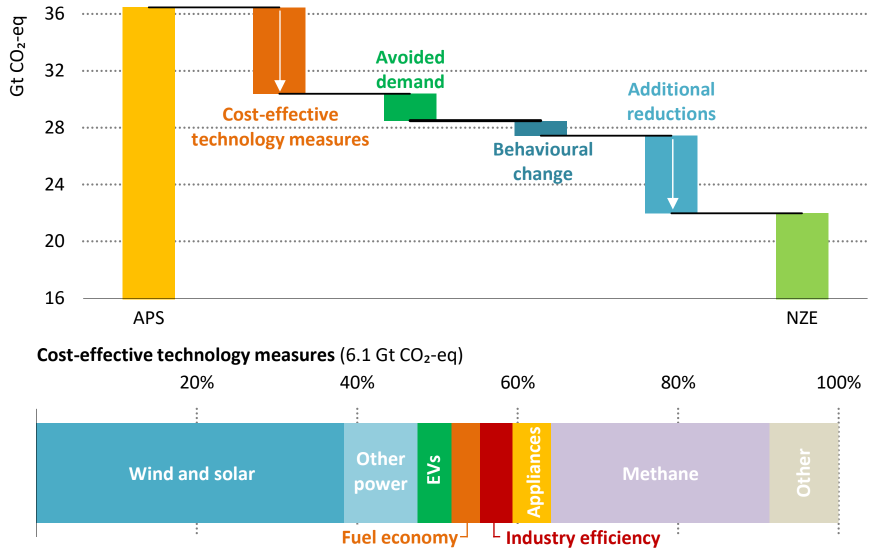
The ambition gap to 1.5 °C

An energy guidebook for COP26

SUMMARY

- Announced net zero pledges and updated Nationally Determined Contributions have been fully incorporated into the IEA's new Announced Pledges Scenario (APS). The APS closes less than 20% of the gap in 2030 between the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE), leaving an "ambition gap" of 12 gigatonnes (Gt) CO_2 that needs to be closed to put the world on the pathway to reach net zero emissions by 2050. Including fossil fuel methane emissions increases the gap to 14 gigatonnes of carbon-dioxide equivalent (Gt CO_2-eq).
- Over 40% of this gap between the APS and the NZE pathway could be bridged with cost-effective technology measures, and an additional 25% could come from measures to temper demand, including materials efficiency and digitalisation.

Figure 3.1 ⊳ Breakdown of measures to close the ambition gap by 2030



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Over 40% of the 2030 ambition gap between the APS and NZE can be closed with cost-effective technology measures

- Accelerating the decarbonisation of the electricity sector is the single most important way to close the 2030 ambition gap, and could cut emissions by around 5 Gt. We estimate that up to 60% of the gap in the electricity sector can be closed through cost-effective expansion of wind, solar photovoltaics (PV), hydro and nuclear power, reducing the need for coal by 350 gigawatts (GW) by 2030 compared with the APS.

Stopping all new investment decisions in coal would cancel the construction of 200 GW and avoid 0.8 Gt of CO_2 emissions in 2030. Another 150 GW of coal capacity could be closed at no cost to consumers in addition to the 480 GW retired in the APS to 2030.

- Reducing methane emissions is also a critical lever to close the 2030 ambition gap. Fossil fuel methane emissions are almost 2 Gt CO_2-eq higher in the APS than in the NZE in 2030, largely because about 60% of current methane emissions come from countries without net zero pledges.[1] We estimate that almost 1.7 Gt CO_2-eq of this gap could be closed cost-effectively in the NZE by 2030.
- Energy efficiency in end-use sectors and measures to reduce demand together could contribute to cut about 2.6 Gt of the ambition gap. We estimate that almost 80% of the energy efficiency potential in the NZE could be achieved cost-effectively by 2030. Key measures include stronger standards for fuel economy and appliance efficiency, as well as more robust policy emphasis on materials efficiency in industry.
- Electrification, hydrogen and carbon capture, utilisation and storage (CCUS) account for a bit less than 2 Gt of the emissions reductions gap between the APS and NZE by 2030. Making the most of the increasing cost-effectiveness of electric vehicles (EVs) in all regions could lead to 60 million more electric cars on the road in 2030 than under announced pledges. Innovative technologies for iron and steel production based on hydrogen or CCUS remain expensive by 2030, but pushing their deployment to NZE levels in the short term is an investment that accelerates innovation and enables 660 million tonnes (Mt) of steel to be produced cost-effectively using these technologies in 2050, almost four-times more than in the APS.
- Although electrification, hydrogen-based fuels, CCUS and carbon removal are responsible for only 15% of the ambition gap in 2030, they account for 40% of the gap between the scenarios in 2050. Announced pledges included in the APS lag far behind key NZE milestones related to the deployment of these technologies. The gap can be closed with "breakthrough programmes" in areas like electrification, hydrogen-based fuels, CCUS and carbon removal, extra funding for demonstration projects, and enhanced international co-operation on innovation.
- Bridging the ambition gap from the APS to the NZE by 2030 would require an increase of clean energy investment of about USD 1.7 trillion, relative to the APS. 70% of this would go to emerging market and developing economies. Well over USD 1 trillion of the additional investment would be to support measures that are cost-effective in 2030. Public finance plays a catalytic role in mobilising finance in the NZE: annual clean energy investments by domestic and international public finance institutions in emerging market and developing economies total at least USD 65 billion under announced pledges, but this rises to over USD 200 billion by 2030 in the NZE.

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[1] One tonne of methane is considered to be equivalent to 30 tonnes of CO_2 based on the 100-year global warming potential (IPCC, 2021).

3.1 Introduction

The 26th Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) takes place in November 2021 in Glasgow, having been postponed from 2020 due to the Covid-19 pandemic. It comes five years after the entry into force of the Paris Agreement, and provides a critical opportunity to strengthen the ambition of the global response to climate change. The COP26 Presidency has set a number of key objectives for the meeting:

- Gather new 2030 emissions reduction pledges from countries, in line with the goal of net zero emissions by 2050.
- Strengthen national adaptation efforts and enhance international collaboration on enabling adaptation.
- Deliver on developed countries' pledge to mobilise USD 100 billion in annual financial support for developing countries.
- Finalise the detailed rulebook for the Paris Agreement and enhance collaboration between governments, business and civil society to enable climate action in key sectors.

In advance of COP26, the Intergovernmental Panel on Climate Change (IPCC) released the first volume of its Sixth Assessment Report, *Climate Change 2021: The Physical Science Basis* (IPCC, 2021). The report confirms that the global surface temperature has already warmed by 1.1 degrees Celsius (°C) compared to the pre-industrial era. Stabilising the global surface temperature requires achieving net zero CO_2 emissions together with sharp reductions in other greenhouse gas (GHG) emissions. The remaining carbon budget for limiting warming to 1.5 °C (with a 50% probability) will last only around 11 years at the current rate of emissions. The report highlighted the observed increases in extreme weather events such as heat waves, floods, droughts and storms, and the growing robustness of scientific attribution of such events to climate change caused by humans.

A rising number of countries have announced new long-term net zero pledges or submitted updated Nationally Determined Contributions (NDCs) to the UNFCCC in the run up to COP26, or both. This chapter explores to what extent these announced ambitions and targets, including the most recent ones, will deliver the emissions reductions required to achieve net zero emissions by 2050. It examines actions that could help to close the gap between current stated ambitions and the net zero emissions pathway, and suggests cost-effective measures that our analysis identifies as priorities.

The "ambition gap" represents the divergence between current ambitions and the pathway to achieve net zero emissions by 2050. The focus in this chapter is the ambition gap between the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 Scenario (NZE). There is also a gap between stated policy targets and current measures, referred to as the "implementation gap", which is analysed as the divergence between the Stated Policies Scenario (STEPS) and the APS and is presented in Chapter 4. Together the ambition and implementation gaps define the actions required to transition from current measures as reflected in the Stated Policies Scenario to the realisation of the Net Zero Emissions by 2050 Scenario.

Chapter 3:

- Provides an overview of the NZE to give context for the discussion of the ambition gap (section 3.2).
- Summarises the analysis of the ambition gap and highlights four key points for policy makers (section 3.3).
- Examines in detail the ambition gap in the electricity sector (section 3.4).
- Examines in detail the ambition gap in end-use sectors (industry, transport and buildings) (section 3.5).
- Discusses the critical issue of reducing fossil fuel methane emissions (section 3.6).
- Considers the role of behavioural change in the NZE pathway (section 3.7).
- Considers the consequences of the ambition gap for the achievement of the UN Sustainable Development Goals related to air pollution (section 3.8).

3.2 Achieving net zero emissions by 2050

The NZE is designed to reach net zero CO_2 emissions from energy and industrial processes by 2050, without offsets from other sectors, while ensuring secure energy supplies, economic growth and development (IEA, 2021a). The NZE stays within the remaining cumulative emissions budget of 500 gigatonnes (Gt) from 2020 onwards, consistent with a 50% chance of limiting warming to below 1.5 °C (IPCC, 2021).[2] The NZE is a path towards net zero emissions by 2050: it is far from being the only possible path. We know that the real-world transition is sure to involve surprises in terms of technologies, policies and behaviours.

In addition to the objective of net zero emissions by 2050, several other principles guided the design of the NZE:

- It draws on all available technologies and emissions reduction options, including those currently at demonstration or prototype stage. It does not entail the adoption of technologies that are not currently known and understood today, but does assume a significant shortening of the time to large-scale deployment for technologies currently under development. The NZE also aims to limit, as far as possible, the deployment of negative emissions technologies.
- It requires substantial international co-operation, with all countries contributing to the net zero goal (Box 3.1). Co-operation accelerates technology innovation and diffusion, and facilitates emissions reductions in emerging market and developing economies.
- It aims to ensure an orderly transition, including by maintaining energy security, minimising energy market volatility and avoiding stranded assets where possible.

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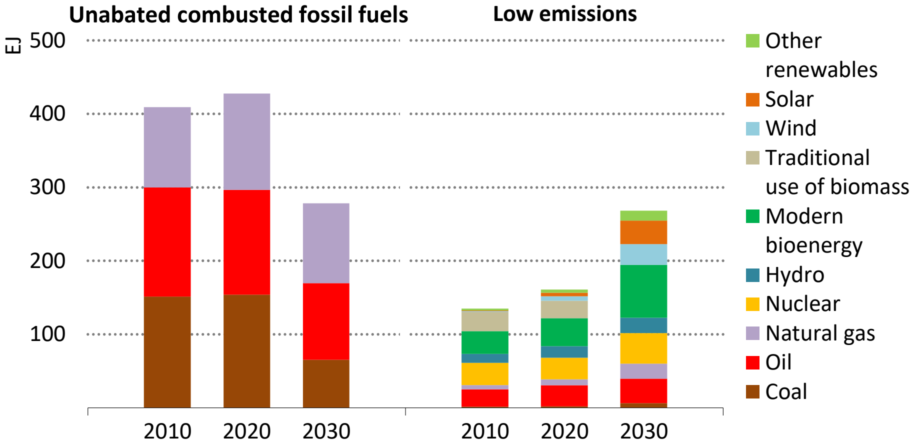
[2] This budget is based on Table SPM.2 of the 2021 IPCC report of Working Group 1 (IPCC, 2021). The size of the remaining CO_2 budget for limiting temperature rise to a given level is impacted by the trajectory of non-CO_2 greenhouse gas emissions.

- An equitable transition is central to the NZE. While advanced economies reach net zero emissions before emerging market and developing economies in the NZE, the pathway also achieves full energy access and significant reductions in air pollution as set out in the UN Sustainable Development Goals, and ensures that energy affordability is maintained.

At the heart of the NZE is a massive transition in the way we produce and consume energy (Figure 3.2). Global GDP grows by around 40% between 2020 and 2030, but total energy supply falls by around 7%. Electrification of end-uses, more efficient energy technologies and behavioural change enable a decoupling of economic growth from energy demand. Low emissions sources of energy supply grow by two-thirds between 2020 and 2030. The expansion of solar, wind, and modern bioenergy is particularly significant, while hydropower and nuclear also contribute. Today about one-quarter of total energy supply is from low emissions energy sources and this expands to around one-half by 2030 in the NZE.

Figure 3.2 ▹ Transition in global total energy supply by source to 2030 in the Net Zero Emissions by 2050 Scenario



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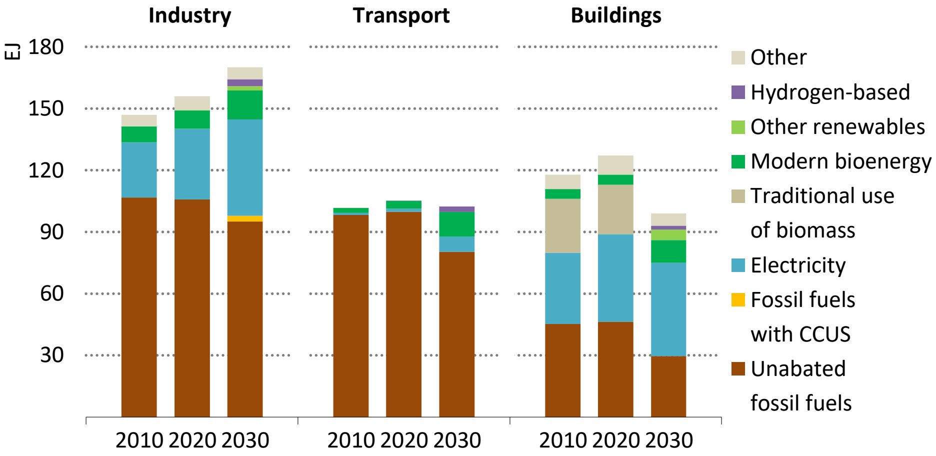
Rapid growth of low emissions energy supply sources significantly displaces unabated fossil fuels by 2030, especially coal

Notes: EJ = exajoules. Other renewables include marine and geothermal energy. Modern bioenergy includes modern solid biomass, liquid biofuels and biogases derived from sustainable sources; it excludes the traditional use of biomass. Low emissions coal, oil and natural gas include fuel combustion equipped with CCUS, as well as fossil fuel used in non-energy purposes. Non-renewable waste use is not reported.

Thanks to this growth in low emissions energy supply, demand for unabated fossil fuels declines by 30% between 2020 and 2030. Coal falls by more than 50% over this period to around 2 500 million tonnes of coal equivalent (Mtce). Oil initially rebounds from the low level seen in 2020, but it soon starts to decline and falls to 72 million barrels per day (mb/d) in 2030. Natural gas follows a slightly different trajectory, with demand increasing for several years in the 2020s before peaking and falling to 3 700 billion cubic metres (bcm) by 2030, which is below its 2020 level. As a result of the declining demand for fossil fuels, no new oil and gas fields are approved for development, and no new coal mines or mine extensions are required.

The transition on the supply side goes hand-in-hand with a rapid transition in the way we consume energy (Figure 3.3). In the NZE, electricity gains ground in all end-use sectors by 2030. In aggregate its share in total final energy consumption rises from 20% to 26% by 2030. Although this may seem like a relatively small change, it implies a rapid turnover rate for the huge global stock of energy-consuming equipment and massive growth in the sales of electric heat pumps, electric vehicles (EVs) and appliances. For example, global sales of EVs increase from 4.6% of total car sales in 2020 to around 60% by 2030.[3]

Figure 3.3 ▷ Final energy consumption by source and sector to 2030 in the Net Zero Emissions by 2050 Scenario



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Electrification and the adoption of low emissions fuels accelerate in the 2020s

Notes: EJ = exajoules. CCUS from ammonia production is excluded from this figure as it applies to process emissions, not energy consumption.

Some new technologies and low emissions fuels that have an important future role make vital progress in the 2020s. Hydrogen-based fuels and fossil fuels equipped with CCUS account for 3% of total final consumption by 2030, up from almost nothing today. While this may sound insignificant, it is nonetheless important. Without innovation and learning-by-doing to drive down their costs over the next decade, it would be much more difficult for these technologies to ramp up after 2030 to contribute to achieving net zero energy emissions by 2050. The share of modern bioenergy more than doubles by 2030 and its growth is particularly significant in long-distance transport.

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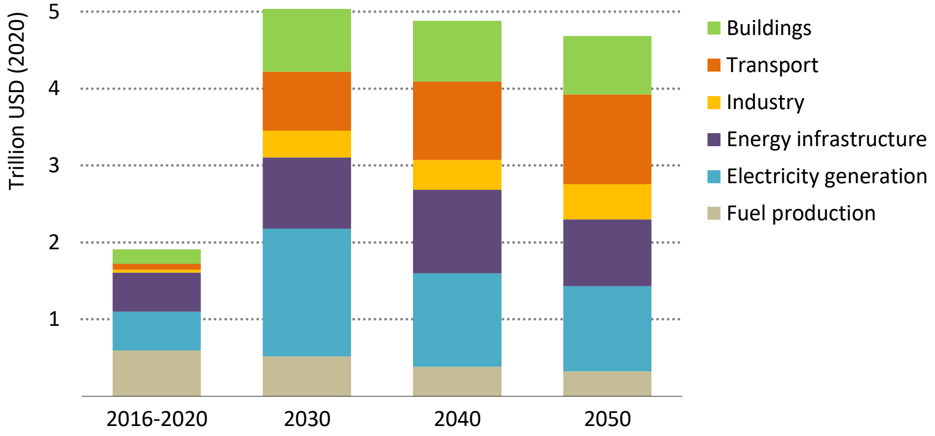
[3] EVs include battery electric and plug-in hybrid electric vehicles.

Energy efficiency, avoided demand[4] and behavioural change are essential to reducing energy demand. Between 2020 and 2030, the energy intensity of the global economy decreases by 4.2% per year in the NZE, more than double the average rate of the previous decade. Without this improvement, total final consumption would be about a third higher in 2030, significantly increasing the cost and difficulty of decarbonising energy supply.

Figure 3.4 ▷ Average annual energy investment 2016-2020, and in the Net Zero Emissions by 2050 Scenario



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Meeting the accelerated decarbonisation goals of the NZE requires a surge in global energy investment to USD 5 trillion by 2030, with 85% of spending directed to clean energy

Notes: Energy infrastructure includes electricity networks, public EV charging, CO_2 pipelines and storage facilities, direct air capture facilities, hydrogen refuelling stations, import and export terminals for hydrogen, and fossil fuel pipelines and terminals. Buildings, transport and industry categories include investment in energy efficiency, electrification and end-use applications for low emissions fuels (see section 3.5).

The deployment of low emissions technologies requires a surge in energy investment (Figure 3.4). In the NZE, total energy sector capital spending increases from around 2.5% of GDP per year in recent years to around 4.5% of GDP in 2030, before easing to 2.5% in 2050. By 2030, the vast majority of investment goes towards clean energy technologies, of which the largest share is for power generation with total annual investment increasing from around USD 0.5 trillion over the past five years to nearly USD 1.7 trillion in 2030. By then, more is being invested in power generation from renewables in a single year (USD 1.3 trillion) than the largest amount ever invested in fossil fuel production in a year. The record for investment in fossil fuel supply was USD 1.2 trillion in 2014. Investment in energy infrastructure increases from around USD 0.4 trillion to over USD 0.9 trillion in 2030.

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[4] Avoided demand is energy service demand changes enabled by technology developments, such as digitalisation.

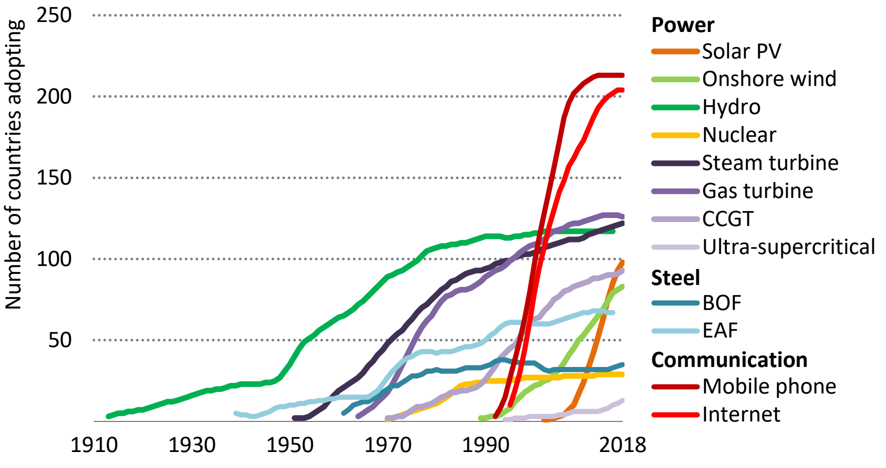
Electricity grids account for the lion's share of this, although investment in CO_2 transportation and storage, EV charging and hydrogen infrastructure also increases substantially, albeit from a low base.

Total investment in end-uses includes all investment in efficiency, electrification and the use of low emissions fuels based on hydrogen, as well as renewables and CCUS. In the NZE, these investments accelerate to USD 1.9 trillion in 2030, and continue to rise afterwards. The increase is particularly significant in transport, where the purchase of EVs drives up spending, and in buildings, where investment is driven by retrofit programmes and electrification.

Box 3.1 ▻ International technology diffusion

The NZE requires very rapid diffusion of clean energy technologies across the world. Historically, many energy technologies have diffused slowly, with substantial lags between early and late adopters (Figure 3.5). Widespread diffusion has often taken decades, with late adopters typically located in emerging market and developing economies.

Figure 3.5 ▻ Number of countries that have adopted selected energy and non-energy technologies, 1910-2018



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Compared with historical rates, a substantial acceleration in international diffusion of clean energy technologies is required on the path to net zero emissions

Notes: CCGT = combined-cycle gas turbine; BOF = basic oxygen furnace; EAF = electric arc furnace. Adoption is not defined here as the first observed exploitation of the technology, but rather exploitation at or above a threshold level, defined as 3% of the maximum ever observed per capita technology exploitation of the early adopters.

Sources: IEA calculations based on data from Comin and Hobijn, (2009); Maddison Project Database, (2020); S&P Global (March 2021); WSA, (various years); World Bank, (2021).

Technologies with large unit sizes and complex installation requirements have typically diffused more slowly than technologies with small unit sizes that are relatively easy to take up. Outside the energy sector, mobile phones and the internet are good examples of technologies that have very rapidly been adopted worldwide.

In the energy sector, wind and solar PV power generation technologies have spread globally at a relatively rapid pace. Tackling climate change demands global diffusion of other low-carbon technologies at a similar pace. In the APS, however, there is a risk in that the gap between the early and late adopters of clean technologies could widen. This is particularly the case for complex technologies with large unit sizes such as CCUS, advanced bio-refineries or hydrogen use in industry, where diffusion is likely to be slower than for wind and solar PV unless strong efforts are made to accelerate diffusion. This underscores the need to strengthen co-operation to accelerate the diffusion of new clean energy technologies if the ambition gap between the APS and NZE is to be bridged.

3.3 Moving from announced pledges to achieve net zero emissions by 2050

Recent announcements of net zero pledges signal an acceleration of policy ambition on climate change. Countries accounting for between 60-70% of global CO_2 emissions have announced net zero emissions pledges.[5] The APS includes all recent major national announcements of 2030 targets and longer term net zero and other pledges, regardless of whether these have been anchored in implementing legislation or in updated NDCs. It also includes all commitments made in new and updated NDCs, regardless of whether they are underpinned by specific implementation plans. According to national studies, some net zero targets include plans for offsets outside the energy sector, and these have been integrated into the design of the scenario. In the APS, countries fully implement their national targets to 2030 and 2050, and the outlook for exporters of fossil fuels and low emissions fuels like hydrogen is shaped by what full implementation means for global demand for these fuels.

Announced pledges could bridge slightly less than 20% of the gap between the Stated Policies Scenario and the Net Zero Emissions by 2050 Scenario

Total CO_2 and methane emissions reach 39 Gt CO_2-eq in 2030 in the STEPS, up from around 38 Gt in 2020. Full implementation of announced pledges lowers 2030 emissions to 36 Gt in the APS while the NZE reduces them to 22 Gt, leaving an ambition gap of 14 Gt. Full delivery of announced pledges therefore closes slightly less than 20% of the total gap between the STEPS and NZE in 2030 (Figure 3.6). This improves somewhat in the longer term, with the APS closing a little less than 40% of the gap between the STEPS and NZE in 2050.

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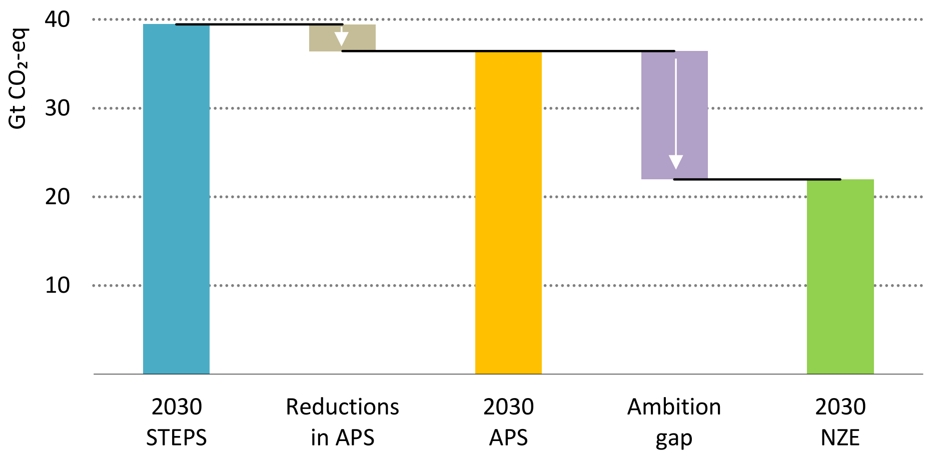
[5] The range is determined by decisions to include or exclude countries based on the target date of the net zero pledge and the degree of commitment implied in the formulation of the pledge, e.g. draft policy document versus adopted policy document.

Figure 3.6 ▹ CO_2 and methane emissions from energy and industrial processes in the three scenarios, 2030



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Announced pledges would close less than 20% of the gap between the STEPS and NZE

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

This *World Energy Outlook* (*WEO*) incorporates new analysis of the long-term temperature impacts of our scenarios using the MAGICC climate model, which has been used extensively in IPCC assessment reports (see Chapter 1 for more details). If it were to be accompanied by policies that reduce non-energy GHGs proportionately, and if emissions trends were to continue on a comparable trajectory after 2050, the STEPS would lead to a rise in global average temperatures of about 2.6 °C in 2100.[6] This falls short of the goals of the Paris Agreement to limit warming to well below 2 °C, and to pursue efforts to limit the temperature increase to 1.5 °C. The APS could lower 2100 warming to 2.1 °C, an improvement on the STEPS, but still above the Paris Agreement goals. In the NZE, warming in 2100 is kept below 1.5 °C (Figure 3.7).

All countries bear responsibility for some part of the ambition gap. Under net-zero pledges, the emissions of advanced economies with pledges do not decline in the aggregate as fast as they do in the NZE pathway. The same is true for emerging market and developing economies with pledges, notably from China and particularly over the period to 2030. Updated NDCs do not help much to narrow the gap: it has been estimated that only around 60% of new or updated NDCs submitted to the UNFCCC as of September 2021 actually represent an increase in ambition compared to the previous NDCs (Climate Watch, 2021). Countries without net zero pledges or updated NDCs include a number of large, fast growing and low income emerging market and developing economies. In these countries, transition is much faster in

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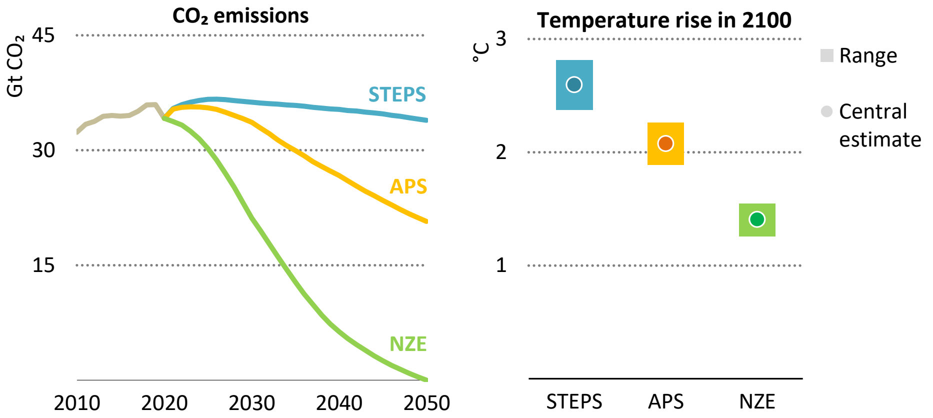
[6] The temperature rise in this section refers to median warming above the 1850 -1900 average.

the NZE than in the APS, but this assumes that they introduce more stringent policies than those currently in force: it also assumes enhanced international co-operation and financial support. Taken as a group, countries with net zero pledges and countries without net zero pledges are each responsible for about half the ambition gap, indicating that all countries need to increase their level of ambition if the gap is to be closed.

Figure 3.7 ▻ **Global energy-related and industrial process CO_2 emissions by scenario and temperature rise above pre-industrial levels in 2100**



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Announced pledges would not meet the Paris Agreement temperature goals

Notes: Central estimate = median temperature in 2100. Range = 33rd – 67th percentile.

Box 3.2 ▻ The global significance of China's net zero pledge

China is the world's largest energy consumer and carbon emitter. In September 2020, the Chinese president announced China's aim to have CO_2 emissions peak before 2030 and to achieve carbon neutrality before 2060.

A pathway towards this vision is the focus of a recent collaboration between the IEA and leading energy experts in China, reported in *An Energy Sector Roadmap to Carbon Neutrality in China* (IEA, 2021c). This pathway, reflected in the APS, has China's emissions peaking near 2030 in line with its current commitments.

The "China Roadmap" explores opportunities for China to narrow this gap in 2030 by accelerating near-term actions, which could facilitate reaching its NDC aim of making "best efforts to peak early" and provide more flexibility after 2030 as China strives to reach net zero emissions by 2060.

An accelerated trajectory is attainable. If China meets its non-binding target to raise the non-fossil fuel share of total energy supply to 20% by 2025 (from around 16% in 2020), the IEA projects that CO_2 emissions from fuel combustion will be on track to plateau in the mid-2020s and decline modestly to 2030. In both the APS and the accelerated trajectory, energy sector investment climbs significantly in absolute terms, but falls as a share of overall economic activity.

Accelerated action would bring substantial benefits for China. It would further its central role in global clean energy technology value chains and support its emerging position as a world leader in clean energy innovation and the new energy economy. While accelerated action would lead to the loss of 2.3 million jobs in fossil fuel supply and fossil fuel power plants, it would also increase employment in China's clean energy supply by 3.6 million by 2030: the 1.3 million net increase in jobs is three-times that in the APS.

A faster transition would also avoid around 20 Gt of locked in emissions to 2060 from long-lived assets in the power and industry sectors that the APS sees built in the period to 2030. As a result it would reduce by nearly 20% the required average annual pace of emissions reductions after 2030 to reach carbon neutrality by 2060, compared with the APS, leaving more time for markets to adjust, and businesses and consumers to adapt. Beyond the direct impact on emissions, an accelerated transition in China could have a significant impact on innovation, given China's size and industrial strength, and thus facilitate a faster global transition.

Electricity sector decarbonisation is the biggest single lever for closing the 2030 ambition gap

In the APS, total electricity sector CO_2 emissions fall slightly less than 20% from 2020 to 2030, all from countries with net zero pledges, while those without such pledges increase their electricity sector emissions in aggregate. Despite the nearly 20% fall, electricity sector emissions in the APS are around 5 Gt higher in 2030 than in the NZE, which means that the electricity sector accounts for around 35% of the 2030 ambition gap between the APS and NZE scenarios.

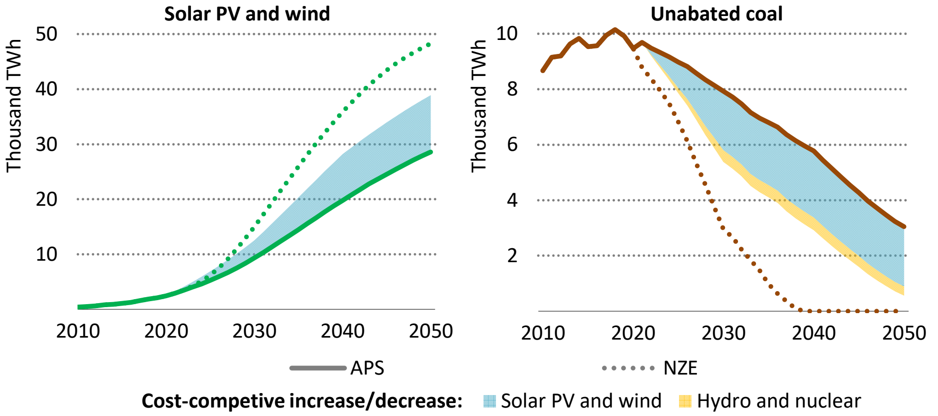
Emerging market and developing economies account for the vast majority of this ambition gap in the electricity sector. This reflects the fact that coal tends to dominate the electricity sector in emerging market and developing economies, while most advanced economies have made net zero pledges and start from electricity sectors less reliant on coal. To close the gap, the annual rate of global wind and solar PV capacity additions from 2021 to 2030 would need to be almost twice as high as it is in the APS.

The accelerated electricity sector transition in the net zero pathway requires a large increase in investment in generation and networks in the current decade, compared to the levels seen in the APS. However, low technology costs and the availability of low cost financing in many markets means that policy makers could establish enabling conditions in which up to 60% of the additional generation of solar and wind in the NZE could be achieved at no additional cost to consumers (Figure 3.8). Additional cost-effective measures related to hydropower, nuclear lifetime extensions and some new nuclear projects could displace up to an additional 1 000 terawatt-hours (TWh) of coal- and gas-fired generation in 2030.

We calculate that about 2.3 Gt CO_2 emissions could be cut in 2030 at no cost to electricity consumers by deploying cost-effective wind and solar PV, closing about half of the emissions gap between the APS and NZE in the electricity sector. An additional 0.6 Gt of emissions reductions could be achieved through other cost-effective measures relating to hydropower, nuclear lifetime extensions and new nuclear in some markets.

Section 3.4 examines the electricity sector transition in the APS and NZE in more detail, and explores policy options to accelerate it in line with the NZE pathway.

Figure 3.8 ▷ Global solar PV, wind and unabated coal-fired electricity generation in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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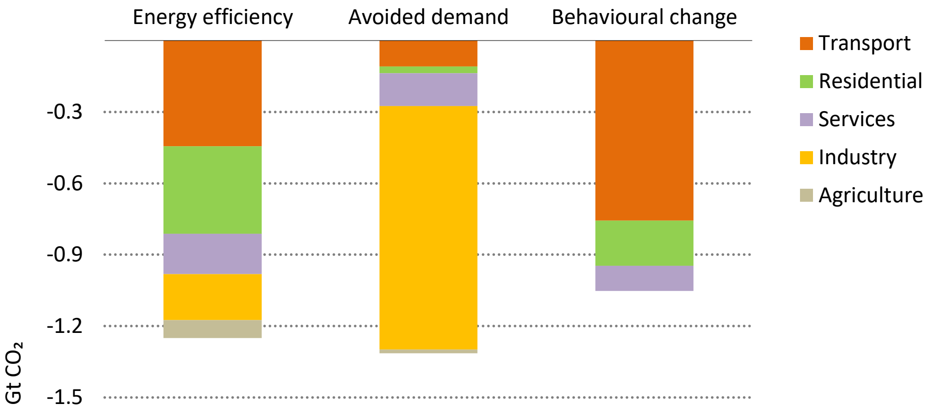
By 2030, 60% of the increase in solar and wind generation seen in the NZE could be achieved at no additional costs to consumers

Note: Cost-effective solar PV and wind are evaluated based on total system costs (Box 3.5).

Energy efficiency and avoided demand are essential to bridge the ambition gap

Much stronger policies for end-use energy efficiency in the NZE reduce emissions by about 1.3 Gt in 2030, compared with the APS, and are of particular importance in the transport and buildings sectors. We estimate that almost 80% of the energy efficiency potential in the NZE could be achieved cost-effectively by 2030. Avoided demand through measures such as digitalisation and materials efficiency helps to reduce emissions by a further 1.3 Gt in 2030. The largest share is in the industry sector, where opportunities for materials efficiency are substantial. In the short term, this helps to compensate for the fact that the industry sector has fewer energy efficiency opportunities, and low emissions technologies are less mature in industry than in most other sectors. Behavioural change contributes a bit more than 1 Gt by 2030 to closing the emissions gap, particularly in the transport sector (Figure 3.9).

Figure 3.9 ▻ **Emissions reductions from end-use efficiency, avoided demand and behavioural change in 2030 between the Announced Pledges and Net Zero Emissions scenarios**



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Energy efficiency improvements and avoided demand would close almost 20% of the ambition gap between the APS and NZE, while behavioural change also plays a role

Note: includes CO_2 emissions reductions in industrial processes due to avoided demand.

More vigorous action in energy efficiency would therefore close about 10% of the ambition gap, and additional measures to avoid demand would close a further 10%. However, the importance of these measures goes beyond emissions reductions. Lower demand reduces the amount of low emissions energy that must be supplied, helps to lower the overall costs of transition and increases the resilience of the energy system.

Box 3.3 ▻ Cost-effectiveness analysis of options to close the ambition gap

The modelling of the Announced Pledges and Net Zero Emissions by 2050 scenarios allow us to identify the levers that reduce emissions at the level of sectors, technologies and policy options. Detailed investment and fuel expenditure data for many of these levers enable a comparison of costs between the APS and NZE. These comparisons assume enabling policies consistent with the level of policy stringency in the NZE. It should be noted that the comparisons of the two scenarios do not take into account the co-benefits of climate action, such as improvements in air pollution or the long-term benefits of mitigating climate change.

For end-use technology options such as EVs, a total cost of ownership or levelised cost of production approach is employed, which takes into account investment and discounted fuel expenditure for the lifetime of the equipment. For energy efficiency options, we compare annuitised investment with fuel expenditure at the sub-sectoral level to identify which measures are cost-effective. All analysis is at the country or regional level, taking into account country or regional investment costs, fuel prices and policies.[7] A total system cost approach is used for the electricity sector, taking account of investment, fuel, balancing and transmission costs (see Box 3.5 for detail).

The assessment of the cost-effectiveness of materials efficiency, digitalisation and other measures which lead to avoided demand is handicapped by the lack of granular data on the investment costs of mitigation options. For example, it was not possible to assess the investments needed to raise the plastic recycling rate, increase steel scrap recycling or promote clinker substitution. For this reason, avoided demand measures are not shown under the heading of cost-effective technology measures in Figure 3.1, although many of these measures would probably cut emissions cost-effectively. The same issue arose for behavioural measures; therefore they are not included in our assessment of cost-effective options.

Some technologies fall far behind in the APS by 2030, risking the 2050 net zero goal

After 2030, end-use sectors decarbonise in the NZE by switching to the use of electricity, hydrogen-based fuels, CCUS in industry, or advanced bioenergy. CCUS is critical to addressing process emissions from cement, natural gas-based hydrogen and biofuel production, for the production of synthetic fuels, and to reach negative emissions from bioenergy with carbon capture and storage and direct air capture with storage. In the electricity sector, most of the heavy lifting is done by renewables in the NZE, but bioenergy, CCUS and hydrogen-based fuels play a critical role in providing low-emissions dispatchable capacity and delivering negative emissions when CCUS is combined with bioenergy.

These emissions reduction options contribute only around 15% to closing the ambition gap between the APS and NZE by 2030. However, their contribution increases after 2030 and accounts for around 40% of the emissions reductions between the two scenarios by 2050. In the NZE, measures to promote the electrification of heavy-duty transport and industry, and the use of hydrogen, ammonia and CCUS, require immediate efforts to bring down costs and build enabling infrastructure. If the deployment of these options is not accelerated in the current decade, the impact on 2030 emissions may be small, but the risk to the feasibility of net zero emissions by 2050 would be substantial.

It is therefore a matter of concern that some of the emissions reductions options that are most off-track in the APS by 2030 are those related to electrification, hydrogen-based fuels and CCUS, particularly in the hard-to-abate sectors (Figure 3.10) (Box 3.4 details the milestone comparison method). By 2030, the APS only achieves 40% of the level of deployment of clean shipping fuels seen in the NZE, less than 15% of the level of deployment of CCUS in industry, and less than 10% of the deployment of hydrogen in industry.

Deployment targets and more substantial funding for research and development (R&D) are essential to drive down the costs and bring forward the availability of technologies critical to

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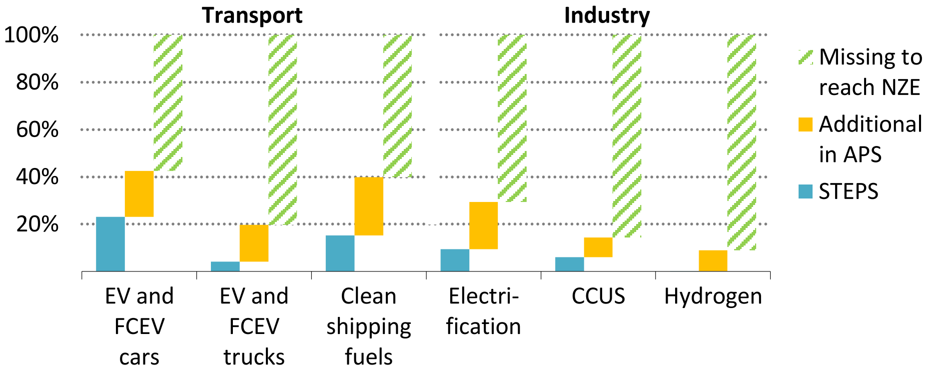
[7] The IEA World Energy Model represents the largest countries individually and smaller countries as regional aggregates.

long-term decarbonisation. In the NZE, around USD 90 billion of public money is mobilised to complete a portfolio of demonstration projects before 2030. Currently, only about USD 25 billion is budgeted for that period. Robust policy monitoring is also important in order to ensure that technologies are on track and also to enable learning-from-experience in sectors where innovation is still needed.

Figure 3.10 ▷ Tracking progress towards 2030 milestones in transport and industry by scenario



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A number of key milestones in the NZE related to clean energy transitions in end-uses significantly lag in the APS

Notes: The 2030 milestones are those set out in the Net Zero Emissions by 2050 Scenario. EV = electric vehicles, FCEV = fuel cell electric vehicles. Clean shipping fuels include biofuels, electricity and hydrogen-based fuels. Low-carbon hydrogen is deployed in the STEPS in industry, but in such small quantities relative to the NZE milestones that it is barely visible when indexed to the NZE.

Box 3.4 ▷ Measuring progress towards 2030 milestones in the *WEO* scenarios

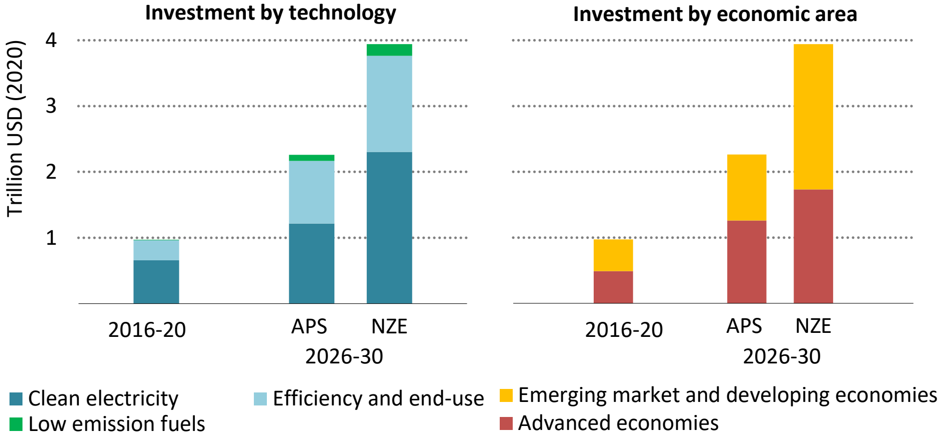
A number of figures in this chapter, e.g. Figure 3.10, present a comparison of key 2030 NZE milestones relative to the STEPS, APS and NZE scenarios. Each milestone is represented as an index in the figures, with the NZE value at 100%. This allows milestones with different units to be shown on the same figure. For each milestone the index is calculated as the change over the period 2020 to 2030, rather than the 2030 value alone. This gives a better indication of the change required to reach the milestones.

For example, the share of electricity in total final consumption in 2030 in the APS is 22% compared with 26% in the NZE. At first glance, this might suggest that there is not much difference between the APS and the NZE on this score. However, the increase from 2020 to 2030 in the share of electricity in total consumption is only two percentage points in the APS (from 20% to 22%) compared with six percentage points in the NZE (from 20% to 26%). The APS thus achieves only about one-third of the increase in electrification from 2020 to 2030 that is achieved in the NZE. Calculating the change in this indicator therefore provides a better indication of the degree to which electrification lags in the APS compared to the NZE.

An additional USD 1.7 trillion of annual clean energy investment is required to achieve the NZE, 70% of which needs to occur in emerging market and developing economies

The APS sees substantial growth in annual clean energy investment, reaching around USD 2.3 trillion by 2030. This is a major step up from the level of recent years. But it still falls well short of the level of clean energy investment seen in the NZE, which rises to around USD 4 trillion annually by 2030 (Figure 3.11). The largest investment gaps in moving from the APS to NZE are in clean power (generation and grids), where annual spending is USD 1.1 trillion higher in the NZE, and in energy efficiency and end-use decarbonisation, where annual spending is over USD 0.5 trillion higher. Investment in low emissions fuels in the NZE is only around USD 0.1 trillion higher than the APS by 2030, but it sees the fastest growth among all areas of clean energy investment.

Figure 3.11 ▷ Average annual investment in clean energy by type and economic area, 2016-2020, and by scenario, 2026-2030



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Clean energy investment in the NZE is 75% higher than in the APS, with around 70% of the extra investment needed in emerging market and developing economies

Emerging market and developing economies account for around 70% of the extra investment in clean energy that is required to bridge the gap from the APS to the NZE by 2030. Over 60% of this increment comes from the private sector in the NZE. Mobilising this scale of capital will require significant policy efforts to address project risks and ensure adequate risk-adjusted returns for developers, banks and investors, including through commercial arrangements that support predictable revenues, enhanced creditworthiness of counterparties and enabling infrastructure, among other factors.

Although private finance accounts for most clean energy investment, public sources of capital play a particularly important role in catalysing investment in markets where access to capital is constrained, in sectors lacking bankable projects, and in funding energy infrastructure. Around two-thirds of the additional publicly sourced investment in emerging market and developing economies required in the NZE comes from domestic state-owned enterprises, which play a particularly important role in developing electricity grids. Public finance institutions, including international development banks and domestic green banks, account for the remaining one-third of the additional public investment required. Annual clean energy investments by domestic and international public finance institutions in emerging market and developing economies rise to more than USD 200 billion in 2030 in the NZE, compared with at least USD 65 billion in the APS.[8]

3.4 Electricity sector

Current status and gap to NZE

Global CO_2 emissions from electricity generation increased by just 9% over the last decade even though electricity demand rose by 25%. Renewable energy technologies collectively met almost 65% of electricity demand growth over the decade, led by the rapid expansion of solar PV and wind as their deployment increased fivefold. Innovation and low cost finance have helped drive down the costs of solar PV and wind, and they are now the cheapest new sources of electricity in most markets. Coal-to-gas switching, particularly in the United States, also curbed electricity sector emissions.

Nevertheless, the electricity sector was responsible for 12.3 Gt CO_2 emissions in 2020, or 36% of all energy-related CO_2 emissions. Coal contributed just over one-third of electricity supply but around three-quarters of electricity sector CO_2 emissions. Natural gas was the second-largest source of both electricity and CO_2 emissions in the sector.

In the APS, electricity demand increases from around 23 300 TWh today to about 30 300 TWh by 2030, an increase of 30%, while global CO_2 emissions from electricity generation fall by around 18% to 10.1 Gt in 2030 (Figure 3.12). The major drivers of demand growth are growth in all end-use sectors and the production of low-carbon hydrogen, which goes from almost nothing today to some 540 TWh by 2030.

In the NZE, total electricity demand rises to about 33 200 TWh in 2030, almost 10% higher than in the APS. Electricity demand for low-carbon hydrogen production increases to 3 850 TWh by 2030 in the NZE, more than seven-times the level in the APS, and electricity demand in the transport and industry sectors is higher in the NZE than in the APS. However, the more significant effort on energy efficiency in the NZE, notably in the buildings sector, helps to offset the effects of increasing electrification and hydrogen production. Electricity sector emissions drop to 5.1 Gt in 2030 in the NZE, making the ambition gap around 5 Gt. Emissions from coal-fired power plants decline by about 70% to 2030 compared with an 18% reduction in the APS.

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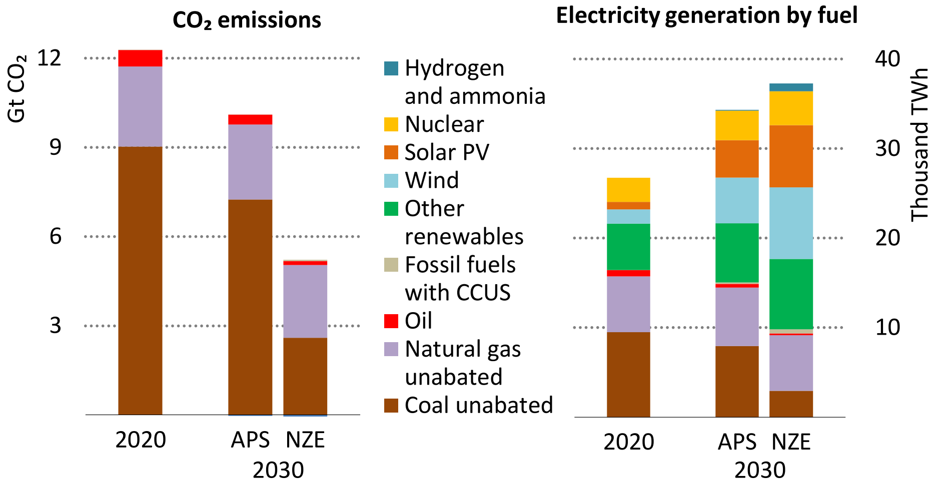
[8] Public finance institution spend includes primary finance for clean energy projects (debt, equity, grants), but does not include flows to financial intermediaries, guarantees or indirect means of public participation, such as technical assistance. The estimate here differs from official climate finance provided and mobilised by developed countries for developing countries -– which includes bilateral or multilateral development funding specifically targeted at climate change mitigation and adaptation – in both scope and measurement approach.

Figure 3.12 ▷ Global electricity sector CO_2 emissions and generation by source in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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Clean electricity transitions accelerate in the APS, though unabated fossil fuels are only cut by 10% to 2030, leaving a 5 Gt emissions gap with the NZE, the largest of any sector

Note: Other renewables include hydropower, bioenergy, marine and geothermal energy.

Beyond 2030, emissions from electricity generation steadily decline to 4.8 Gt by 2050 in the APS, of which unabated coal-fired power plants account for over 2.7 Gt. In the NZE, the electricity sector reaches net zero emissions globally by 2040.

Renewables are set to become the foundation of electricity systems around the world. Over the next decade, announced pledges drive a renewables expansion that is fast enough to keep pace with electricity demand growth and reduce the need for fossil fuels in electricity. The share of renewables increases from almost 30% of global electricity generation in 2020 to about 45% in 2030 in the APS. At that point, the share of renewables in generation exceeds that of fossil fuels, although it is still around fifteen percentage points short of the level reached in the NZE.

Solar PV and wind lead the way, thanks to low costs, widespread availability and policy support in over 130 countries: their capacity more than triples over the next decade, which is nearly enough to meet all electricity demand growth to 2030, and their share of generation rises from under 10% in 2020 to nearly 30% in 2030. Other commercial technologies – hydropower, bioenergy and geothermal – also contribute to the expansion of renewables, while earlier stage technologies such as concentrating solar power and marine power gain a foothold.

Other low emissions sources increase their output by over 800 TWh over the next decade in the APS, complementing the growth of renewables. Nuclear power capacity in operation expands by over 10% by 2030 in the APS, with 25 countries completing new reactors. This more than offsets retirements of ageing reactors, mainly in advanced economies. In the NZE, further efforts to extend the safe operation of existing reactors and accelerate new builds in countries favourable to nuclear power raise its output by another 15% by 2030. Beyond 2030, advanced nuclear power technologies such as small modular reactors expand opportunities for nuclear to produce low emissions electricity, heat and hydrogen.

Fossil fuel power plants equipped with CCUS together with those equipped to use hydrogen and ammonia contribute around 230 TWh of electricity generation by 2030 in the APS. This puts them in a position to make more significant contributions beyond 2030. In the NZE, the unprecedented pace of innovation and uptake sees their contribution by 2030 rise to 1 300 TWh, or 4% of total generation, putting them in a stronger position to make additional long-term contributions to clean energy transitions after 2030.

Global unabated coal-fired electricity generation falls by around 15% from 2020 to 2030 in the APS as low emissions sources of generation are scaled up. In advanced economies, where over 20 countries have announced or are considering to phase out its use, unabated coal-fired generation falls by three-quarters from today's level to 2030, led in particular by the United States and European Union. The shift away from coal is more challenging in fast growing emerging market and developing economies. China remains the largest user of unabated coal in the electricity sector in the APS, accounting for nearly 60% of the global total in 2030. India and Southeast Asia are the next largest users of unabated coal, and are responsible for about 15% and 10% of global use for electricity generation in 2030.

Natural gas is the largest source of electricity in advanced economies today, and the growth of renewables in the APS drives down emissions in part by reducing unabated natural gas-fired generation by 20% from 2020 to 2030. This is, however, well short of the 30% reduction in the NZE. In emerging market and developing economies, unabated natural gas-fired generation increases by about one-third to 2030 in both the APS and NZE. Gas-fired capacity remains an important part of electricity system flexibility in all scenarios to 2050, though the amount of unabated natural gas-fired generation varies widely. It continues to rise in the APS, while falling by 95% on the path to net zero emissions in 2050.

Closing the gap from the APS to the NZE

Bridging the gap between the APS and NZE scenarios in the electricity sector requires policy makers to take action to:

- Scale up the supply of low emissions electricity from wind and solar.
- Accelerate the deployment of dispatchable sources of low emissions electricity such as hydropower and nuclear.
- Stop investment in new unabated coal-fired power plants, while retrofitting, repurposing or retiring existing unabated fossil fuel plants.
- Enhance the flexibility of electricity systems to accommodate high shares of variable renewables.

Accelerating the growth of renewables and other low emissions sources of electricity is the most important step in closing the gap from the APS to the NZE in the electricity sector. Renewables-based generation needs to increase by 12% each year over the next decade in the NZE, compared with 8% per year in the APS. Building on the record level of 248 GW achieved in 2020, solar PV and wind capacity additions reach almost 470 GW in the APS in 2030, but exceed 1 000 GW in the NZE. As a result, global electricity generation from solar PV and wind is 60% higher in the NZE than in the APS.

Given their low technology costs and the availability of low cost financing in many markets, we estimate that up to 60% of the additional solar PV and wind generation between the APS and NZE in 2030 would be cost-effective, and could be enabled by policy levers without raising total system costs or consumer electricity prices (Box 3.5). The related impact on fossil fuels would close 2.3 Gt of the ambition gap. We also estimate that other cost-effective measures related to hydropower, nuclear lifetime extensions and new nuclear power in some markets could close a further 0.6 Gt of the ambition gap.

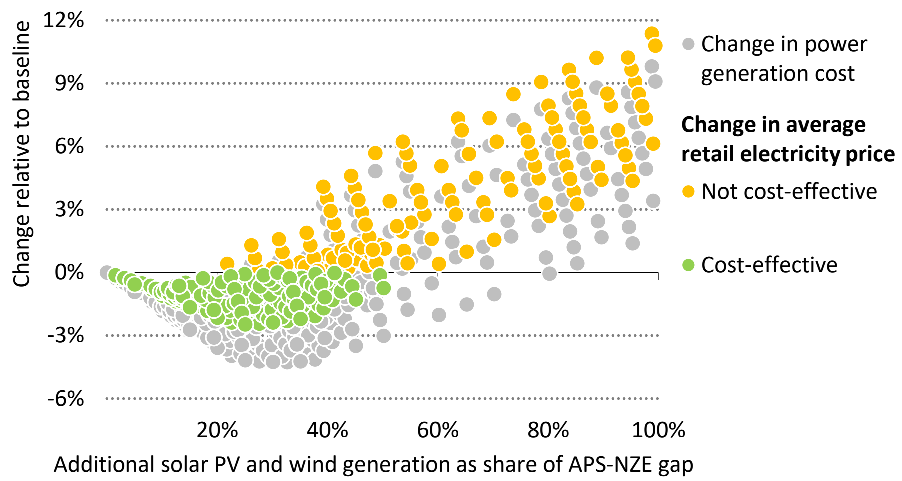
Box 3.5 ⊳ Evaluating the cost-effective share of wind and solar expansion

The cost-effective expansion of wind and solar PV was evaluated based on simulated end-user electricity prices in the World Energy Model (WEM), which reflects total power system costs including investment, fuel, operation and maintenance, balancing and grid costs. The exercise considered how much additional wind and solar PV would be cost-effective if the enabling conditions in the NZE were applied, including those related to fuel and CO_2 prices and expanding the availability of low cost financing for wind and solar PV.

Starting from the Announced Pledges Scenario, over 400 additional model runs were performed for each of the 26 WEM regions, steadily increasing the contribution of solar PV and wind up to the amount in the NZE. The additional solar PV and wind generation displaced coal- and gas-fired generation based on their operating costs, simulated operations and presence in each region. Based on their simulated contributions to system adequacy, the additional solar PV and wind capacity also displaced the need for some fossil-fuelled capacity built in the APS.

The evaluation revealed that up to 60% of the worldwide additional wind and solar PV generation in the NZE relative to the APS in 2030 would be cost-effective where policy makers created an environment that enabled this to happen. For example, up to about 50% of the additional wind and solar PV that features in China in 2030 in the NZE could be added without increasing average electricity prices (Figure 3.13). In other words, half of the gap between the APS and NZE in the deployment of wind and solar PV in 2030 in China could be closed without raising costs to consumers. It is particularly important to consider the total system costs when evaluating cost-effectiveness in the electricity sector. If the evaluation had been based on total generation costs that exclude grid-related costs, for example, the amount of cost-effective solar PV and wind would have been exaggerated. Similarly, a focus on technology costs alone would have failed to capture many essential system dynamics and might have provided a misleading assessment.

Figure 3.13 ▻ Change in electricity prices and generation costs for additional solar PV and wind generation in China, 2030



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About 50% of the additional wind and solar generation in China in the NZE is cost-effective, provided policy makers establish enabling conditions

Scaling up the market for renewables starts with policy frameworks that provide a clear long-term vision, encourage competition and limit risks for investors throughout the supply chain, from equipment manufacturing to project developers and off-takers. For example, well-planned auction schemes and renewable energy mandates have emerged as effective and efficient approaches in many markets to expand renewable energy. At the same time, action to strengthen the financial health of the sector, including regulations to ensure appropriate cost recovery, is essential to limit off-taker risk for new projects. Electric utilities and distribution companies face financial difficulties in several emerging market and developing economies, notably in India and Africa.

The pace of nuclear power expansion can also be accelerated in the short term, though to a lesser degree, given the length of time it takes to build new nuclear power plants. Annual additions of nuclear power increase from an average of 7 GW from 2016-20 to 23 GW in 2030 in the APS. This is a major achievement, but still short of the 33 GW added in 2030 in the NZE. Retrofitting coal- or gas-fired capacity with CCUS is an important way to help existing fossil fuel power plants contribute to clean energy transitions, and completing the retrofit of 15-25 large projects each year in the second-half of the 2020s would be consistent with the pathway to net zero emissions electricity systems.

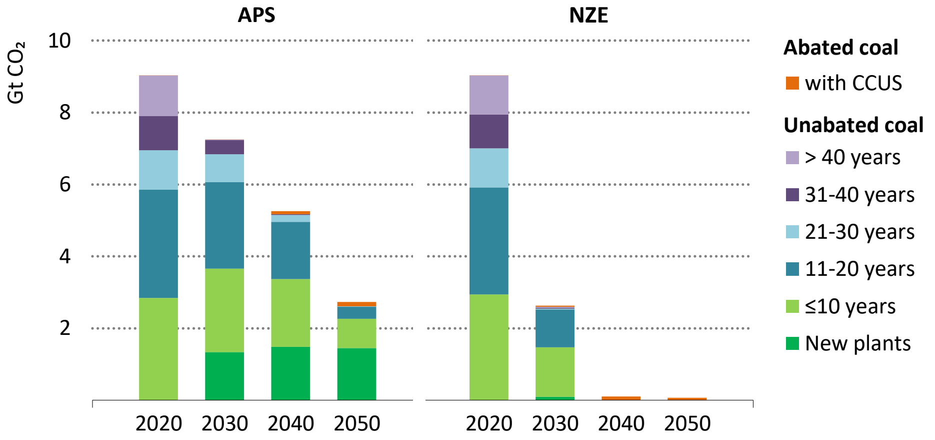
Expanding other low emissions dispatchable capacity and non-emitting sources of flexibility are the next critical steps to close the gap from the APS to the NZE. Hydropower, including pumped storage, has long been a leading source of electricity system flexibility and has the potential to expand its role much further through the modernisation of existing projects, electrification of existing dams and new projects. Bioenergy can offer dispatchable power and low emissions when using sustainable supplies in dedicated power plants, co-fired with coal in solid form or with natural gas as biogas. Geothermal can also be an attractive option where resources are favourable. Ammonia and hydrogen produced from low emissions sources offer a scalable solution that can be co-fired in existing coal- and gas-fired power plants, or used in fully converted or new facilities.

Scaling up energy storage systems will be critical to address the hour-to-hour variability of wind and solar PV, especially as their share of generation increases. Meeting rising flexibility needs while decarbonising electricity is a central challenge for the electricity sector and calls for tapping all sources of flexibility, including power plants, grids, demand-side response and storage (see Chapter 4). Utility-scale battery storage capacity increases 30-fold from 2020 to 2030 in the APS, compared with over 60-fold in the NZE. Ensuring electricity security throughout clean energy transitions also calls for operational and market reforms (see Chapter 6). For example, it is important for markets and regulations to place a proper value on electricity system flexibility and contributions to system adequacy in order to provide signals for investment compatible with net zero pathways.

In the NZE, the expansion of low emissions electricity generation and dispatchable capacity allows a rapid shift away from unabated coal-fired generation. There are over 2 100 GW of coal-fired capacity in operation today, and many are young. However, there are also many ageing plants with rising maintenance costs that face challenging market conditions. The business case for the continued use of any coal-fired power plant depends in many cases on the need for their output and services to the grid, including the contribution they make to capacity adequacy, system stability and flexibility. Where low emissions sources are able to step in and provide all those services, operating existing coal plants or building new ones quickly becomes uneconomic.

If all the cost-effective opportunities for low emissions sources are realised, we estimate that over 350 GW of coal-fired capacity in the APS in 2030 would not be needed, representing about 20% of the global coal plant fleet at that time. Stopping all new investment decisions would cancel the construction of 200 GW of coal-fired power plants in the APS and would save an estimated 0.8 Gt CO_2 emissions in 2030, closing about 15% of the gap in electricity sector emissions between the APS and NZE. This would also allow an extra 150 GW of coal-fired capacity to be permanently closed by 2030, in addition to the 480 GW retired in the APS, without compromising electricity security or raising electricity bills for consumers. In total, the net upfront investment in capacity and grid infrastructure would increase by about USD 300 billion per year on average over the next decade.

Figure 3.14 ▷ CO_2 **emissions from coal-fired power plants by age and scenario**



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The oldest and least efficient coal plants are due to be phased out in the APS, but those built recently will continue operating for decades without strengthened policy

Note: The age of coal plants is as of 2021.

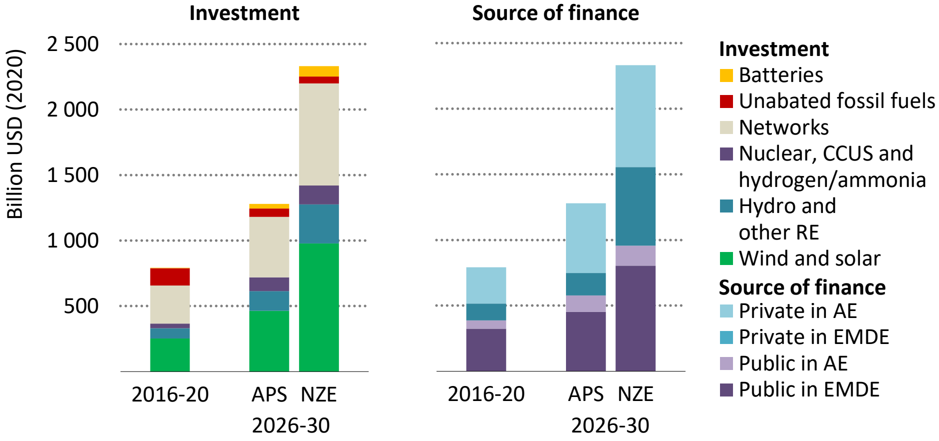
Tackling emissions from coal-fired power plants calls for making the best use of the existing fleet of coal plants until they can be retired. A multi-pronged approach is the most cost-effective way to cut emissions while maintaining electricity security, particularly in emerging market and developing economies. One option is to repurpose facilities to reduce operations and focus on flexibility services, facilitating the integration of renewables and cutting emissions. Another is to retrofit facilities with carbon capture technologies or to co-fire coal with high shares of ammonia or sustainable biomass, enabling continued operations while greatly reducing emissions. Younger and more efficient facilities are the best candidates for retrofitting with carbon capture technologies, and younger plants fitted with such technologies are the only kind of facilities still in operation in the NZE by 2040 (Figure 3.14).

Once coal-fired power plants are no longer needed for their electrical output or system services, financing their retirement becomes critical to ensuring the financial health of the sector (Chapter 1, section 1.7 discusses the financial and social aspects of coal phase-outs around the world). In the APS, the average age of coal-fired capacity at retirement is around 35 years in emerging market and developing economies, and this falls to 25 years in the NZE. In advanced economies, coal plants are already almost 35 years old on average: they are retired after another eight years on average in the APS and five years in the NZE.

Financing the transition of the electricity sector in the NZE

The NZE requires a threefold increase in electricity sector investment by 2030, compared with historical levels, taking it up to an annual average of USD 2.3 trillion by the late 2020s. As a share of GDP, investment in electricity would need to increase from nearly 1.0% over the 2016-2020 period to 2.2% over the second-half of the 2020s. Investment in renewables accounts for 55% of this total. While announced pledges put electricity sector investment on an upward trend, spending falls short of what is needed for the net zero pathway in the NZE by about USD 1.1 trillion in 2030 (Figure 3.15).

Figure 3.15 ▷ Average annual investment by type and source in the electricity sector, 2016-2020, and by scenario, 2026-2030



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Investment in renewables and networks increases to fulfil announced pledges, but much more is needed to achieve the net zero emissions pathway, most of it from private capital

Notes: AE = advanced economies; EMDE = emerging market and developing economies; Other RE = other renewables. Investment values represent annual averages for the indicated time periods.

It would be challenging to deliver an increase in investment of this scale, but there are some precedents. For example, annual investment in internet and communication technologies increased by more than 2% of GDP in OECD countries between 1990 and 2000. Although average global annual investment in the power sector doubled over the last two decades from USD 400 billion in 2001-05 to USD 800 billion over the last five years, the NZE requires both faster growth and changes in the sources of finance. In the NZE, the power sector depends increasingly on private sources of capital, international funds and low cost debt financing. Over 60% of capital expenditure on power generation and 40% of spending on grids is financed by private funds in the NZE. Financing from international sources also increases by more than five-times compared with recent levels.

Power companies, generally reliant on international debt financing, would need to continue to play a major role, but other companies with large balance sheets and global experience – including oil and gas firms or other diversified energy actors – could play an important part too. Refinancing could also help recycle capital, bring in institutional investors and improve returns for developers.

Mobilising investment at the speed and scale required would demand substantial changes at the domestic level as well as the international level to improve policy and regulatory frameworks and develop pipelines of projects with the right risk-return balance. International efforts should focus on helping countries, especially emerging market and developing economies, to enhance their investment frameworks for clean power and networks (including by making more effective use of blended finance to catalyse private capital), and to find the right business models to finance the phase-out of coal, while at the same time supporting the displaced coal workers to find new jobs, including in clean energy where possible (see Chapter 1, section 1.7).

3.5 End-use sectors

3.5.1 Industry

Current status and gap to the NZE

Industry energy consumption represents almost 40% of current global total final consumption and is still dominated by fossil fuels, in particular coal. This high level of reliance on fossil fuels together with the CO_2 emitted in raw material reduction processes (e.g. from limestone in cement production) means that the industry sector emits 8.7 Gt CO_2 today, making it the second-largest emitting sector after power generation.[9]

The challenge ahead for the industry sector is to meet growing industrial product demand while curbing CO_2 emissions. In the APS, the demand for primary industrial products like iron and steel, cement, and primary chemicals rises between today and 2030 by around 10-30%, depending on the sub-sector. Almost all of this growth occurs in emerging market and developing economies as they industrialise and urbanise. The globalisation of supply chains has already led to emerging market and developing economies, and in particular China, accounting for a large share of global industrial production.

In the APS, global industry CO_2 emissions rise above pre-crisis levels in 2021, reach a peak in the late 2020s, and are still higher than today in 2030. A decline in emissions in advanced economies is dwarfed by their continued growth in emerging market and developing economies. Industry emissions are lower in the NZE and reach a peak five years earlier than in the APS. Of the 2.8 Gt CO_2 emissions difference between the APS and the NZE in 2030, cement and steel account for more than half of the gap (Figure 3.16). By source, unabated coal accounts for more than half of the 2.8 Gt gap, process emissions for more than 20% and combustion of oil and gas for around 15% each.

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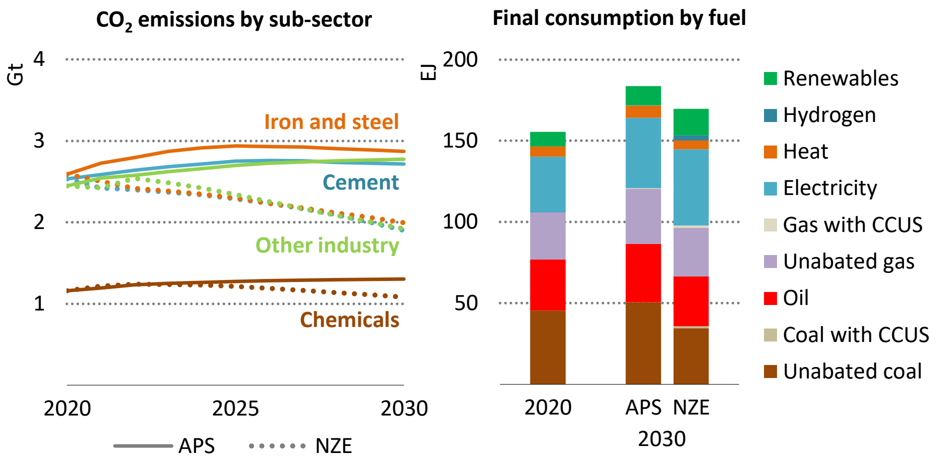
[9] All CO_2 emissions in this section refer to direct CO_2 emissions, i.e. it does not include emissions of the electricity and heat sector, unless otherwise specified.

Figure 3.16 ▷ **CO₂ emissions by sub-sector and final energy consumption by fuel in industry in the Announced Pledges and Net Zero Emissions by 2050 scenarios**



CO_2 emissions by sub-sector

Final consumption by fuel

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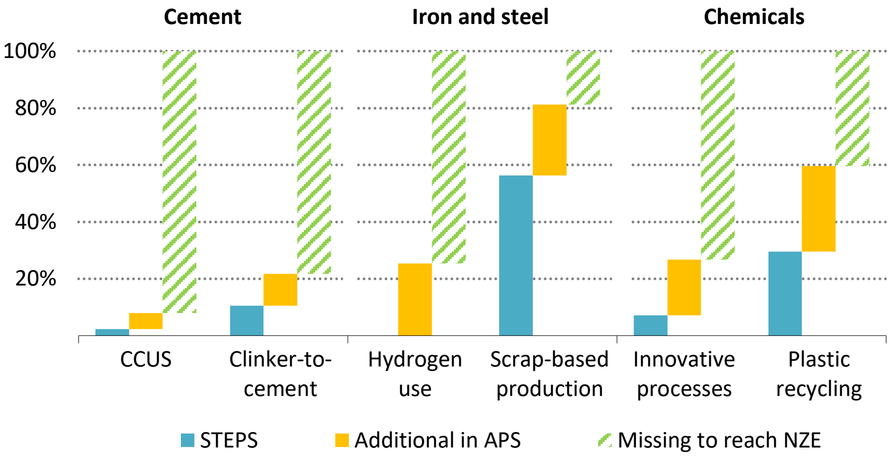
Industry is the largest end-use sector in terms of energy use and CO_2 emissions; its challenge is to meet rising demand for materials while transitioning from unabated fossil fuels

Note: Gas = natural gas.

The **iron and steel** industry is the largest contributor to the ambition gap accounting for 0.9 Gt of the gap between the APS and NZE. Most of the difference is the result of lower steel demand in the NZE, which is brought about by improved design in construction, vehicles and machinery, and by a switch away from coal, especially in emerging market and developing economies. Coal is primarily displaced by electricity, which sees its share in total energy use increase from 15% in the APS to 23% in the NZE, although there is also some switching to natural gas. Electric arc furnaces (EAF) play a key part in the transition from coal together with natural gas-based direct reduced iron (DRI). An increase in the steel recycling rate is also necessary to enable the growth of EAF production routes: in the NZE, the scrap share in metal input reaches 38% by 2030, compared to 31% today. Additional CCUS deployment in the NZE accounts for about 10% of the emissions gap in 2030, although it makes a bigger contribution after 2030 through the deployment of innovative smelters. Low emissions steel production using hydrogen-based DRI and EAF accounts for less than 1% of the gap in 2030, but it too ramps up rapidly in the following decades.

The **cement** sub-sector is the second-largest contributor to the ambition gap between the APS and NZE. Emissions are slightly higher in 2030 in the APS than they are today, while they fall by a quarter in the NZE. Almost half of the emissions reduction in the NZE compared to the APS comes from a 120 Mtce reduction in coal use which is achieved through reducing material demand, improving kiln efficiencies and shifting from coal to bioenergy. A further reduction in emissions comes from additional CCUS deployment to address both combustion and process emissions, with CCUS increasing from 15 Mt CO_2 in the APS to 220 Mt CO_2 in the NZE in 2030 (Figure 3.17). Alternatives to clinker are also deployed to cut process emissions further: in the NZE, the clinker-to-cement ratio[10] declines from a global average of around 0.71 today to 0.65 by 2030 (0.7 in the APS).

Figure 3.17 ▷ Tracking progress towards 2030 milestones by industry sub-sector and scenario



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Despite good progress in some areas, technology transformation in the industry sector needs to happen much faster than in the APS to meet climate goals

Notes: The 2030 milestones are those set out in the Net Zero Emissions by 2050 Scenario. The baseline is 2020. Innovative processes refer to electric steam crackers, electrolysis or pyrolysis methanol-to-olefins, low-carbon hydrogen ammonia and methanol production.

Light industries, together with aluminium and pulp and paper production, account for a further 0.7 Gt of the emissions gap. The difference reflects reduced use in the NZE of coal, natural gas and oil in almost equal parts: fossil fuel use decreases strongly in the NZE, reaching 21 EJ by 2030 compared to 28 EJ in the APS.

The **chemicals** industry accounts for just 0.25 Gt of the 2030 emissions gap between the APS and NZE, despite experiencing the highest level of material demand growth of all industrial sectors. Almost half of the difference is due to a reduction in natural gas use in the NZE; a third to reduced oil use, and almost 15% to lower process emissions. Increased materials efficiency and new energy efficient processes making use of biomass-based fuels and CCUS are key to cutting emissions to 2030 and beyond.

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[10] Clinker-to-cement ratio is the mass of clinker required to produce one unit of cement. The smaller the ratio the lower the process emissions. Clinker alternatives include calcined clay, volcanic ash or blast furnace slag.

Closing the gap from the APS to the NZE

Decarbonisation is slower to take-off in the industry sector than elsewhere, reflecting the long lifetimes of production facilities and related infrastructure, and the lack of ready access to key alternative technologies, a number of which are still at an early stage of commercialisation. Efforts to close the ambition gap between the APS and the NZE in the industry sector should focus primarily on strengthening policy frameworks for energy and materials efficiency; quickly setting up a comprehensive regulatory framework giving clear direction and incentives for new investment; accelerating electrification of all industrial sub-sectors; and increasing innovation and investment for CCUS technologies and hydrogen-based processes, including by ramping up international co-operation.

- Governments should put in place ambitious policy frameworks to promote material and energy efficiency improvements in the industry sector. Materials efficiency gains are the primary way to avoid energy consumption and CO_2 emissions in the short term. Lifetime extensions of buildings save steel and cement, for example, even though they may require the refurbishment or repurposing of buildings; improved manufacturing techniques could reduce avoidable losses (e.g. in cutting body panels from metal sheets for cars) via improved design, process digitalisation or material substitution; and light-weighting, especially for cars, could reduce material use. Governments should promote energy efficiency for its multiple benefits, notably emissions reduction, cost savings and improved competitiveness: the US Department of Energy Better Plants Program is one example of what might be done.
- Governments should take timely decisions together with industry on large-scale deployment of near zero emissions technologies: by 2024 in advanced economies and 2026 in emerging market and developing economies, governments and companies should have developed strategies for incorporating these technologies into the next series of capacity additions and replacements for industrial plants. This includes decisions on whether to pursue CCUS, hydrogen, or a combination of both. Measures such as emissions mandates and standards, carbon pricing, operational subsidies (such as those in the Netherlands SDE++ scheme) and CCUS-specific market mechanisms could all help to achieve the required level of ambition.
- Governments should enforce policies to increase the competitiveness of electrification over the next decade. Carbon pricing, such as the European Union Emissions Trading System (EU ETS), already provides a framework for action, but additional financial support or incentives may be required to promote the retrofitting of existing assets. Examples of relevant programmes include the National Key Technologies R&D Programme in China, the European Union Horizon programme and ETS Innovation Fund, and the Japan Innovation Fund.
- Governments should set breakthrough cost targets, support demand through mandates or deployment targets, and strengthen R&D in innovative technologies. A large share of future emissions reductions in the industry sector depends on technologies that are not yet available at commercial scale (Box 3.6). The scaling up of CCUS still faces a lot of

technical, economic, infrastructure and societal hurdles, although a number of countries are moving forward: for example, the US Energy Act of 2020 includes an economy-wide portfolio of measures such as support of pilots and demonstration projects, CO_2 storage projects, loans for large-scale projects and carbon removal competition prizes. Despite the growing number of countries that have developed hydrogen strategies, governments also need to be more proactive in supporting hydrogen demand through mandates or incentives. International collaboration is critical to achieving the rate of innovation required through action to co-ordinate R&D, create larger markets for low emissions products, and provide a level playing field.

Beyond these measures, each industrial sub-sector requires specific actions to close the gap. In the cement sub-sector, for example, the development of supply chains for alternatives to clinker has an important part to play. Countries or regions could develop flexible standards and building codes for concrete, of which cement is the key component, that do not prescribe specified amounts of clinker, and this could facilitate the increased uptake of blended cements without compromising safety and performance. In the iron and steel sub-sector, procurement obligations for low emissions steel in public projects would expand the size of its market and help to overcome concerns about industrial competitiveness, while increased recycling and reuse of plastics would reduce energy and related emissions growth in the chemicals industry.

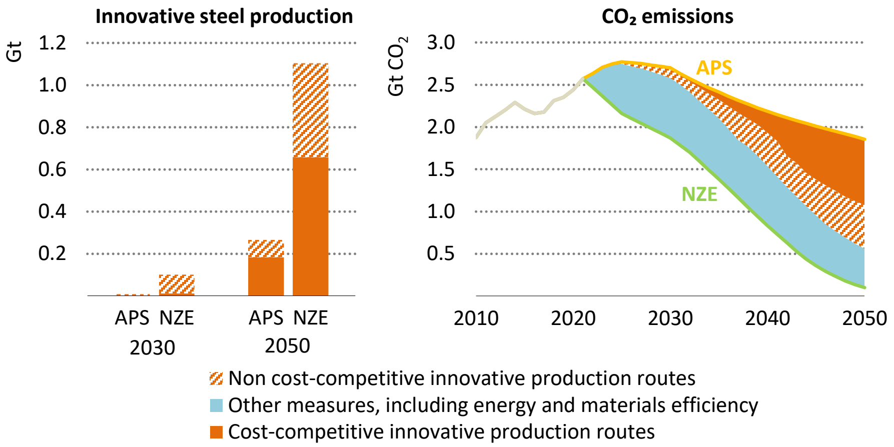
As most energy-intensive industrial products are sold in globalised markets, it is important to find ways to avoid carbon leakage. Governments and international trade associations should push for international standards that can help to increase the market for low-carbon products and prevent unfair competition. Well-designed carbon border adjustment mechanisms may have a role to play here.

Box 3.6 ▷ Can low-carbon steel production compete with conventional processes?

The major challenge for the iron and steel sub-sector in terms of decarbonisation is to find alternative routes for emissions-intensive primary production. Increasing the cost-effectiveness of low emissions production routes is key to mitigating industry emissions without impacting prices.

To try to answer this question, we calculated the levelised cost of production of three low emissions primary production routes: smelting reduction equipped with CCUS, direct reduced iron with CCUS, and hydrogen-based DRI. We compared this with the costs of the main incumbent emissions-intensive technology, which is the blast furnace and basic oxygen furnace method of production (BF-BOF). The assessment was done at the regional level. Capital expenditure for low emissions technologies is assumed to decrease over time and operating expenditure includes energy and CO_2 prices.

Figure 3.18 ▷ Cost-competitive steel production from innovative technologies and related CO_2 emissions in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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Innovative steel production technologies become cost-competitive in the long term, if the move from experimental to industrial scale takes place before 2030

Figure 3.18 shows total production from innovative routes in the APS and NZE, and the share which is cost-competitive. It also breaks down steel sub-sector emissions reductions between the APS and the NZE from innovative production routes and other measures such as energy and materials efficiency.

In 2030, the vast majority of reductions come from energy and materials efficiency, which tend to be cost-effective measures. However, the NZE involves a more rapid expansion of innovative production routes by 2030 than the APS does, which drives down costs and accelerates deployment of enabling infrastructure.

This investment pays off in the longer term. Of the 14.7 Gt cumulative CO_2 emissions savings from innovative processes to 2050 in the NZE compared to the APS, 50% are cost-competitive. Technological improvement drives down electrolyser and CCUS investment costs, while a rising CO_2 price also favours low emissions routes. CCUS provides an efficient lever to avoid locked in emissions particularly in relatively young BF-BOF steel plants in Asia (see Chapter 4, Box 4.1).

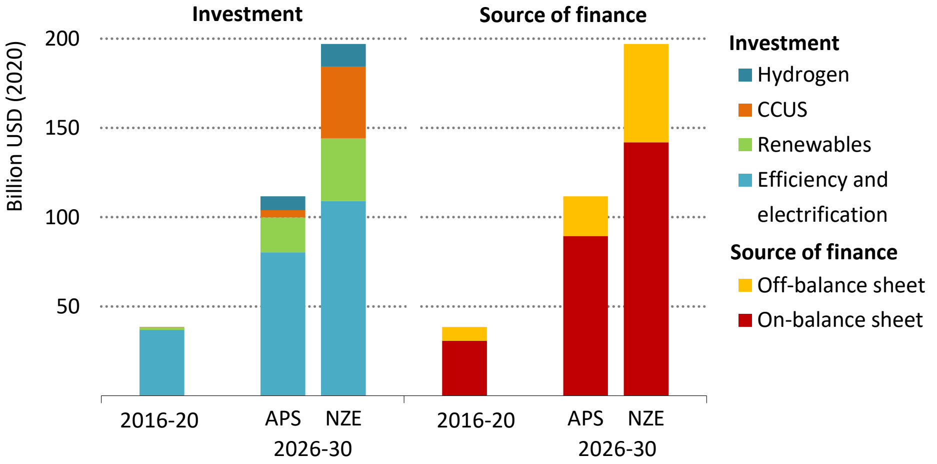
In the iron and steel sub-sector, major stakeholders have already identified the need for low-carbon steel by setting targets or initiating demonstration projects. This includes both steelmaking companies (e.g. ThyssenKrupp, ArcelorMittal, Voestalpine, SSAB and Ovako) and steel consumers ready to pay a premium for low-carbon steel or to invest in innovative steel production through direct partnerships (e.g. BMW and Volvo).

Our calculations suggest that breakthrough programmes targeting cost-effective production from innovative routes by 2030 could achieve worthwhile results and bring about further cost reductions in the longer term. In the shorter term, supporting innovation and demonstration projects could speed up the technological readiness of processes such as CCUS and electrolysers and increase their competitiveness, while setting long-term targets could facilitate the creation of a sizeable market for low-carbon steel.

Financing the industry sector transition to the NZE

Bridging the ambition gap to meet the NZE pathway will require the financing of early projects in new technologies critical for industrial decarbonisation and laying the groundwork for attracting capital at scale. The gap to be bridged is a large one. Global annual investment in industrial decarbonisation expands to over USD 110 billion in the APS by 2030, up from less than USD 40 billion today. However, investments in the NZE climb to almost USD 200 billion (Figure 3.19).

Figure 3.19 ▻ Average annual clean energy investment in industry by type and source, 2016-2020, and by scenario, 2026-2030



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Meeting NZE milestones requires investment in industry to increase fivefold by 2030, supported by new financing options in technologies critical for industrial decarbonisation

Note: The source of finance indicates investment financed on the balance sheet of the industrial company, as well as those using off-balance sheet arrangements, such as project or third-party finance.

Many of the industrial technologies needed to meet long-term net zero emissions goals remain at early stages of market readiness and transaction sizes tend to be small, making it challenging to attract project finance from banks and institutional investors. Policies that support effective risk allocation for early commercial-scale projects incorporating low-carbon hydrogen, CCUS and the development of shared infrastructure around industrial clusters will play a vital role in realising economies of scale and attracting new, external sources of capital.

There is a need for stronger international mechanisms to fund early stage technologies as well as public funds to catalyse project development. Direct investments by institutional investors in new industrial technology companies have risen rapidly, but totalled less than USD 10 billion over the past five years. While large companies will be instrumental in anchoring initial projects, there is a good deal of scope for development finance institutions to provide blended finance: industrial decarbonisation currently comprises a very small part of their clean energy commitments. This is particularly critical for emerging market and developing economies, which may not have the resources to fund early stage deployment of low emissions industrial technologies like hydrogen or CCUS. Table 3.1 provides several examples of the financial and commercial arrangements for recent industrial demonstration projections.

Table 3.1 ▷ Examples of commercial-scale project development for industrial clusters, hydrogen and CCUS

Project	Country	Technologies	Source of finance	Commercial arrangement	Status
Puertollano Green Hydrogen Plant	Spain	Solar PV, battery storage, hydrogen electrolysis	Utility balance sheet	Use of hydrogen to produce ammonia and electricity by a fertiliser company.	Construction
Humber Industrial Cluster	United Kingdom	CCUS, hydrogen infrastructure/ electrolysis, wind	Private consortium, government grants	Use by heavy industry, refiners, power plants, mobility and grid injection.	Planned
Western Green Energy Hub	Australia	Solar PV, wind, hydrogen electrolysis	Private consortium, government grants	Off-take by mining companies, ammonia supply for export.	Planned
Porthos Port of Rotterdam	Netherlands	CCUS, hydrogen	Private consortium, government grants	Companies supply CO_2, public-private partnership manages transport/storage, use by refineries.	Planned
Haru Oni Hydrogen Project	Chile	Wind, hydrogen electrolysis, synthetic fuels, direct air carbon capture and storage	Private consortium, government grants	Export-oriented supply of synthetic fuels.	Construction (demo phase)
Varennes Project	Canada	Hydrogen electrolysis, synthetic fuels	Private consortium, government grants	Feedstock from landfills, sale of synthetic fuels.	Planned

Projects that aim to provide low emissions hydrogen in place of hydrogen sourced from fossil fuels are likely to underpin early development because they will be able to draw on existing infrastructure and commercial arrangements. Creating bankable project pipelines at scale will rely on fixed-price contracts with creditworthy off-takers to absorb pricing risks, as well as on infrastructure development which has the potential to support further development of a tradable market. While early use cases focus on existing applications such as refining or ammonia production, scaling up depends on extending contracts to counterparties with growing fuel demand (e.g. heavy industry and transport fleets) and on tradable certificates of origin to improve bankability, as envisaged in the European Union. International hydrogen trade is driving some export-oriented projects (e.g. in Australia, Chile and Oman), but scaling this up depends on the development of international standards, certification and price setting regimes.

The development of industrial clusters around infrastructure for CCUS and hydrogen is also critical to laying the groundwork for financing those technologies at scale. CCUS projects under development in Canada, Netherlands and United Kingdom are creating industrial hubs with shared CO_2 transport and storage infrastructure that help achieve economies of scale and reduce commercial risks for developers.

3.5.2 Transport

Current status and gap to the NZE

Transport has the highest level of reliance on fossil fuels of any sector and accounts for 37% of CO_2 emissions from end-use sectors (7.1 Gt in 2020).[11] In recent years, transport has seen the fastest growth in CO_2 emissions of any sector as a result of increasing demand and limited uptake of alternative fuels. By 2030, transport emissions are nearly 2.5 Gt higher in the APS than in the NZE, with road transport accounting for around three-quarters of the ambition gap between the two scenarios (Figure 3.20).

One of the major reasons behind the higher emissions in APS is strong demand growth in emerging market and developing economies, many of which do not have net zero pledges. For example, over 40% of global car sales in 2030 take place in emerging market and developing economies without pledges. Weaker energy efficiency and avoided demand policies result in around 1.3 Gt more emissions in the APS in 2030 than in the NZE. In the APS, transport energy demand is 24% higher in 2030 than in 2020, whereas in the NZE it is at roughly the same level as in 2020.

Another major reason for the ambition gap in transport is slower electrification in the APS together with lower deployment of bioenergy and hydrogen-based fuels. This contributes about 1 Gt to the ambition gap. Oil products still account for more than 80% of transport consumption in 2030 in the APS, although electricity reaches close to 5%. In the NZE, however, the share of oil products decreases to around 75% by 2030, and electricity meets close to 10% of demand. The NZE also sees hydrogen-based fuels making inroads, with ammonia starting to be used more in shipping, for example. The difference in the energy mix in transport between the APS and NZE widens dramatically after 2030.

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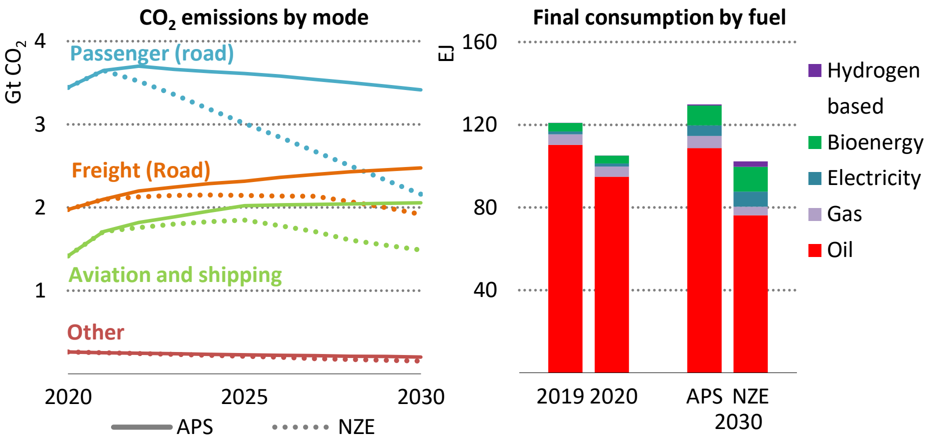
[11] All CO_2 emissions in this section refer to direct CO_2 emissions, i.e. it does not include emissions of the electricity sector or upstream emissions from fuel supply, unless otherwise specified.

Figure 3.20 ▹ CO_2 emissions and final energy consumption in transport in the Announced Pledges and Net Zero Emissions by 2050 scenarios



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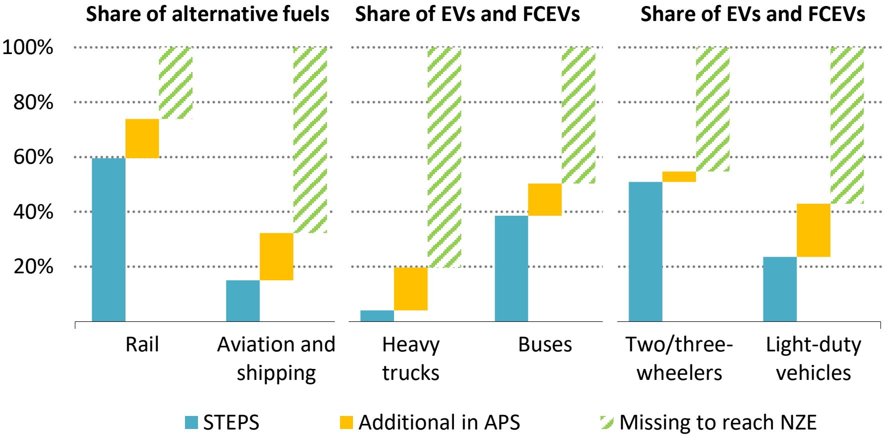
By 2030, total CO_2 emissions from transport are more than 40% higher in the APS than in the NZE

Note: Other includes emissions from rail, non-specified transport and pipelines.

Figure 3.21 ▹ Tracking progress towards 2030 milestones in the transport sector by scenario



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Decarbonisation of rail and light-duty vehicles is more advanced than in heavy trucks and aviation and shipping, relative to the NZE pathway

Notes: The 2030 milestones are those set out in the Net Zero Emissions by 2050 Scenario. EVs = electric vehicles; FCEVs = fuel cell electric vehicles. Aviation and shipping include both domestic and international activity. Light-duty vehicles include passenger cars and light commercial vehicles. The share of EVs and fuel cell electric vehicles refers to their share in annual sales. Alternative fuels include electricity, bioenergy, hydrogen and hydrogen-based fuels.

In the APS, some regions with net zero ambitions and strengthened NDCs push the transition in the transport sector towards what is required under an NZE pathway. At the global level, however, the transport sector is not on track to reach net zero emissions by 2050, although some modes make better progress than others (Figure 3.21).

Road transport accounts for over 15% of total energy-related CO_2 emissions today. The APS sees road CO_2 emissions increase by around 10% up to 2030, whereas the NZE sees emissions decline by a quarter by 2030 from the current level: the APS reaches this level of road CO_2 emissions only by 2050. Electric two/three-wheelers reach a 60% market share by 2030 in the APS, a significant increase over the current market share of around 30%, but well below the 85% achieved in the NZE. Electric two/three-wheelers have lower additional cost than electric cars and need less power to charge. For this reason, they are widely used in emerging market and developing economies. The market share of EVs in annual car sales reaches around 30% in the APS by 2030, but rises to over 60% in the NZE.[12] The story is similar for electric vehicles in annual truck sales, only starker: EVs account for around 5% of new sales of heavy trucks in the APS by 2030, compared to around 25% in the NZE.

Ambitious new targets have been put forward in several countries that would put them close to reaching the NZE milestones. The United Kingdom has set a target to ban the sale of new internal combustion engine (ICE) cars from 2035 (including hybrids), and Canada recently announced a similar target for 2035. The European Union recently released its Fit for 55 package, which proposes standards effectively banning new ICE car sales from 2035. In recent years, China has been at the centre of the EV transition, and its targets for fuel economy improvements and low emission vehicle shares are a step forward, but a commitment to phase out ICE car sales is essential to achieve carbon neutrality in the long term.

Rail is the most electrified sector among all transport modes, with electricity accounting for over 40% of energy consumption in 2020. In the APS, the share of electricity reaches almost 60% in 2030, compared with nearly 65% in the NZE. Plans for further electrification of railways are in place in several countries (e.g. Germany, India and United Kingdom), as are some projects involving hydrogen trains (e.g. Germany).

Aviation and shipping see early action on innovation, infrastructure development and international co-operation in the NZE to achieve emissions reductions. Oil makes up less than 85% of total aviation fuel demand in 2030 in the NZE, with the rest met by biojet kerosene and synthetic kerosene. For shipping, the oil share reaches around 80% over the same period. In the APS, however, oil still accounts for more than 90% of both aviation and shipping fuel demand in 2030. Policy measures such as blending mandates and excise duties for petroleum products used in these modes would help to support the consumption of alternative fuels.

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[12] EVs include battery electric and plug-in hybrid electric vehicles.

Closing the gap from the APS to the NZE

Closing the ambition gap between the APS and NZE requires robust targets across transport modes in all regions, supported by strong policies and incentives. However, the transition faces three particular challenges: driving energy efficiency and behavioural change to reduce energy demand; accelerating the electrification of road and rail modes through supportive policies and the roll-out of infrastructure; and speeding up innovation and infrastructure investment to enable decarbonisation in heavy-duty trucks, aviation and shipping after 2030.

- To close the gap with the NZE, governments need to strengthen fuel economy mandates and implement policies to facilitate modal shift. By 2030, the average fuel economy of both ICE heavy trucks and ICE cars is around 15% better in the NZE than in the APS. Strict fuel efficiency standards, accompanied with policy frameworks for regulating second-hand sales of inefficient models in emerging market and developing economies, are both critical. Fuel efficiency measures also need to be brought in for shipping and aviation. Behavioural change is an important complement to these measures. ICE cars continue to make up around 80% of the cars on roads in 2030 even in the NZE, and measures to limit their use have an immediate and large impact on emissions. In the NZE, the use of ICE cars in large city centres is significantly reduced in most places by 2030, speed limits on motorways are reduced to 100 kilometres per hour, and car drivers moderate their use of air conditioning, helping to reduce fuel consumption. These measures all depend on changes in behaviour and broad social acceptance. To achieve the same level of emissions reductions without such behavioural changes, 100% of new car sales would need to be EVs or FCEVs by 2026, up from about 5% today.
- Governments should seize on the increasing competitiveness of EVs and underpin it with supportive policies and accelerated deployment targets. EVs can already be a cost-effective option for consumers in certain countries and for some modes (Box 3.7). However, there are a number of barriers to their wider deployment, particularly in emerging market and developing economies, and these need to be addressed. One barrier is price: less than 10% of EV models offered globally cost less than USD 15 000. Insufficient public charging infrastructure is another barrier. Emerging market and developing economies today account for only 0.3% of total installed public charging infrastructure. In addition, these economies rely on the global second-hand car market, and therefore tend to lag behind technology developments in advanced economies.[13]
- Governments should set targets and frameworks to establish EV charging infrastructure at scale. This should include the provision of a stable long-term framework for the private sector to invest in markets where demand is well established. The NZE requires a massive roll-out of infrastructure to support the decarbonisation of the transport sector, with 40 million fast chargers and 18 000 hydrogen refuelling stations installed by 2030. The APS sees significant progress, but it is not on the same scale: 15 million fewer fast chargers are installed by 2030, and hydrogen refuelling capacity is around half that of the NZE. Robust government policies on infrastructure roll-out are important in

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[13] The numbers in this paragraph apply to emerging market and developing economies excluding China.

electrifying heavy-duty trucking, which sees the biggest gap between the APS and the NZE. It is challenging for emerging market and developing economies to invest in low emissions supply chains for ports and airports, given that they lack quality basic infrastructure in these areas: international co-operation is required to foster the development of the needed infrastructure, with advanced economies playing a key role.

- Governments need to enhance investment in commercialising key technologies for heavy-duty, long-distance transport such as shipping and in aviation, including by improving incentives for such investments. Emissions reductions in these modes are dependent on innovation in key technologies: the share of low-carbon fuels for both aviation and shipping exceeds 15% by 2030 in the NZE, for example, but it reaches only around 6% in the APS. The technologies in question include advanced batteries cells with an energy density of more than 400 watt-hours per kilogramme (Wh/kg), fuel cells, advanced biofuels and synthetic fuels.

Today, more than 360 000 flights have used biofuels, but only six airports have regular biofuel distribution. Less than 5% of all airports handle 90% of international flights. For shipping, the 20 largest ports in the world account for more than half of global cargo. There is a huge opportunity for the international aviation and shipping sectors to focus on the main demand clusters until low-carbon technologies become more cost-competitive.

Box 3.7 ▷ Are EVs cost-competitive in the NZE?

EVs are already competitive with ICE vehicles on a total cost of ownership basis[14] in some regions, especially in places such as the European Union and India where taxes raise the retail price of fuels. But EVs also face non-economic barriers that are not overcome in the STEPS or the APS, especially in emerging market and developing economies. For instance, emerging market and developing economies rely heavily on the second-hand market, which is unlikely to have many EVs until after 2030; rapid adoption of electric light-duty vehicles is particularly dependent on public charging infrastructure within cities; heavy-duty vehicles need an extensive network of fast charging points; and weak or unreliable grids risk delaying electrification in many emerging market and developing economies.

We have assessed the economic potential of EVs in different road vehicle segments at a regional level. Ignoring non-economic barriers, we estimate that the global electric car fleet could cost-effectively reach over 250 million by 2030, around 30% higher than in the APS and only around 15% lower than in the NZE (Figure 3.22).

Progress towards the milestones in the NZE could be made for urban buses, delivery vans and two/three-wheelers by addressing issues such as model availability and lack of infrastructure, while the main need for heavy-duty trucks is further technology development to reduce the high cost and low energy density of batteries so as to make electric heavy-duty trucks cost-competitive across the world.

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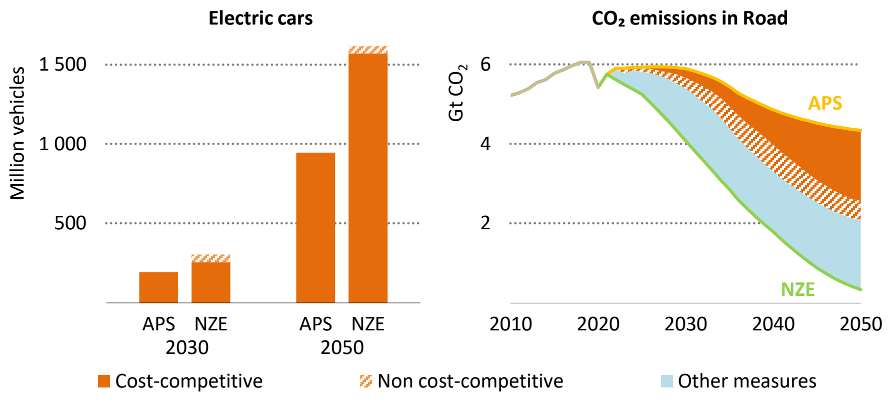
[14] The total cost of ownership includes both purchase cost and running cost, i.e. fuel and maintenance costs, over the lifetime of the vehicle. The assumed lifetime depends on the particular market.

Figure 3.22 ▷ Cost-competitive stock of electric cars in 2030 and 2050, and CO_2 emissions reduction in road transport to 2050 by scenario



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Electric vehicles are critical to closing the transport sector ambition gap and are largely cost-competitive

Note: Other measures includes energy efficiency, avoided demand, as well as the impact of fuel switching to fuels other than electricity, including bioenergy and hydrogen-based fuels.

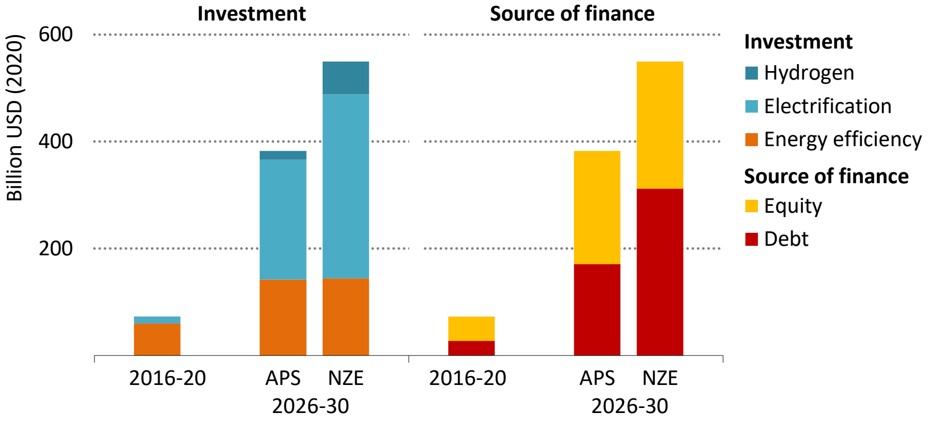
Financing the transport sector transition to the NZE

Global transport-related clean energy investment rises from around USD 75 billion today to over USD 380 billion in the APS and USD 570 billion in NZE by 2030. The scale of this increase requires a rapid growth in low interest debt financing and risk capital equity investment across all types of zero-emission vehicles and charging infrastructure (Figure 3.23).

From a very low base, investment in EVs increases over 15-times in the APS and over 25-times in the NZE by 2030. This requires concerted policy efforts to improve funding and business models for EV charging in emerging market and developing economies, where the weak financial performance of utilities and municipalities in a number of markets constrains the roll-out of publicly funded fast charging infrastructure for heavy trucks and buses.

It is essential for governments to set clear targets for the deployment of EV charging infrastructure and EVs. Governments and state-owned companies can support the development of new business models via calls for proposals for innovative charging solutions. The electrification of transport in emerging market and developing economies in particular depends on support for manufacturing to drive down costs, as well as on new measures to boost demand, for example through government procurement and dedicated credit lines for consumer lending. Development finance institutions and green banks could lend support by expanding concessional loan programmes to consumers and business owners for EV chargers at a below-market rate. Other policy options include supportive tax incentives to enable manufacturers and operators to lower costs of EV charging installation and operation.

Figure 3.23 ▷ Average annual clean energy investment in transport by type and source, 2016-2020, and by scenario, 2026-2030



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Transport clean energy investments need to increase almost eightfold in the NZE by 2030, especially for electrification in emerging market and developing economies

Note: Hydrogen = hydrogen and hydrogen-fuel based vehicles and shipping; Electrification = electric vehicles and shipping; Energy efficiency = energy efficiency for road vehicles.

3.5.3 Buildings

Current status and gap to the NZE

Today's buildings sector accounts for almost one-third of total final energy consumption and 15% of end-use sector direct CO_2 emissions, and its share of emissions rises to around 30% if indirect emissions from the electricity and heat used in the buildings are included. Energy use in the buildings sector accounts for almost 3 Gt of direct CO_2 emissions today.[15] Direct emissions from the buildings sector decline by 15% to 2030 in the APS, but by almost 40% in the NZE, resulting in an ambition gap of 0.7 Gt by 2030.

In the APS, energy demand in the buildings sector remains at a level similar to today, despite substantial growth in global GDP and urbanisation. In the NZE, energy efficiency and avoided demand due to behavioural change and passive design measures go much further: demand is 25% below the level in the APS level by 2030, and substantially lower than today, despite growth in global residential floor space of more than 20%.

Emissions reductions in the APS are driven by announced economy-wide emissions reduction targets in many advanced economies which lead to reductions in CO_2 emissions for space and water heating and cooking. Around 80% of the residential floor area growth in the

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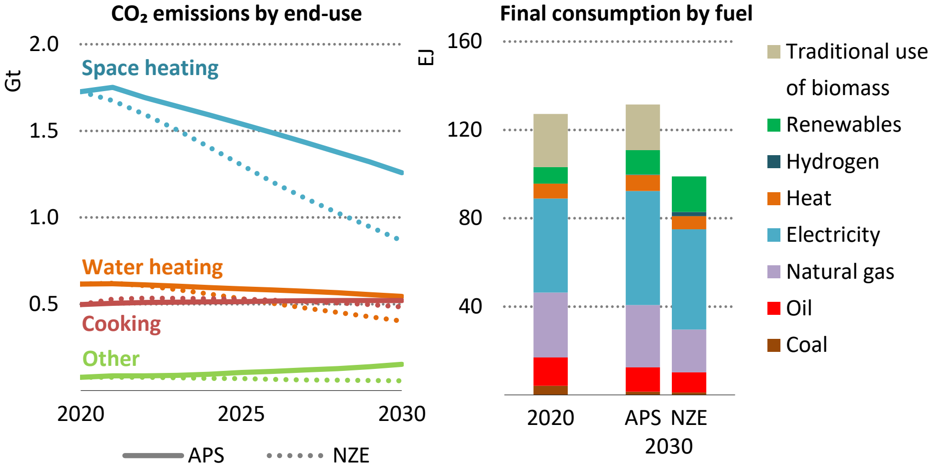
[15] All CO_2 emissions in this section refer to direct CO_2 emissions, i.e. it does not include emissions of the electricity and heat sector, unless otherwise specified.

buildings sector is in emerging market and developing economies, many of which have not announced net zero pledges. Reflecting this, the APS is far from sufficient to achieve the emissions reductions required in the NZE, resulting in a widening ambition gap (Figure 3.24).

Figure 3.24 ▹ **CO_2 emissions by end-use and final energy consumption by fuel in the buildings sector in the Announced Pledges and Net Zero Emissions by 2050 scenarios**



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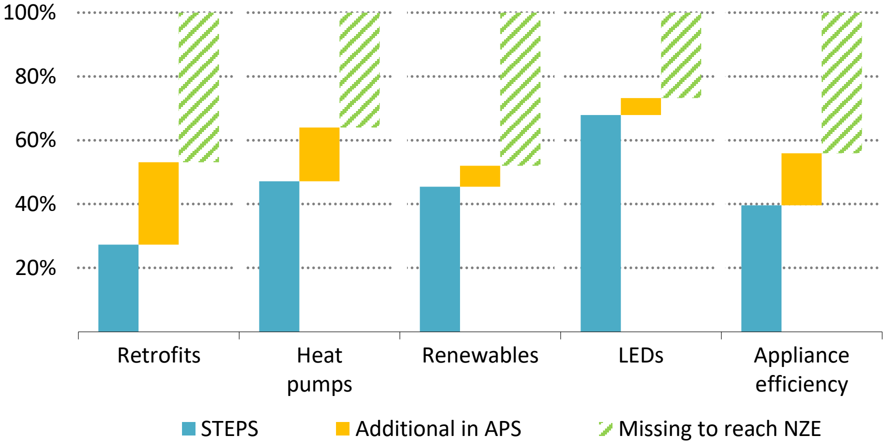
Announced pledges point to a 15% reduction in CO_2 emissions in the buildings sector by 2030, which is insufficient to drive down fossil fuel use in line with the NZE pathway

Note: Other includes emissions from desalination, lighting and fossil fuel-powered appliances.

In the APS, the share of electricity in energy consumption in the buildings sector increases to almost 40% and that of renewables above 8%. The NZE sees a similar shift in the energy mix in the sector, albeit at a more rapid pace and combined with greater energy efficiency improvements: electricity's share of energy consumption increases to 46% and that of renewables to 16% by 2030. Universal access to clean cooking solutions is realised by 2030 in the NZE, eliminating the traditional use of biomass.

Some economies with net zero pledges push the transition in some end-uses towards what is required under an NZE pathway, but at a global level the world remains well short of reaching NZE milestones. Even low cost and rapidly implementable measures such as ensuring that LEDs account for 100% of lighting sales by 2025 are not fully achieved in the APS, and an important share of less efficient lighting remains in use by 2030 in the APS (Figure 3.25). Heat pump deployment accelerates in all scenarios, driven by improving economics and policies. Full achievement of targets in the APS pushes heat pump sales above the level in the STEPS in key markets such as the European Union, but there remains a major heat pump deployment gap between the APS and NZE.

Figure 3.25 ▷ Tracking progress towards 2030 milestones in the buildings sector by scenario



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Ambition needs to increase across all end-uses in buildings to put the world on track with the NZE pathway

Notes: The 2030 milestones are those set out in the Net Zero Emissions by 2050 Scenario. Retrofits refer to the residential floor area retrofit to zero carbon-ready building standards. Heat pumps refer to the number of residential heat pumps installed. Renewables refer to the share of renewables in meeting residential heat demand. LEDs refer to the share of light-emitting diodes in the residential lighting stock. Appliance efficiency refers to the average efficiency of the residential appliance stock.

Space heating accounts for 60% of global CO_2 emissions today in the buildings sector. It is responsible for 60% (almost 400 Mt CO_2) of the ambition gap between the APS and NZE in 2030. While technical solutions to decarbonise space heating are available and mature, there remain economic and non-economic barriers. Global emissions from space heating decline by 3% annually to 2030 in the APS. They decline by almost 5% in countries with announced net zero pledges, which account for three-quarters of all CO_2 emissions from space heating, but increase slightly in countries without pledges. By 2050, space heating in countries with net zero pledges is almost completely decarbonised.

The APS assumes full achievement of the announced pledges and targets in the buildings sector. Examples of the suite of targets and policies for the buildings sector in the European Union include the Energy Performance of Buildings Directive and the Renovation Wave for Europe strategy. The EU building sector targets accelerate retrofits and reduce space heating energy demand by almost 20% to 2030 and around 55% to 2050 from current levels, with emissions falling to close to zero by 2050. Canada, Japan and Korea also have announced targets for new buildings to meet stringent efficiency standards by 2030, and by 2025 for buildings over 1 000 m^2 in Korea. Other advanced economies are developing timelines for implementation of zero carbon-ready building codes.[16] For example, the United Kingdom has announced the Future Homes Standard which is set to come into effect in 2025 and end fossil fuel heating in new homes. Many countries have pledged funding for building retrofits in their Covid-19 recovery programmes.

Energy efficiency and avoided demand deliver the largest share of emissions reductions in space heating in the APS, but they fall short of what is required in the NZE. Improving efficiency in existing building is especially important in advanced economies: around 10% of their existing residential building stock is retrofitted by 2030 in the APS, compared to more than 20% in the NZE. Changes to the space heating fuel mix are also critical: fuel switching and electrification provide one-third more emissions reductions to 2030 in the NZE compared with the APS. Heat pumps are key to electrifying space heating: their sales average 3.5 million per month in residential buildings in the APS, boosted to around 5 million units per month in the NZE.

Cooking is the activity most dominated by fossil fuels in buildings today, with liquefied petroleum gas (LPG), natural gas and coal meeting over three-quarters of global cooking energy demand. For those with access to modern cooking technologies, a lack of targets and policies to incentivise switching away from natural gas or LPG based cooking means that fossil fuel use for cooking in the APS increases by 6% by 2030. Adding to the challenge of decarbonising cooking is the need to provide clean cooking access to the 2.5 billion people that currently lack it.

Universal access to clean cooking is achieved by 2030 in the NZE, alongside progress towards the wider decarbonisation of cooking. By 2030 CO_2 emissions from cooking in the NZE are 3% lower than today and 7% lower than in the APS. Emissions decline in the NZE despite the role of LPG in delivering clean cooking access to around 40% of the 2.8 billion people that gain access between today and 2030. While low-carbon cooking plays a dominant role in the NZE, LPG is the only cost-effective solution available today in some places, notably in rural sub-Saharan Africa. The use of LPG for clean cooking results in a slight increase in CO_2 emissions, but a net reduction in overall GHG emissions because it eliminates the methane, nitrous oxides and black carbon emissions caused by the traditional use of biomass (see Chapter 4, section 4.2.2). Beyond 2030, cooking emissions decline by over 15% per year in the NZE, with electricity substituting for some LPG, and with remaining LPG use increasingly decarbonised through the adoption of bio-sourced butane and propane.

Closing the gap from the APS to the NZE

Efforts to close the ambition gap in the buildings sector face five particular challenges: ensuring that the millions of buildings constructed in the next decades are built in a way that is consistent with achieving NZE, especially in emerging market and developing economies where the majority of construction occurs; accelerating retrofits of existing buildings to

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[16] A zero carbon-ready building is highly energy efficient and either uses renewable energy directly, or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat.

improve their energy efficiency; scaling up the use of electricity and renewables in buildings; achieving universal access to clean cooking and electricity by 2030; and delivering high efficiency appliances and cooling equipment. All the technologies needed to address these challenges are available today: the key requirements are stronger policy action, international co-operation and targeted financial support for households.

- Governments should develop and promulgate mandatory zero carbon-ready building energy codes which take account not just of direct emissions from building operation but also of indirect and embodied emissions (IEA, 2021a). Governments should move quickly to adopt such codes for all new buildings. Ambitious building codes exist today in some regions, as do targets for all new buildings to be zero carbon-ready and for bans on fossil fuel-fired equipment in new constructions. Almost all of these codes and targets are in advanced economies, while 80% of the projected increase in global residential floor area to 2050 will take place in emerging market and developing economies, but there is more for all governments to do.
- Governments should put in place incentives, education campaigns, access to concessional finance, stringent building codes for existing buildings, and facilitate new business models focusing on energy as a service in order to help overcome economic and social barriers to retrofits. Retrofits can reduce building energy demand by well over 60% and enable switching to zero direct emissions heating technologies such as heat pumps. More than 85% of the existing building stock is retrofitted by 2050 in the NZE thanks to action to accelerate retrofits in the 2020s. The challenges are significant, and include the major upfront capital costs of retrofits, disruption to building occupants, split incentives between tenants and building owners, and long payback periods. However, failure to take action during the coming decade to drastically accelerate the rate of retrofit of existing buildings would make later efforts to bridge the ambition gap more difficult and more costly.
- Governments should take measures to speed up fuel switching, which has the single biggest impact on direct emissions from the building sector through to 2030. System-wide emissions reductions linked to electrification increase rapidly as electricity supply is decarbonised in the NZE. Action to accelerate electrification and switching to renewables should build on targets in the APS and include bans on sales of new fossil fuel-fired boilers by 2025 except where fuel supply will be completely decarbonised before 2050. Incentive programmes and blending mandates could help to scale up the deployment of biomethane, making use of existing gas infrastructure. In many emerging market and developing economies, solar thermal is a very cost-effective option for water heating and could be incentivised: uptake in the APS is at only two-thirds of NZE levels. Electrification of heating and cooking could meanwhile be supported by capital subsidies for heat pumps, training programmes for technicians, awareness campaigns and carbon prices.
- Governments should work together to achieve universal access to clean cooking by 2030. The Covid-19 pandemic has led to a reversal of recent progress in many economies. International efforts, including financial commitments, are required to

ensure that the world's poorest and most energy insecure households are not left behind as the world attempts to close the ambition gap.

- Governments should implement minimum energy performance standards (MEPS) which incorporate a doubling of the average energy efficiency of key products by 2030 in line with the Super-Efficient Equipment and Appliance Deployment (SEAD) target (Box 3.8 details the SEAD). Appliances and cooling are the fastest growing uses of energy in buildings today, and their expansion is set to continue as incomes increase, more appliance are purchased, and millions of global households acquire air conditioners and other cooling equipment. Mitigating electricity demand growth from appliances and cooling is critical to electricity sector decarbonisation. This challenge is especially acute in India, Southeast Asia and Africa. MEPS are the most powerful tool available to policy makers. MEPS will need to be upgraded faster than in the past so as to ban sales of the most inefficient appliances and shift almost all sales to the best available technology by 2030. Global co-operation on high efficiency appliances and cooling equipment could reduce costs for consumers by facilitating co-ordination of MEPS and driving innovation.

Behavioural change also contributes to reducing emissions from buildings in 2030 in the NZE by around 170 Mt CO_2 more than the APS (see section 3.7). Overall, behavioural change contributes one-quarter of the additional direct emissions reductions in the buildings sector in the NZE relative to the APS by 2030. It also reduces the sector's electricity demand and indirect emissions, accounting for over 3% of the indirect emissions reductions from buildings between the APS and NZE. Changing heating and air conditioner temperature set-points, line drying and reducing washing temperatures all have a part to play. These savings can be achieved without the need for any new technologies or investments, but they do require enhanced consumer awareness and engagement.

Box 3.8 ▷ Efficient and affordable appliances with international co-operation

Worldwide, the average energy efficiency of key equipment sold today needs to double by 2030 to be on track for net zero. MEPS, including bans on sales of the most inefficient appliances, are the primary tool for shifting sales toward the most efficient technologies. More than 120 countries are currently using or planning to use MEPS for lighting, cooling or refrigeration, as detailed in the IEA's forthcoming *Energy Efficiency Market Report 2021*. However, different stringency levels and a lack of international co-operation together result in substantial variation in the efficiency of appliances and equipment within and between countries. The best available air conditioning equipment in a market is typically twice as efficient as that market's average product sold (IEA, 2018). National and international action on the coverage of MEPS needs to expand and increase in stringency in order to drive the shift in sales toward best available technologies required in the NZE. Such actions should be accompanied by complementary labelling programmes.

Consumer affordability concerns are at the forefront of decision making when it comes to increasing the stringency of efficiency standards because of a perception that more efficient technologies cost more. However, the IEA's market research suggests that highly efficient devices can be similar in price to less efficient ones in a given market, and are sometimes actually lower in price (IEA, 2020a). In addition, lower operating costs from higher efficiency create substantial savings over the life of a product, making many efficient products more cost-effective than less efficient models on a total cost of ownership basis.

Today LEDs are more cost-effective than almost all other forms of lighting in all regions. This suggests that a shift to 100% LEDs in lighting sales would benefit consumers. The most efficient air conditioner models are cost-competitive today in around two-thirds of cases, and this increases to three-quarters by 2030 in the NZE as equipment costs for the most efficient models decline and electricity prices rise. Purchasing high efficiency household appliances such as refrigerators and washing machines leaves more money in consumer pockets over the lifetime of the product in the majority of regions, and the benefits increase in the NZE. Overall, two-thirds of the improvements in the efficiency of appliances and air conditioners between the APS and NZE in 2030 are cost-effective, increasing to almost 100% by 2050.

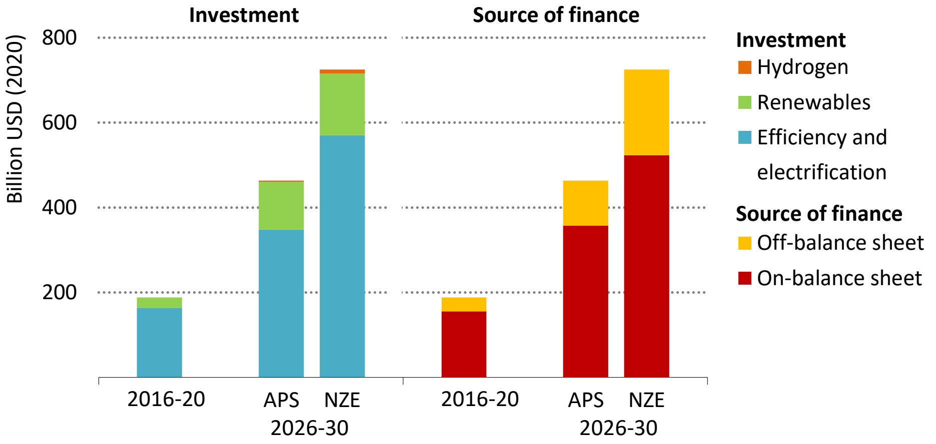
International co-operation to encourage the uptake of more efficient appliances and align MEPS and efficiency labelling has the potential to accelerate action and drive down the costs of efficient appliances. This is the ambition of the Super-Efficient Equipment and Appliance Deployment (SEAD) initiative, a collaboration among more than 20 governments, the IEA and other partners to accelerate and strengthen the design and implementation of energy efficiency policies for appliances and equipment. In 2020, SEAD and the COP26 presidency launched the COP26 Product Efficiency Call to Action, which aims to set countries on a trajectory to double the efficiency of key products sold globally by 2030. G7 leaders endorsed the Call at the 2021 Summit.

Financing the buildings sector transition to the NZE

Being on track for the NZE in the buildings sector requires additional annual clean energy investment of about USD 500 billion in this decade. This is almost four-times what has been spent in recent years and almost 60% higher than the projected level of investment in the APS. The largest gap is in emerging market and developing economies, where investment levels need to increase almost sevenfold by 2030 to stay on track.

Spending on energy saving measures today still relies heavily on the equity of households or companies, especially in emerging market and developing economies, and that remains the case in both the APS and NZE. However, new ways of quantifying energy savings, for instance through smart metering or energy performance contracts, open the door to innovative approaches that use future energy savings as collateral for upfront financing. New financing mechanisms such as leasing arrangements offered by energy services companies (ESCOs) relieve households from the requirement to mobilise initial capital, and offer an opportunity to finance economy-wide energy efficiency measures even in a context of constrained access to affordable finance. These measures are sometimes referred to as non-self-financed or off-balance sheet financing.

Figure 3.26 ▷ Average annual clean energy investment in buildings by type and source, 2016-2020, and by scenario, 2026-2030



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Investment in the building sector almost quadruples by 2030 in the NZE, most of which is self-financed, but meeting NZE goals relies on enhancing external financing options

Note: Examples of off-balance sheet financing mechanisms include operating lease arrangements or energy performance shared savings contracts, where a household or a company uses energy efficient equipment provided by a third-party in exchange for rent payment.

In emerging market and developing economies, rapid urbanisation and development calls for huge investment in ensuring that new construction is zero carbon-ready, driven by the adoption of building energy codes. Expanding the use of green certification schemes could attract international refinancing and help to build local capacity ahead of the roll-out of a building energy code. Bulk procurement programmes like those used in India, where the ESCO Energy Efficiency Services Limited organised large-scale sourcing of efficient lighting and air conditioners, could drive down costs and help households in emerging market and developing economies purchase efficient and low-carbon equipment. Funding from development banks will be also essential to catalyse investment in net zero buildings in emerging market and developing economies. A commitment from development finance institutions to finance only zero carbon-ready buildings as part of their portfolios would send a clear signal to governments and investors about the world's commitment to decarbonise buildings and stay on track to reach climate goals.

In advanced economies, an annual retrofit rate of 2.5% of the existing building stock to meet zero carbon-ready building standards and electrification of end-uses such as heating together drive up investment needs in the NZE by 2030. Spending will rely heavily on the availability of dedicated financing options for both homeowners and tenants, for example through green recovery packages. The capitalisation of green banks with a specific mandate to raise and allocate funds for energy efficiency investments could help boost access and support the use of green finance. Green bonds designed to finance low-carbon buildings account for a quarter of the bonds issued under the Climate Bond Initiative since 2015, with this share ultimately expected to reach 40% (CBI, 2021). Green mortgage-backed securities that re-finance and crowd-in private sector investment in green buildings are also being issued in some advanced economies.

3.6 Methane emissions from fossil fuel operations

Current status and gap to the NZE

Methane emissions are the second-largest cause of global warming today. The recent IPCC Sixth Assessment Report highlighted that rapid and sustained reductions in these emissions are key to limit near-term warming (IPCC, 2021). The energy sector is one of the largest sources of methane emissions: we estimate that oil and gas operations emitted just over 76 Mt of methane globally in 2020 and that coal operations emitted a further 41 Mt. Total emissions in 2020 represented almost 10% of all energy sector GHG emissions. Methane emissions in 2021 are very far off a net zero by 2050 path.

Today methane emissions from fossil fuel operations are equivalent to around 3.5 Gt CO_2-eq.[17] In the NZE, total methane emissions from fossil fuels fall by around 2.7 Gt CO_2-eq between 2020 and 2030. To put this in perspective, the reduction in energy-related CO_2 emissions between 2020 and 2030 in the NZE is around 12 Gt, so this decline in methane emissions represents an additional 22% reduction in energy-related GHG emissions. Only about one-third of this decline is the result of an overall reduction in fossil fuel consumption. The larger share comes from a rapid deployment of emissions reduction measures and technologies which leads to the elimination of all technically avoidable methane emissions by 2030. Virtually all abatement measures in the oil and gas sector could be deployed cost-effectively over the next ten years in the NZE, and about two-thirds of measures in the coal sector as well.

The gap between methane emissions in the APS and NZE in 2030 is particularly large (almost 65 Mt) (Figure 3.27). This is largely because only about 40% of methane emissions from fossil fuel operations occur in countries with net zero pledges. The two largest emitters are China and Russia, which between them account for well over one-third of related methane sources, and they have not committed to absolute methane reductions before 2030.

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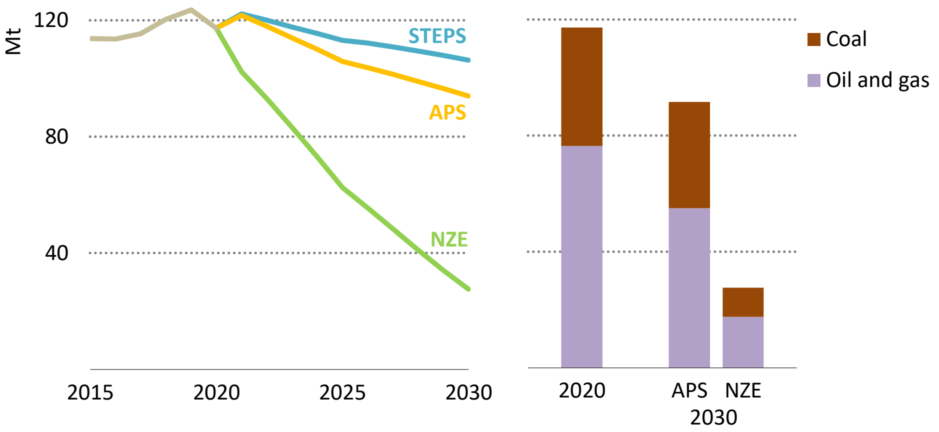
[17] One tonne of methane is considered to be equivalent to 30 tonnes of CO_2 based on the 100-year global warming potential (IPCC, 2021).

Figure 3.27 ⊳ Methane emissions from fossil fuel operations to 2030 by scenario



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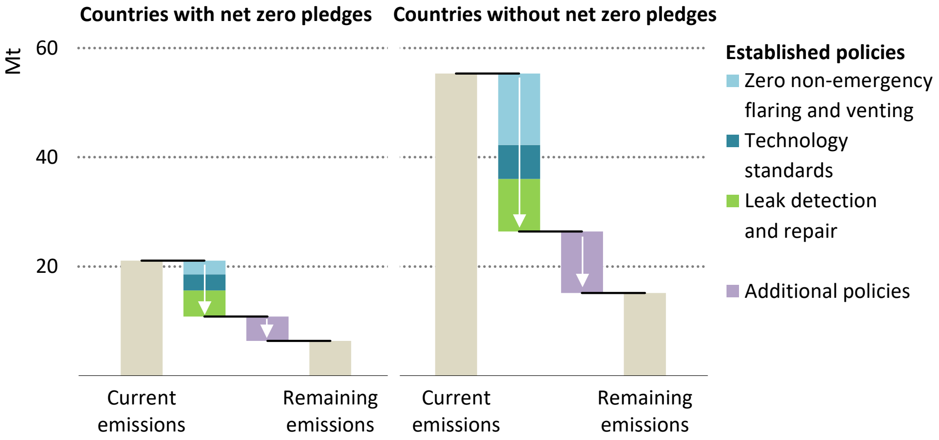
Most methane emissions originate in countries without net zero emissions pledges, resulting in a major gap between the APS and NZE

Closing the gap from the APS to the NZE

Even those countries committed to net zero goals are currently not doing enough to address methane emissions; more ambition is needed to manage both coal-related and oil and gas emissions. Coal methane reductions should be driven by a strong decline in coal production, complemented by policies to increase coal mine methane utilisation and abate emissions from abandoned mines. Oil and gas methane reductions should be driven by the deployment of a wide variety of generally well-known technologies and measures. If countries were to implement a set of well-established policy tools – namely leak detection and repair (LDAR) requirements, staple technology standards and a ban on non-emergency flaring and venting – related emissions could be halved within a very short timeframe (Figure 3.28).

- LDAR programmes are the primary strategy for addressing fugitive emissions from leaking components and malfunctioning equipment. The reduction potential of LDAR programmes depends on their scope, as well as the frequency and method of inspections. Current techniques often involve an on-the-ground inspection with optical gas imaging cameras, but new and emerging technologies, including continuous monitoring sensors, aircraft, drones and satellites, have significant potential to reduce the cost of detecting fugitive sources when used in combination with less frequent on-the-ground surveys. The more often inspections take place, the more quickly leaks are detected and abated; however, cost increases with frequency. For the purposes of this assessment, we assume adoption of a quarterly on-the-ground inspection requirement, a frequency that has been successfully implemented across a number of jurisdictions. Quarterly LDAR has been shown to reduce an estimated two-thirds of fugitive emissions, which would represent a reduction of almost 14.5 Mt methane (CH_4) if applied to all oil and gas operations.

Figure 3.28 ▷ Methane emissions abatement from oil and gas by policy tool



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Established policy tools could drive over 70% of technically available methane emissions abatement options, though they need to be complemented with additional policies

- Technology standards are designed to reduce emissions associated with the normal operation of certain equipment, such as compressors or pneumatic devices. There are alternative technologies that can perform the same function as these components, but with lower or zero emissions. Regulations that set limits on emissions from certain types of equipment or that require the replacement with lower or preferably zero emitting alternatives could significantly reduce emissions. For the purposes of this analysis, this category includes measures that mandate the installation of well-known technologies at new facilities or the replacement of higher emitting components with lower emitting alternatives at existing projects. If policy makers adopted these measures, this would lead to a reduction of up to 9 Mt CH_4.
- Policies designed to achieve zero non-emergency flaring and venting could reduce methane emissions from intentional flaring and venting activities by as much as 15.5 Mt CH_4. Many alternatives to flaring are available to companies. While pipelines are one option, others include capture and reinjection, capture for use on site, or capture for compression to take by truck to processing facilities and then to market. Clamping down on flaring alone could create some perverse incentives to vent, which is much worse from an emissions perspective, and this underlines the importance of taking an integrated approach to flaring and venting.

Further reductions could come through policies that provide more flexibility for companies, but that rely on more robust measurement and verification systems, such as performance standards or emission taxes. We estimate that putting a price of USD 450 on each tonne of methane emitted (equivalent to USD 15/tonne CO_2-eq) would be enough to deploy nearly all of the abatement measures. Another possibility is to set company or facility-specific emissions limits which decline over time in line with country level climate goals. Where companies do not have the technical or financial resources to invest in methane abatement, offsetting systems or financing mechanisms may have a role to enable reductions. These instruments are particularly relevant for legacy sources such as abandoned wells and mines.

Countries with climate pledges may also be able to use their buying power to encourage trading partners to tackle methane emissions, given that over 40% of the oil and gas produced in countries without net zero pledges goes to countries with such pledges. Instruments such as preferential rates for lower carbon fuels, carbon border adjustment mechanisms, intensity standards or emissions certificates could underpin these efforts. However, policy support will also be necessary to ensure deep cuts in methane emissions in emerging market and developing economies, and could be provided through preferential financing schemes for abatement efforts, technical assistance and capacity building.

Based on average natural gas prices from 2017-21, almost 45% of current oil and gas methane emissions could be avoided at no net cost by abatement measures which cost less than the market value of the additional gas that is captured. This may lead to some voluntary action to reduce emissions, especially if markets value fuels with lower carbon intensity. However, a lack of information, inadequate infrastructure or misaligned investment incentives limit the extent to which companies will act on their own. Transparency mechanisms such as the planned International Methane Emissions Observatory[18] are likely to play an increasing role in helping the financing sector, policy makers and industry to ensure that deep cuts are made in methane emissions. Governments looking for swift methane reductions should start with their national oil company (NOC), if they have one: NOCs account for over 30% of methane emissions from oil production and almost 40% of emissions from natural gas production.

Annual investment of around USD 13 billion would be required to put into effect all available methane abatement measures in the oil and gas sector. This is less than the total value of the captured gas that could be sold, meaning that methane emissions from oil and gas operations could be reduced by close to 75% while providing overall savings to the global oil and gas industry. Recent technology developments, in particular satellite observation, promise to facilitate targeted action. Nevertheless, some obstacles still have to be overcome, including the lack of policy precedents in certain sectors, e.g. gas distribution, and limited regulatory and technical capacity in several jurisdictions. Outreach efforts and support for methane reduction strategies will be needed to bring all stakeholders together to act decisively on methane.

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[18] The International Methane Emissions Observatory (IMEO), established by the UN Environment Programme with support from the European Union and in partnership with the IEA, is an initiative to collect and reconcile data from various sources, including company reporting through the Oil and Gas Methane Partnership 2.0, direct measurements from peer-reviewed studies, satellite observations, and national inventories.

3.7 Behavioural change

Getting to net zero depends to a significant extent on the choices made by people and companies. Although they are influenced by regulation and markets, the choices and values of consumers are not absolutely determined by them, and are of critical importance for clean energy transitions. Raising the level of climate ambition, however, requires more from consumers than a systematic preference to buy clean technologies. They also need to change behaviour to reduce their energy consumption and emissions footprint. In our scenarios, behavioural change refers to ongoing changes (which may be either brought about by regulations or voluntary) in the way that consumers use energy in daily life.[19]

This section discusses the different roles of behavioural change in the APS and NZE, and explores the extent to which such change is a critical factor in some end-uses in closing the gap between the scenarios in 2030.

3.7.1 Role of behavioural change and materials efficiency

The APS incorporates behavioural change in some regions which reduce energy-related activities compared to the Stated Policies Scenario (STEPS), but these changes are limited in both scale and scope.[20] This reflects the lack of announced government policies and commitments to building the public infrastructure that would be needed to bring about more comprehensive behavioural changes. Most of the impacts of these changes occur in industry. Technically straightforward options to boost materials efficiency such as extending the lifetime of buildings, increasing steel recycling rates and stepping up the reuse of chemicals contribute to an overall saving of 100 Mt CO_2 in 2030. There are also small reductions in road transport activity which reflect a move away from private mobility in favour of public transport in some regions, as well as small reductions in demand for passenger aviation, but energy service demand in buildings is the same in the APS as in the STEPS (Figure 3.29).

The behavioural changes in the NZE are far more comprehensive than those in the APS, and would require dedicated and sustained policy interventions. Around half of the emissions savings from behavioural changes in the NZE in 2030 are associated with transport. A further one-third of emissions savings come from improvements in materials efficiency in industry, and one-fifth from behavioural changes in buildings.

The behavioural changes in the NZE play a particularly important role in helping to accelerate emissions reductions in the period to 2030, including by reducing emissions from the continued use of existing carbon-intensive assets such as fossil fuel vehicles, or buildings that have not been retrofitted. In some end-uses, behavioural change plays a pivotal role in closing the ambition gap that separates the APS and the NZE in 2030 (Table 3.2). For the most part, behavioural change plays a more important role in closing this gap in advanced economies than in emerging market and developing economies.

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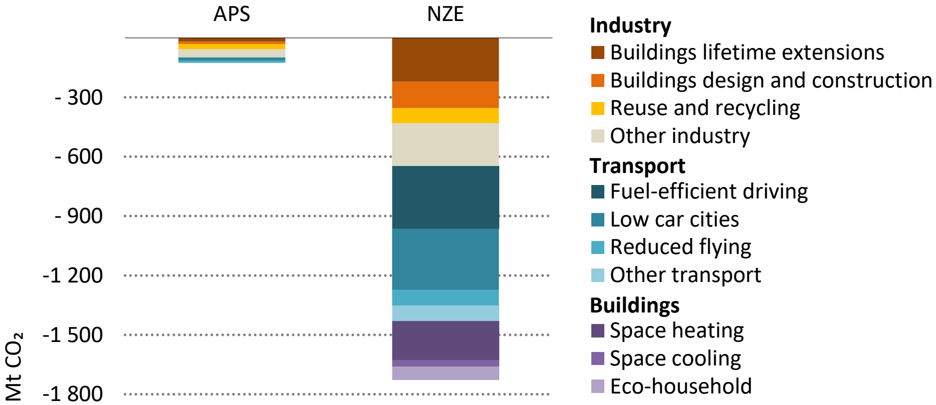
[19] In addition to energy-related behavioural changes, pathways assessed by the IPCC which limit warming to 1.5 °C, as well as some national net zero plans, rely substantially on non energy-related behavioural changes, such as a shift towards lower meat diets, to reduce GHG emissions across the whole economy.

[20] Where specific policies have been announced to bring about behavioural changes in national net zero pledges, e.g. the banning of certain domestic aviation routes, these are incorporated in the APS.

Figure 3.29 ▷ Impact of behavioural change and materials efficiency by sector and scenario, 2030



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Only limited behavioural changes are included in the APS, while the NZE projects far more, but needs targeted policies to realise them

Note: Materials efficiency gains in industry involve a mixture of technical innovation, standards and regulations to support best practice, as well as behavioural changes by manufacturers and the consumers of manufactured goods alike, such as increased recycling. Given the ambiguity in attributing materials efficiency gains to technology-driven avoided demand or behavioural change, the distinction between avoided demand and behaviour is not clear cut. We have allocated materials efficiency to avoided demand in Figure 3.9, which also includes structural and economic effects, such as the response of consumers to higher prices. In this figure 3.29 we include aspects of avoided demand in industry related to materials efficiency under behaviour.

In 2030, the impacts of specific behavioural changes include:

- **Road transport**: The most important measures for reducing emissions include phasing out the use of ICE cars in large cities, increasing the use of ridesharing for urban car trips and reducing speed limits on motorways. Together these save around 450 Mt CO_2 in 2030, which is two-thirds of the emissions saved by behavioural change in road transport.
- **Passenger aviation**: In advanced economies, keeping air travel for business purposes at 2019 levels by increasing the use of teleconferencing contributes 30% of the savings in emissions from international aviation in the NZE in 2030 compared to the APS; a lack of growth in long-haul flights for holidays delivers a further 20%.
- **Buildings**: Setting air conditioning at or above 24 °C plays a significant part in bringing emissions from space cooling down to the level in the NZE, generating around 15% of the savings in emissions from space cooling in the NZE compared to the APS in advanced economies and around 5% of the savings in emerging market and developing economies. Reducing space heating temperatures to 19-20 °C plays a similarly important part in cutting emissions from space heating to the level in the NZE in almost all regions: this measure alone reduces emissions by 200 Mt CO_2.

- **Industry**: Extending the lifetime of buildings reduces materials demand and helps cut emissions in industry. There are nine-times more lifetime extensions in the NZE than in the APS. This accounts for nearly 20% of the difference in emissions from cement production between scenarios in advanced economies, and more than 30% of the difference in emerging market and developing economies.

Table 3.2 ⊳ Role of behavioural change in closing the ambition gap

End-use	Behavioural change	Advanced economies	Emerging market and developing economies	Co-benefits
Transport				
Cars	Phase out ICE cars from large cities.	🟡	🟡	Air pollution mitigation Public health Reduced congestion Road safety Reduced noise pollution Improved oil security
	Rideshare all urban car trips.	🟡	🟡	
	Reduce motorway speed limits to 100 km/h.	🟡	🟣	
	Work from home three days each week.[21]	🟣	🟣	
Aviation	Replace all flights where high-speed rail can be a feasible alternative.[22]	🟣	🟣	Lower air pollution Lower noise pollution
	Keep air travel for business purposes at 2019 levels.	🔴	🟡	
	Keep long-haul flights for leisure purposes at 2019 levels.	🔴	🟣	
Buildings				
Space heating	Target average set-point temperatures of 19-20 °C.	🔴	🔴	Public health Reduce energy bills
Space cooling	Target average set-point temperatures of 24-25 °C.	🟡	🟣	
Water heating	Reduce set-point temperatures by 10 °C.[23]	🔴	🟡	
Industry				
Iron and steel	Reuse and recycling.	🟣	🟣	Cost savings Incentivising R&D Reduced waste pollution Wildlife protection
	Extend lifetime of facilities.	🟡	🟣	
Cement	Extend lifetime of facilities.	🔴	🔴	
	Facility design and construction.	🟡	🟡	
Chemicals	Reuse and recycling.	🟣	🟡	

Key behavioural change: 🔴 Critical 🟡 Significant 🟣 Moderate

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[21] Only in the 20% of jobs worldwide which can be done from home (IEA, 2020b).

[22] Feasible here means that new rail routes avoid water bodies and elevated terrain; travel times between city centres are similar to flying; centres of demand are sufficiently large to ensure that high-speed rail is economically viable.

[23] Boiler temperatures of at least 60 °C are recommended to kill harmful bacteria (WHO, 2002).

Although the behavioural changes in the NZE would be enacted by people and companies, the onus is on governments to facilitate these changes through transparent and consistent policy support and messaging. Around 70% of the emissions saved by behavioural changes in the NZE in 2030 could be directly influenced or regulated by governments, for example by introducing low emissions zones in cities, or withdrawing licenses to operate regional air routes where a train alternative exists. The remaining emissions savings come from discretionary changes in peoples' lives, such as reducing the water temperature of domestic boilers. Although these types of changes are hard to target through policies or legislation, measures such as awareness campaigns can help to shape routines and habits, and there is a growing focus on how behavioural insights and social science can help shape policies most effectively, (e.g. see IEA, 2021a and IEA, 2021d).

Changes which are perceived as fair and just, particularly those which involve curbing excessive energy use, may be particularly well supported. Citizen assemblies, for example, have revealed widespread support for taxes and quotas to be applied to frequent and long-distance flyers (Climate Assembly UK, 2020). In some cases government legislation may need to lead the way on the basis that public support would strengthen as the co-benefits of the changes became apparent. For example, before congestion charging was introduced in Stockholm, it was supported by around 40% of the public. Five years after its introduction, support had increased to about 70% (Tools of Change, 2014). In other cases, public sentiment can change swiftly and prompt governments to react by introducing legislation and other policy measures. Increased awareness of the harmful environmental effects of single-use plastics is a recent example.

3.7.2 Behavioural changes in advanced economies and emerging market and developing economies

There are large differences in the use of energy services around the world, some of which reflect geographical and climatic variations across regions and others that reflect differing economic and development factors. For example, on a per capita basis, the number of kilometres driven by cars is about eight-times higher in advanced economies than in emerging market and developing economies, and demand for space cooling is more than four-times higher, even though emerging market and developing economies have around four-times more cooling degree days than advanced economies in a typical year.[24] Because of such variations, which for the most part persist in 2030 in spite of strong economic growth in emerging market and developing economies, the opportunities for behavioural change to make a significant impact in curbing energy demand in the near term are greater in advanced economies than emerging market and developing economies (Figure 3.30).

In the NZE, behavioural changes in road transport in advanced economies reduce passenger vehicle-kilometres by 22% in 2030, taking activity to just below the level in 2020. In contrast, the impact of behavioural changes in emerging market and developing economies is half of

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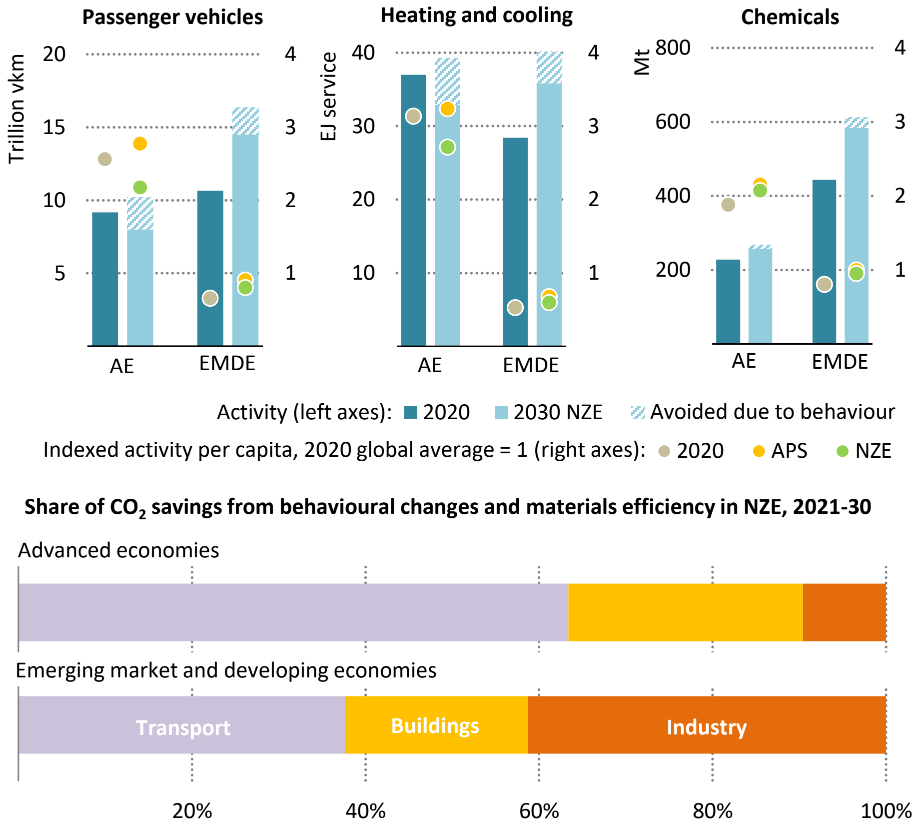
[24] The number of cooling degree days is a measure of cooling demand. It represents the number of degrees that the average temperature during a day is above a given threshold temperature.

this in 2030, and per capita activity continues to expand from current levels by more than 35%. There is a similar split between the two groupings in the impact of behavioural changes on heating and cooling demand and other end-uses, with the result that behavioural changes in the NZE tend to reduce global inequalities in per capita energy consumption by 2030. In contrast to the transport and buildings sectors, the biggest opportunities for gains in materials efficiency are in emerging market and developing economies. For example, improvements in the design and construction of buildings and other infrastructure reduce demand for chemicals in emerging market and developing economies by 5%, or around 30 Mt, in 2030.

Figure 3.30 ▹ Behavioural change impact on energy-related activity and CO_2 emissions



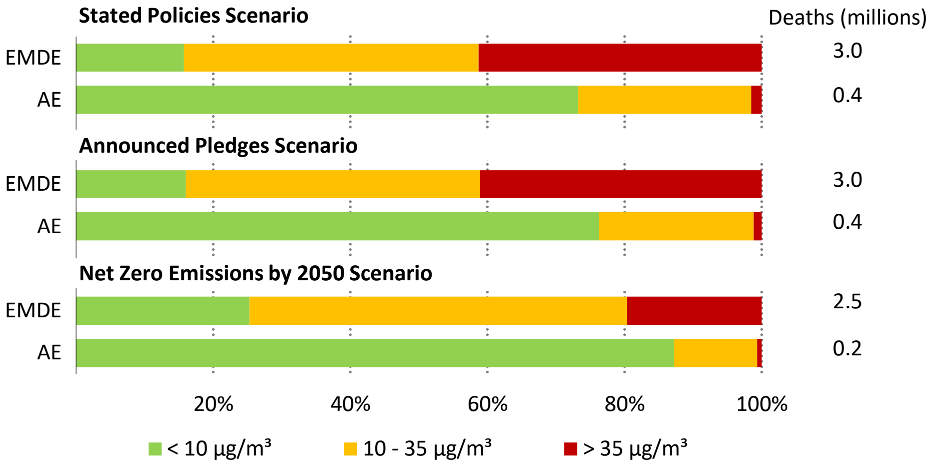
Behavioural changes play different roles at different levels of development, with materials efficiency particularly important in emerging market and developing economies

Notes: vkm = vehicle kilometre; EJ service = useful energy demand in EJ; Mt = million tonnes; AE = advanced economies; EMDE = emerging market and developing economies. Chemicals include ethylene, propylene, BTX, ammonia and methanol.

3.8 Announced pledges and air pollution

Over 90% of the world's population breathe polluted air on a daily basis, leading to more than 5 million premature deaths a year. Air pollution also leads to multiple serious diseases, placing an extra burden on healthcare systems currently struggling to deal with the Covid-19 pandemic. Almost 3 million premature deaths a year are caused by breathing polluted air from outdoor sources (ambient air pollution), and around 2.5 million are the result of breathing polluted air from household sources (household air pollution), due mainly to the traditional use of biomass for heating and cooking. The majority of premature deaths from ambient air pollution and almost all of those from household air pollution happen in emerging market and developing economies, where air pollution also comes with a significant economic cost: it is estimated to reduce the GDP of the largest emerging and developing economies by more than 5% per year (CREA, 2020).

Figure 3.31 ▹ Share of population exposed to various $PM_{2.5}$ concentrations and premature deaths from ambient air pollution in 2030



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Exposure to high concentrations of $PM_{2.5}$ is reduced by more than half in the NZE relative to both the STEPS and APS, contributing to a 20% drop in premature deaths

Note: AE = advanced economies; EMDE = emerging market and developing economies; μg/m^3 = micrograms per cubic metre.

Source: IEA analysis based on IIASA modelling.

In the STEPS, the number of people exposed to polluted air continues to rise in emerging market and developing economies, where in 2030 over 40% of the population breathes air with concentrations of fine particulate matter ($PM_{2.5}$) exceeding 35 microgrammes per cubic metre (µg/m^3).[25] In contrast, only around 2% of people in advanced economies have long-term exposure to such $PM_{2.5}$ concentrations today, and this remains largely unchanged by 2030 in the STEPS. The annual number of premature deaths from ambient sources increases by around half a million in emerging market and developing economies by 2030, whereas it falls by around 25 000 in advanced economies. Premature deaths from household air pollution in emerging market and developing economies fall by just over 200 000 by 2030.

In the APS, announced pledges mean that slightly fewer people are exposed to high concentrations of $PM_{2.5}$ in 2030 than in the STEPS, mainly due to reductions in the traditional use of biomass to heat buildings and reduced emissions from industry. There is also an 8% drop in emissions of nitrogen oxides (NO_X), which reflects reductions in NO_X emissions in the industry and road transport sectors, and a 6% drop in sulphur dioxide (SO_2) emissions, which reflects a reduction in the use of coal in industrial facilities and electricity generation. This contributes to around 45 000 fewer premature deaths from ambient air pollution in 2030 than in the STEPS, with just over one-third of this reduction happening in emerging market and developing economies.

While the STEPS and APS see rising numbers of premature deaths during the next decade, the NZE leads to dramatic reductions. By 2030 there are 1.9 million fewer premature deaths from household air pollution per year than in 2020, and around 250 000 fewer premature deaths from ambient air pollution. The number of people exposed to the highest concentrations of $PM_{2.5}$ halves compared to both the STEPS and the APS, while at the same time the number of people exposed to concentrations lower than 10 µg/m^3 – the threshold below which there is no identifiable impact on increased mortality – increases by around 40% (Figure 3.31).

The steep reduction in early mortality associated with air pollution in the NZE is a consequence of rapid cuts in all the main air pollutants. Even though emissions were suppressed in 2020 due to Covid-19 lockdowns and restrictions, both SO_2 and $PM_{2.5}$ emissions are almost two-thirds lower by 2030 than they were in 2020, and NO_X emissions are down by 40%. Reduced coal in electricity generation is the single biggest contributor to the reduction in SO_2 emissions, while burning less biomass in the buildings sector has the biggest impact on $PM_{2.5}$ emissions, and electrification of road transport reduces NO_X emissions the most.

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[25] Fine particulate matter of less than 2.5 micrometres in diameter is known as $PM_{2.5}$. Concentrations greater than 35 µg/m^3 correspond to the least stringent air quality standard by the World Health Organisation and have been shown to be associated with significant mortality (WHO, 2006).

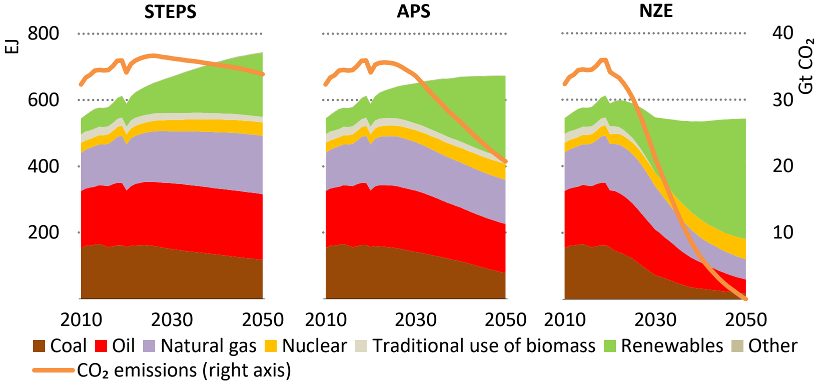
Exploring multiple futures: demand and electricity

No time to waste

SUMMARY

- A lack of adequate supporting policies sees an "implementation gap" emerge between emissions as they would be if today's net zero and other pledges were fully delivered (the Announced Pledges Scenario [APS]) and emissions as they look set to be under current and announced policies (the Stated Policies Scenario [STEPS]). By 2030 this gap reaches 2.6 gigatonnes (Gt) of CO_2, almost 90% of which is in advanced economies where emissions reduction pledges are most prevalent.

Figure 4.1 ⊳ **Total primary energy supply by fuel and scenario**



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Closing the implementation gap between STEPS and APS requires achieving current pledges; new pledges are needed to close the "ambition gap" from the APS to NZE

- Closing the implementation gap would fill less than 20% of the emissions gap between the STEPS and the Net Zero Emissions by 2050 Scenario (NZE) pathway through to 2030, but there are important variations. In advanced economies, emissions decline by one-third to 2030 in the APS, closing half of the total gap between the STEPS and the NZE. Limited pledges in emerging market and developing economies mean that their emissions increase by around 10% in the APS to 2030, closing less than 5% of the gap between the STEPS and the NZE. In 2050, announced pledges in advanced economies close three-quarters of the gap between the STEPS and the NZE.
- The largest implementation gaps are in sectors where clean energy technology options are mature but policies to accelerate their deployment are lacking or insufficient. These gaps highlight where additional policy pushes are required to reach targets. Such pushes could take the form of action to accelerate renewables deployment, for example, or to end new sales of internal combustion engine cars by a given date, or to accelerate building retrofits and construction of new buildings at zero carbon-ready standard, or to remove obstacles to heat pump sales.

- There is also an implementation gap in respect of the achievement of universal energy access by 2030. In the STEPS, some 670 million people remain without access to electricity in 2030 and 2.1 billion without access to clean cooking. Improvements in access have been slowed by the Covid-19 crisis: in recent years, the number of people without access to electricity declined by an average 9% per year, but progress stalled between 2019 and 2021. USD 43 billion annually is required to achieve universal access to electricity and clean cooking by 2030. Investment is only 20% of this level in the STEPS for electricity, and even lower for clean cooking.
- Under announced pledges, energy intensity improvements accelerate to 2.5% per year this decade. Announced pledges also lead to a fall in the share of unabated fossil fuels from 75% in the STEPS in 2030 to 72% in the APS. However, the improvements seen in the APS remain far from what is required by the NZE, which by 2030 sees a 4.2% annual improvement in energy intensity and a decline in the share of unabated fossil fuels in the global fuel mix to below 60%.
- Electrification and energy efficiency play central roles in reducing emissions from end-use sectors, avoiding 2.5 Gt CO_2 by 2030 in the STEPS and a further 0.8 Gt in the APS. Total final consumption growth to 2030 in the APS would be three-quarters higher without efficiency improvements. Electrification further slows demand growth: the average efficiency of electric equipment such as electric cars and heat pumps is higher than that of fossil fuel powered alternatives.
- Electricity supply sees major changes as the use of unabated coal falls globally by 10% to 2030 in the STEPS, by 18% in the APS, and by 70% in the NZE. The share of renewables rises from nearly 30% of generation in 2020 to over 40% in 2030 in the STEPS, 45% in the APS and 60% in the NZE. The combined capacity additions of solar PV and wind rise in all scenarios in the 2020s: to 310 gigawatts (GW) in 2030 in the STEPS, nearly 470 GW in the APS and over 1 000 GW in the NZE. The APS and NZE also see greater use of carbon capture, ammonia, hydrogen and nuclear power, while natural gas use rises to 2050 in the STEPS, but peaks by 2025 in the APS, providing system flexibility and displacing coal in emerging market and developing economies.
- The implementation gap for electricity supply between the STEPS and APS is largest in advanced economies, where ambitions were raised recently, for example in the European Union and United States. The ambition gap between the APS and NZE is more significant for emerging market and developing economies: their unabated coal use rises until the mid-2020s before starting a long-term decline, whereas the NZE calls for a near-term peak and 60% reductions by 2030.
- The electricity sector is responsible for 36% of global CO_2 emissions today, which is more than any other sector. Its emissions decline by 10% to 2030 in the STEPS and by nearly 20% in the APS. These reductions are far short of those in the NZE, where electricity sector emissions fall by close to 60% by 2030 on the way to reaching net zero in advanced economies collectively in 2035 and in all countries in 2040.

4.1 Introduction

Global and country level ambitions for energy sector transitions, as represented in the Announced Pledges Scenario (APS), fall short of what is required to be on track in the Net Zero Emissions by 2050 Scenario (NZE). However, there is a risk that the ambitions assumed to be achieved in the APS will not in fact be matched by specific policies and measures, or that any such policies and measures prove inadequate for the job, and as a result that the world falls short even of the pathway set out in the APS.

This chapter draws on two scenarios in particular, the Stated Policies Scenario (STEPS) and the APS, though it also refers to the NZE. The STEPS provides a bottom-up sector-by-sector assessment of policies and measures actually in place or under development, and provides insights into how energy demand may evolve if the ambitions of the APS are not realised, and its implications for climate goals. The APS takes account of all the pledges and promises that have been made, and assumes that additional policies and measures will be put in place so as to enable those pledges and promises to be met in full. The chapter examines various aspects of energy in the STEPS and APS and highlights the gaps that may emerge if ambitions are not underpinned by the policy frameworks and measures necessary to make them a reality. In addition, the analyses draw attention to the key changes that would help close the gap, with a particular emphasis on 2030 as a key milestone on the road to 2050.

Section 4.2 highlights the impact on CO_2 emissions of the implementation gap between announced pledges in the APS and where current and stated policies are taking us in the STEPS. It also explores the implementation gap for access to electricity and clean cooking.

Section 4.3 focuses on the evolution of total primary energy supply and total final consumption over the next decade and beyond in the three main scenarios.

Section 4.4 focuses on transitions in the end-use sectors and the increasing role of energy efficiency and electrification to temper energy demand and emissions growth, looking sector-by-sector at key challenges and examples of success.

Section 4.5 explores the possible trajectories for the electricity sector, underlining the scale of change that is required to realise announced pledges, and how far current and announced policies will take us.

4.2 Implementation gap

Pledges need specific policies and measures if they are to be fulfilled. If current pledges are not backed up by the necessary policy frameworks an “implementation gap” (between the STEPS and the APS) will emerge. This implementation gap is different from the “ambition gap” (between the APS and the NZE) which highlights the additional effort required above and beyond current pledges for the energy sector to achieve net zero emissions by 2050. In the case of universal access to energy by 2030, which is at the heart of the United Nations Sustainable Development Goal 7, the key implementation gap is between achieving universal access to energy by 2030 in the NZE and failing to achieve it in the STEPS and APS.

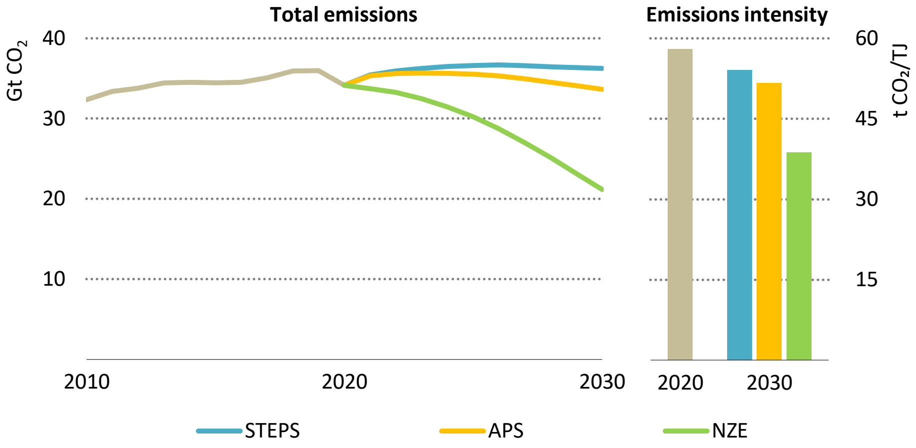
Many governments are in the process of developing specific policies, measures and strategies to deliver on their net zero emissions objectives and new Nationally Determined Contributions under the Paris Agreement. The implementation gap will narrow as they do. Our efforts to identify implementation gaps are intended to provide insights about where additional policies and investment are most needed to help ensure pledges are achieved.

4.2.1 CO_2 emissions

Achieving net zero emissions by 2050 requires a transition of unprecedented speed and scale. Current ambitions – as expressed in the APS – fall short of what is needed to achieve the goals. However, the APS trajectory itself cannot be taken for granted, and the difference in carbon dioxide (CO_2) emissions[1] between the STEPS and the APS illustrates very starkly the size of the policy implementation gap that exists at present.

In the APS, global CO_2 emissions stay below the all-time high of 2019 and return to 2020 levels by 2030 (Figure 4.2). In the STEPS, the policies that are now in force or have been announced are insufficient to prevent emissions surpassing 2019 levels and ending the decade 6% higher than in 2020. Both are far from the NZE trajectory, which sees emissions falling to around 21 gigatonnes (Gt) in 2030. By 2050, the gap between the STEPS and APS widens, with global CO_2 emissions reaching 34 Gt in the STEPS and 21 Gt in the APS in 2050 (two decades later than in the NZE).

Figure 4.2 ▷ **CO_2 emissions and intensity by scenario, 2020-2030**



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Without additional specific policies to deliver on announced pledges, global CO_2 emissions are set to increase further this decade before plateauing

Note: t CO_2/TJ = tonnes of carbon dioxide per terajoule.

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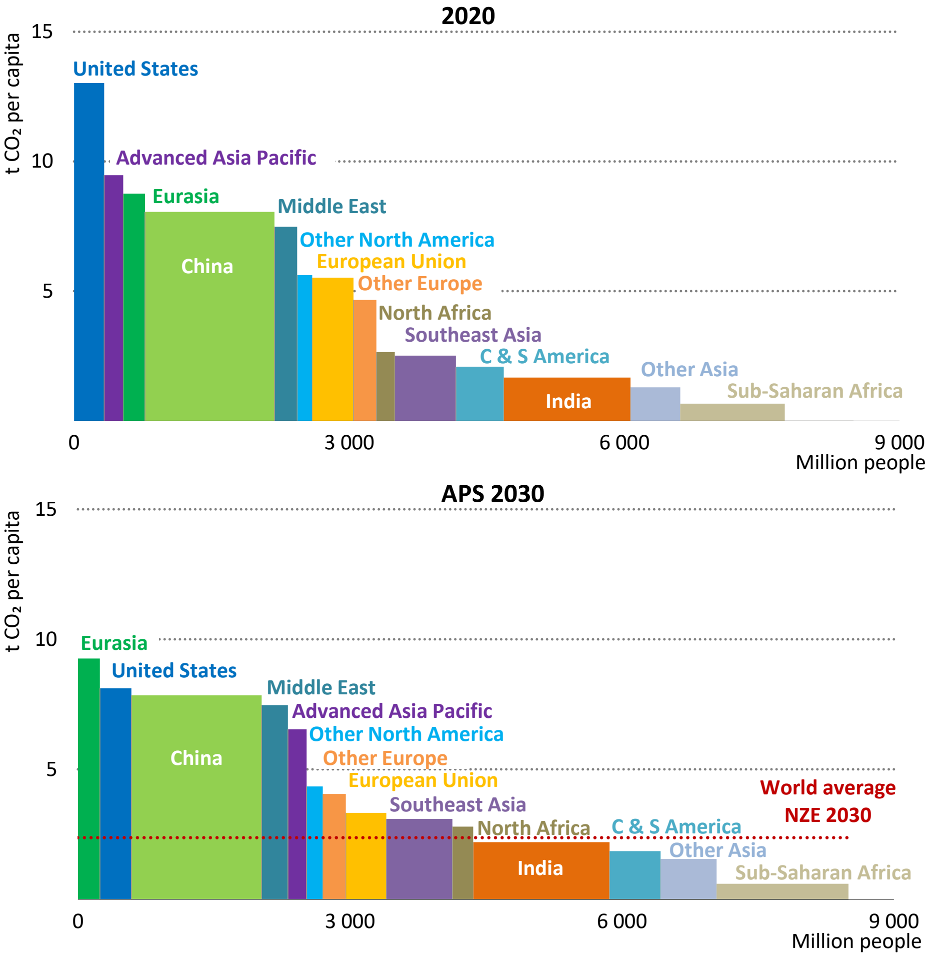
[1] Unless otherwise stated, carbon dioxide (CO_2) emissions in this section refer to energy-related and industrial process emissions.

Distribution of the implementation gap reflects the announced emissions reductions pledges and their inherent level of ambition. To date, most advanced economies and the European Union have announced net zero objectives, covering the vast majority of CO_2 emissions from advanced economies. Across emerging market and developing economies, fewer countries have net zero pledges, representing around half of emissions, with the majority from China.

Figure 4.3 ▻ CO_2 emissions per capita by region in 2020 and 2030 in the Announced Pledges Scenario



Announced pledges lower average CO_2 emissions per capita in advanced economies, but emissions remain well above what is required in the NZE pathway

Notes: C & S America = Central and South America. The world average NZE 2030 excludes CO_2 emissions from international aviation and shipping.

Advanced economies today account for around one-third of global CO_2 emissions, but for almost 90% of the global emissions gap between the APS and STEPS by 2030. This reflects that they are responsible for the majority of commitments to achieve net zero emissions, but it is also an indication that policies are not yet in place across all sectors to make good on the commitments. Two advanced economies are highlighted:

- The United States accounts for about 45% of the total emissions implementation gap between the APS and STEPS, reflecting the ambitious nature of its pledges. By 2030, CO_2 emissions in the United States in the APS are 30% lower than in the STEPS, with per capita emissions falling to 8 tonnes CO_2 per capita (t CO_2 per capita) (Figure 4.3). Despite this decline, per capita emissions in the APS in the United States remain more than three-times higher than the world average in the NZE in 2030.
- The implementation gap in the European Union is less pronounced due to the steps already taken to support the target of a 55% emissions reduction by 2030 relative to 1990 and an objective of net zero by 2050. Nonetheless, current policy measures are not sufficient to achieve these goals, and an implementation gap of 470 million tonnes (Mt) CO_2 is apparent by 2030,[2] equivalent to about a fifth of current emissions in the European Union. Full implementation of its proposed Fit for 55 package would reduce this implementation gap and shift per capita emissions in the European Union toward the global average seen in the NZE in 2030.

Emerging market and developing economies are responsible for a much smaller share of the implementation gap because they have made fewer emissions reductions pledges and they are less ambitious than those of advanced economies. By 2030, the implementation gap across emerging market and developing economies is equivalent to around 1% of current emissions from the group. Despite limited emissions reduction pledges, in many emerging market and developing economies per capita CO_2 emissions remain two-thirds below the advanced economy average by 2030 in the APS. Eurasia, China and producer economies across the Middle East are the exception and they are among the highest emitting regions on a per capita basis by 2030 in the APS. China and some Central and South American countries are among those with pledges in place:

- Current and announced policies enable China to meet its target of peak emissions by 2030, but its pledge to reach net zero emissions by 2060 requires further policies for the period after 2030, which creates a widening implementation gap. In the APS, per capita CO_2 emissions in China in 2030 remain similar to today: this means that they are roughly on a par with those in the United States, with per capita emissions in the United States declining by 40% between now and 2030 in the APS.
- In Central and South America, per capita CO_2 emissions in 2030 decline by more than 10% from 2020 levels, with ambitious climate pledges in several countries such as Argentina, Brazil, Chile and Colombia more than offsetting growth of emissions in other countries in the region which lack a strict climate policy framework.[3]

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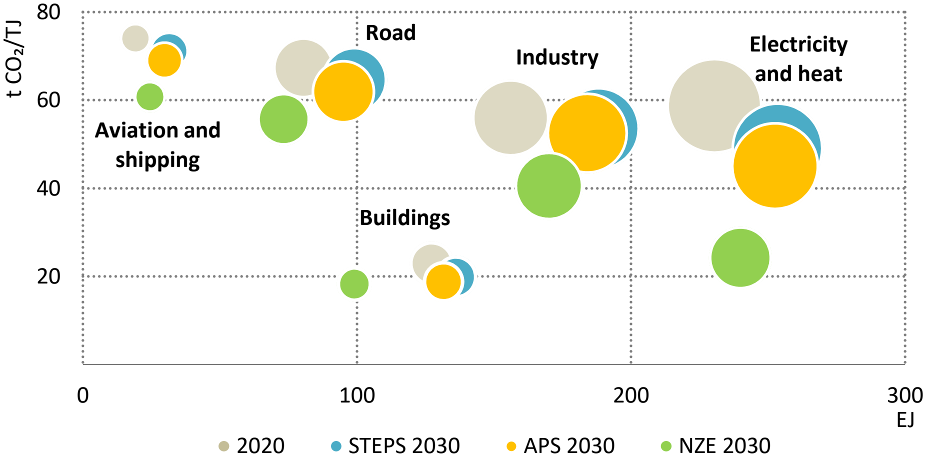
[2] Excluding emissions from international aviation and navigation bunkers.

[3] Clean energy transitions in Central and South America will be examined in depth in a forthcoming publication by the IEA and the Inter-American Development Bank.

All **sectors** see an implementation gap between current ambitions, the APS, and stated or current policies, the STEPS. Measures to close implementation gaps in the 2020s generally involve scaling up mature technologies to boost the use of renewables, electric vehicles (EVs), building retrofits and efficient industrial motors. Many of the policies needed to achieve the required roll-out of these technologies are tried and tested. Some countries are already taking policy action and some are introducing specific targets in particular sectors. Examples include proposals to halt the sale of internal combustion engine (ICE) cars and vans by 2035 in the European Union and Canada, decarbonise the power sector by 2035 in the United States, and end fossil fuel heating for new homes from 2025 in the United Kingdom. However, the actions being taken are not yet sufficiently widespread or hard-hitting to deliver what is needed in the APS.

Many of the hard-to-abate sectors, such as heavy trucking and heavy industry sectors and process emissions, have smaller implementation gaps than other sectors. This is primarily because the lack of available mature technological solutions means that hard-to-abate sectors do not see a significant declines in their CO_2 content and total CO_2 emissions by 2030 in the APS (Figure 4.4). Beyond 2030, achieving economy-wide net zero objectives in the APS is dependent on reducing emissions across the board, including in hard-to-abate sectors. As a result, their emissions fall sharply post-2030 in countries with net zero pledges, although the declines are far from sufficient to achieve net zero in these sectors globally.

Figure 4.4 ▷ Energy use, carbon intensity and CO_2 emissions by sector and scenario, 2020-2030



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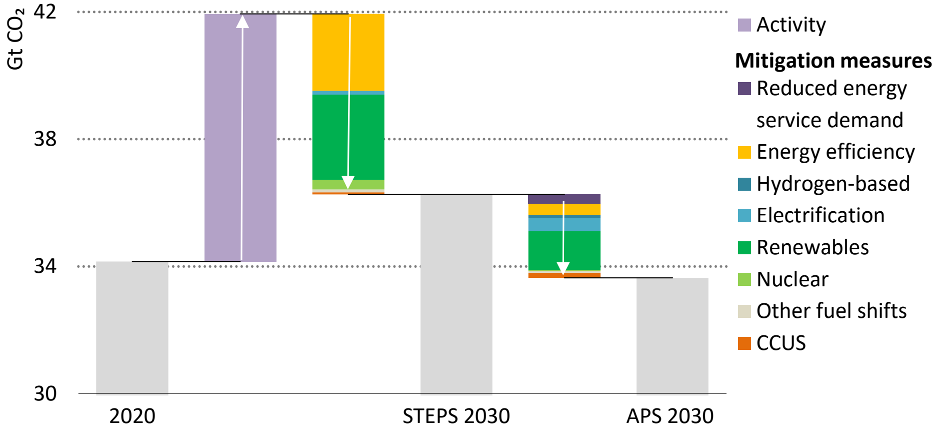
Closing the implementation gap requires parallel efforts to improve energy efficiency and reduce the CO_2 intensity of energy use by electrifying or switching to low-carbon fuels

Notes: t CO_2/TJ = tonnes of carbon dioxide per terajoule; EJ = exajoule. The size of the bubble represents the overall CO_2 emissions by sector. Industry emissions include industrial process emissions.

Closing the emissions gap between the STEPS and the APS is underpinned by the decarbonisation of electricity supply (see section 4.5). Around 40% of the 2.6 Gt implementation gap in 2030 could be closed by the power sector, notably by increasing the role of **renewables** in meeting demand growth and in replacing existing fossil fuel generation assets. Decarbonisation of the power sector happens in parallel to widespread **electrification**, with sectors from passenger and freight transport to industrial processes and heating in the buildings sector all seeing an increase in the role electricity plays in meeting demand. Not all energy uses can be easily electrified, however, and **energy efficiency** is central to efforts to moderate increased demand and thus to ensure that additional electricity demand does not compromise the decarbonisation of electricity supply. Direct use of renewables such as bioenergy, solar thermal and geothermal provides an alternative to electrification and contributes 15% to closing the implementation gap (Figure 4.5). Carbon capture, utilisation and storage (CCUS) provides a way to tackle remaining emissions in both the power and industry sectors, especially beyond 2030. CCUS also provides an opportunity to scale up low-carbon hydrogen production and CO_2 removal (Box 4.1).

Figure 4.5 ▻ Energy and industrial process CO_2 emissions and mitigation levers in the Stated Policies and Announced Pledges scenarios, 2020-2030



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Closing the emissions gap between the scenarios requires rapid growth of renewables in the power sector, increased energy efficiency and electrification

Box 4.1 ▻ Scale up CCUS to close the implementation gap

Carbon capture, utilisation and storage (CCUS) has the potential to contribute to emissions reductions in many regions. Momentum is growing, driven by strengthened climate commitments from governments and industry. The capture capacity of projects announced since the beginning of 2020 exceeds total capacity operating today. This momentum has led to support for investment. It has also increased recognition of the need to establish legal and regulatory frameworks for CCUS, develop CO_2 transport and storage infrastructure, and to put in place targeted policy and financing support.

A variety of CCUS projects are operating or being planned in different sectors. Examples include:

- **Industry:** CO_2 capture is already an integral part of fertiliser production and other industrial processes. Deployment is expanding to the production of steel, chemicals and cement. Today a commercial steel plant is operating with CO_2 capture in Abu Dhabi and work is in progress to retrofit a cement plant in Norway. In the STEPS, capture expands to 30 Mt CO_2 by 2030, while in the APS net zero commitments increase capture to around 60 Mt CO_2. In the NZE, 375 Mt CO_2 are captured in 2030.
- **Electricity and heat:** Two coal-fired power plants are equipped with CCUS, one in Canada and one in the United States, with a combined capture capacity of around 2.4 Mt CO_2 per year.[4] Several other CCUS-equipped plants have been announced or are in various stages of development. By 2030 capture expands to 13 Mt CO_2 in the STEPS, to over 100 Mt CO_2 in the APS and to more than 400 Mt CO_2 in the NZE.
- **Fuel supply:** The majority of current commercial CCUS facilities, which capture about 30 Mt CO_2 per year, are associated with natural gas processing, which offer relatively low-cost capture opportunities. A range of CCUS projects are planned which would capture CO_2 from low-carbon hydrogen and biofuels production, refining and liquefied natural gas. Several involve the development of regional CCUS and/or hydrogen hubs. Capture associated with fuel supply increases to 50 Mt CO_2 by 2030 in the STEPS and to 190 Mt CO_2 in the APS (compared with 780 Mt CO_2 in the NZE).
- **Direct air capture** (DAC): A number of small pilot and demonstration DAC plants are operating around the world today, including some that are providing CO_2 on a commercial basis for beverage carbonation and greenhouses. In Iceland, a facility came online in September 2021, with capacity to capture 4 000 tonnes per year for storage. Large-scale (up to 1 Mt/year) DAC facilities are in development in the United States and the United Kingdom. There is limited deployment of DAC by 2030 in the STEPS and APS, but it grows to around 90 Mt CO_2 in the NZE. This reflects the significance of DAC with storage as a key technology to offset residual emissions and remove legacy CO_2 emissions, as well as its ability to provide a carbon neutral CO_2 input for the production of synthetic fuels.

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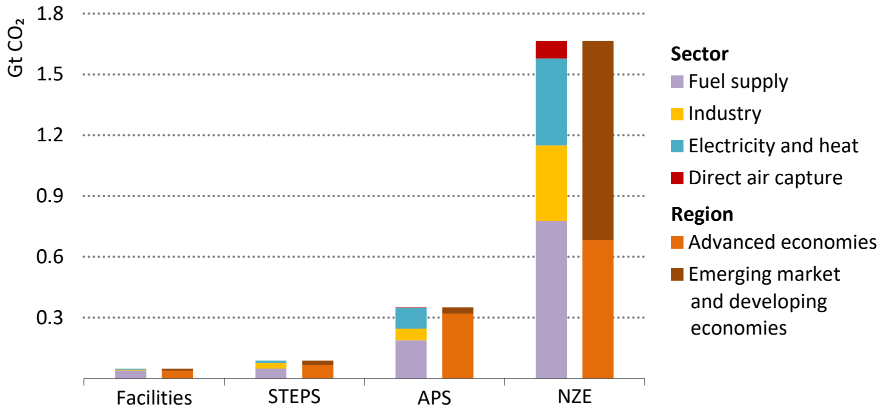
[4] The Petra Nova coal-fired power generation plant in the United States has suspended CO_2 capture operations in response to low oil prices.

Achieving the level of CCUS deployment needed in the APS requires additional concerted efforts to implement supportive policies and financing measures. Projects that are operational today or in construction have the capacity to capture over 40 Mt CO_2 per year (Figure 4.6). This is well short of what is needed in the APS, where deployment in 2030 reaches 350 Mt CO_2 per year, mainly in advanced economies.

Figure 4.6 ⊳ **CO_2 capture capacity by project and scenario, 2030**



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Achieving the level of CCUS needed to reach ambitions in the APS requires targeted policy support and more than a tenfold increase in current capacity

Note: Facilities = operating commercial CO_2 capture projects or under construction (including two with operations currently suspended).

Source: IEA analysis and GCCSI (2021).

The investment environment for CCUS has substantially improved in many places, with significant policy support emerging in Canada, Europe, United States and elsewhere. This includes, for example, grant funding programmes, tax credits and increased carbon prices. Nonetheless, challenges to investment remain. Several characteristics of CCUS projects, such as the need for counterparty arrangements arising from complex chains of capture-transport-storage and the need for regulatory frameworks for long-term ownership/liability of stored CO_2, bring a set of distinct risks, and these are amplified in emerging market and developing economies. Governments and financial institutions have a critical role to play in improving CCUS financing opportunities with policies that help to establish revenue streams, reduce investment risks and ultimately create a sustainable market for CCUS investment.

4.2.2 Energy access

In 2015, all United Nations (UN) members adopted the 2030 Agenda for Sustainable Development, which includes an objective (SDG 7.1) to "ensure universal access to affordable, reliable and modern energy services" by 2030 (United Nations, 2020). This global goal is achieved in full in the NZE, but not in the STEPS or APS. Current and announced policies are insufficient to deliver universal access to electricity and clean cooking by 2030 in the STEPS, while the APS assumes that country level targets are achieved, but not the UN goal. The gap in realising access is one of implementation rather than ambition, and accordingly this section compares how many people gain access to electricity and clean cooking in the STEPS with the outcome in the NZE, where universal access is reached.

Access to electricity

Today 770 million people worldwide still live without access to electricity, mostly in Africa and developing countries in Asia. The Covid-19 crisis delivered a setback, slowing progress on new connections while also weakening the ability of households to pay for electricity (Figure 4.7). Preliminary data show that the global number of people without access was broadly stuck at where it was between 2019 and 2021, after improving 9% annually on average between 2015 and 2019. In sub-Saharan Africa the number of people without access increased in 2020 for the first time since 2013.

Many new connections via networks and mini-grids that were in the pipeline before the pandemic were finalised in 2020, but procurement delays and the need to tackle the public health emergency have held up new project developments. In addition, the deployment of solar stand-alone systems declined by more than 20% in 2020 as lockdowns prevented off-grid companies from reaching new customers and supply chains were disrupted (GOGLA, 2021). Some of the major distributors are seeing sales rebound in 2021, but the impact of the pandemic on household incomes together with price increases for solar cells and other electronic components may continue to impact sales. There is evidence that affordability has become more of a problem than before the pandemic. In 2019, in sub-Saharan Africa, almost half of people without access could not afford electricity for an essential bundle of services, even if provided with a connection.[5] In 2020, due to the pandemic, up to 90 million people with electricity connections in Africa and developing countries in Asia lost the ability to afford an extended bundle of services.[6] Even where households can afford access, now they may opt for cheaper and smaller systems that provide fewer energy services than would have been the case before the Covid-19 pandemic.

Governments and development agencies have provided emergency financial relief to reduce these impacts. Nigeria, for instance, has implemented a recovery plan that includes financing

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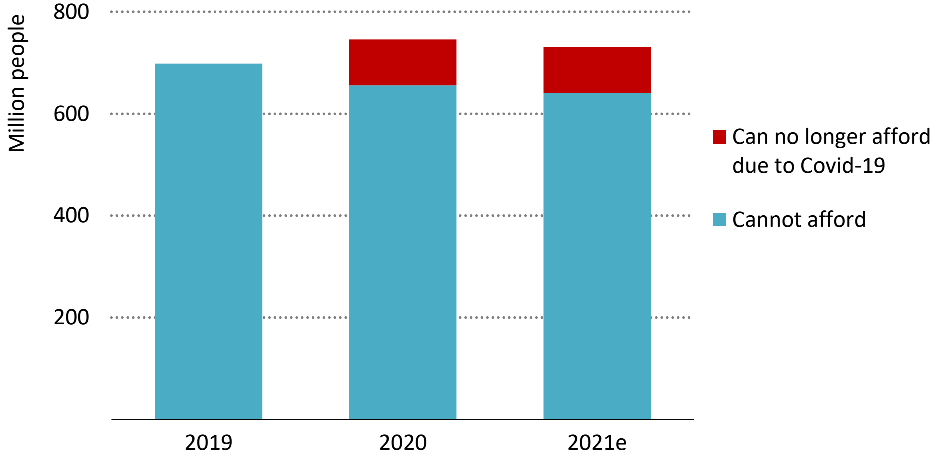
[5] An essential bundle includes four lightbulbs operating for four hours per day, a television for two hours and a fan for three hours.

[6] An extended bundle of services includes four lightbulbs operating for four hours per day, a fan for six hours per day, a radio or television for four hours per day and a refrigerator.

to connect 25 million people through solar home systems and provides monetary incentives for off-grid solar businesses. Poverty or lifeline electricity tariffs – a common tool to target subsidies to those most in need – were expanded during the pandemic. Such tariffs may be required by utility regulators. However, policy support is often limited to grid electricity, even though the reality is that an increasing number of people initially gain access through off-grid solutions.

Figure 4.7 ▷ Population with an electricity connection unable to afford an extended bundle of services in Africa and developing Asia



Even before the pandemic, 700 million people could not afford an extended bundle of electricity services; Covid-19 increased this number by 90 million

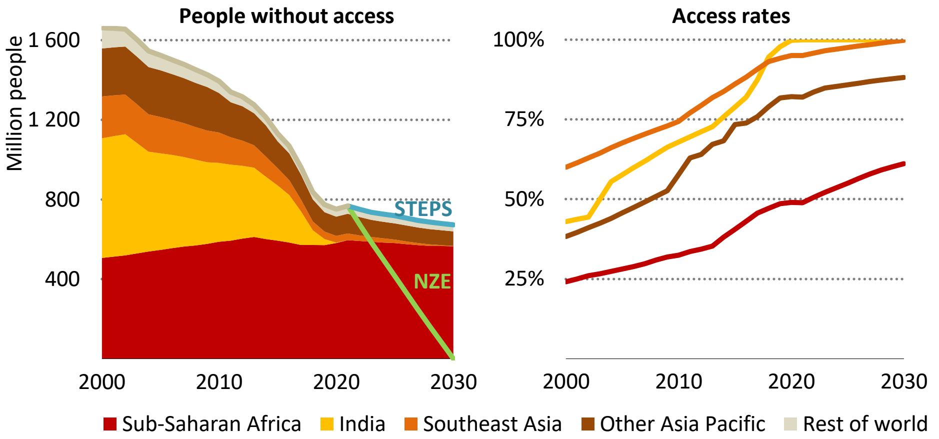
Notes: e = estimated. Affordability refers to the ability to pay for an extended bundle of electricity services.

Source: IEA analysis based on World Bank estimates of the impact of Covid-19 on global poverty (World Bank, 2021).

Achieving full access by 2030 will require connecting almost 100 million people every year, but the world is not on track to reach this goal. In the STEPS, some 670 million are projected to remain without access in 2030 (projections are similar in the APS). Most developing countries in Asia, especially India and countries in Southeast Asia, are on track to achieve near universal access by 2030, but the access rate in sub-Saharan Africa reaches only 60% by the end of the decade, up from 50% in 2019 (Figure 4.8).

Countries with the lowest electricity access rates often lack strong electrification plans and regulatory frameworks (see Table 4.1). These countries make only small improvements in access in the STEPS, and their electricity access rates stay below 30% by 2030. On the other hand, countries with official national electrification plans, clear targets, tracking mechanisms and holistic frameworks for both grid and off-grid solutions already have higher access levels, and move closer to full implementation in the STEPS.

Figure 4.8 ▷ People without access to electricity and access rates by region in the Stated Policies and Net Zero Emissions by 2050 scenarios, 2020-2030



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After significant progress in recent years, led by India, the Covid-19 crisis has stalled improvements in extending access; regaining momentum is vital to achieve the SDG 7.1

Note: Other Asia Pacific includes Bangladesh, Democratic Republic of Korea, Mongolia, Nepal, Pakistan, Sri Lanka, Chinese Taipei, Afghanistan, Bhutan, Cook Islands, East Timor, Fiji, French Polynesia, Kiribati, Lao PDR, Macau, Maldives, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu.

The NZE offers a pathway to deliver electricity to all by 2030. Just under half of households gaining access to electricity do so with a grid connection, while mini-grid and stand-alone systems account for 30% and 25% of new connections respectively. Over 90% of off-grid and around 70% of grid solutions deployed between now and 2030 are sourced from renewables. After 2030, grids will eventually reach most of the customers using off-grid solutions, emphasising the importance of interoperability for off-grid and mini-grid systems built today. Only the most remote users will not have a grid connection by 2050.

Achieving full electricity access by 2030 requires annual investment of over USD 35 billion. This is a tiny fraction of global total energy investment, but well above what is being spent today: investment in electricity access in sub-Saharan Africa is only around 15% of what will be required (SE4ALL and CPI, 2020). Financing is a significant obstacle, since many of the projects – especially those serving rural areas and very poor communities – require public financial support via concessional and blended finance structures (IEA, 2021a) together with improvements in tendering and administrative processes, while at the same time low demand can make it hard to attract private capital.

Table 4.1 ⊳ Implementation of access to electricity policies for countries without universal access in sub-Saharan Africa and Asia

	Countries with access rate:			
	Low (<40%)	Medium (40% - 80%)	High (>80%)	Average
Electricity access regulatory provisions				
Is there a credible electrification plan?	🔴	🟡	🟢	🟡
Does the plan set a minimum service level?	🔴	🟡	🟡	🟡
Are funding support schemes for grid connection available?	🔴	🟡	🟢	🟡
Are mini-grids included in policy support schemes?	🟡	🟡	🟢	🟡
Are stand-alone systems included in policy support schemes?	🟡	🟡	🟢	🟡
Are affordability provisions available?	🟡	🟢	🟢	🟢
IEA average access rate				
2020	21%	59%	96%	57%
STEPS 2030	27%	76%	99%	66%

Level of implementation: 🔴 Low 🟡 Moderate 🟢 Significant

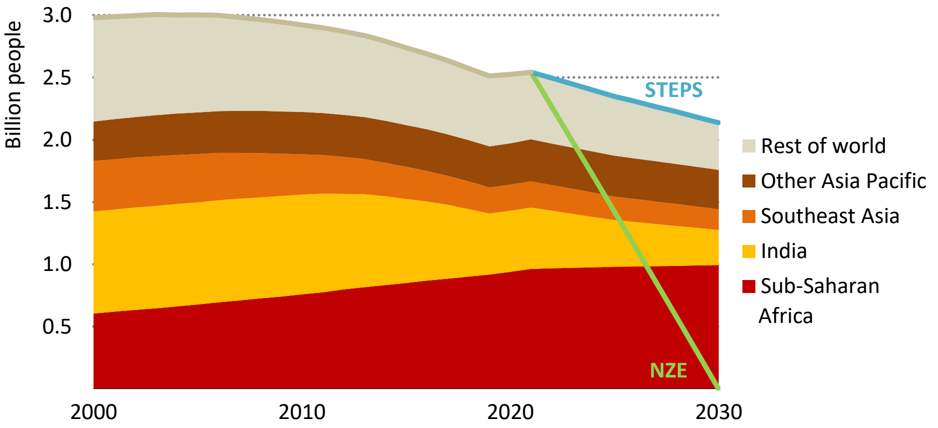
Source: Based on the ESMAP-RISE indicators (ESMAP, 2021) and IEA electricity access data.

Access to clean cooking

More than 2.5 billion people lack access to clean cooking worldwide and, as with electricity, the Covid-19 crisis reversed recent progress towards universal access. Cooking with the traditional use of biomass, coal or kerosene causes 2.5 million premature deaths annually (see section 3.8), slowing social and economic development and entrenching gender inequality. Between 2015 and 2019, the global population without clean cooking access decreased on average by 2% per year, led by efforts in developing countries in Asia.

We estimate that the number of people without access increased by 30 million, or slightly more than 1%, between 2019 and 2021 (Figure 4.9). The pandemic slowed the deployment of clean cooking stoves and fuels, and diminished the ability of households to pay for clean fuels. It also made it more difficult for existing liquefied petroleum gas (LPG) users to travel to refilling stations. In 2020, around 50 million people in developing countries in Asia and Africa reverted to the traditional use of solid biomass for cooking. This shift, together with the increased time spent at home due to Covid-19 lockdown measures, increased exposure to air pollution and the associated health risks. Some governments enacted policies to help manage this issue and ensure continued delivery amid the pandemic. In India, for example, the government provided support for free refills of LPG cylinders. Many of these support schemes may need to be extended to offset the continuing impact of the pandemic.

Figure 4.9 ⊳ Population without access to clean cooking in the Stated Policies and Net Zero Emissions by 2050 scenarios



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In the STEPS, some 2.1 billion people remain without access to clean cooking in 2030; reaching universal access by 2030 will require significant acceleration of progress

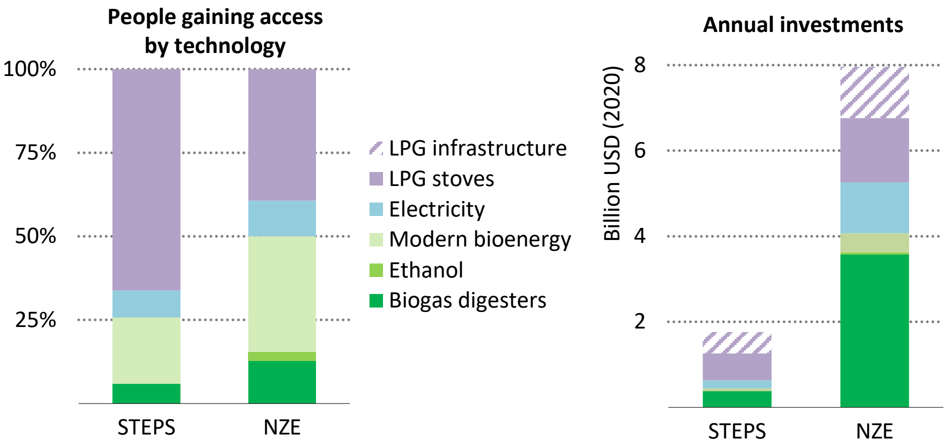
Note: Recent survey data from the World Health Organization for India revised the historic clean cooking access rates. This is due to faster progress than previously assumed, in large part due to the Pradhan Mantri Ujjwala Yojana LPG distribution scheme.

Source: IEA estimates based on historical data (up to 2019) from the World Health Organization household air pollution database (WHO, 2021).

To reach full access to clean cooking by 2030, around 280 million people each year need to gain access – a fivefold acceleration compared with pre-pandemic improvement levels. This does not happen in the STEPS, where 2.1 billion people are still without access to clean cooking in 2030, nor in the APS. The annual investment needed to achieve full clean cooking access by 2030 is around USD 8 billion (Figure 4.10), including about USD 1.2 billion to finance downstream LPG infrastructure such as primary storage units, refilling stations and cylinders (excluding transport). Current investment in clean cooking in sub-Saharan Africa represents only about 3% of the capital expenditure required to reach full access (SE4ALL and CPI, 2020).

In the NZE, a variety of low-carbon technologies are deployed to end the harmful use of solid fuels for cooking and to reduce greenhouse gas (GHG) emissions and other climate forcing agents (e.g. black carbon). The NZE sees faster uptake of electric cooking and biogas digesters than the STEPS, however, LPG remains important in the years to 2030. During that period, the total demand for LPG does not grow rapidly in the NZE, as urban LPG users increasingly switch to electricity, offsetting increased demand from those gaining access (IEA, 2021b). Rural communities gradually make a similar switch in the two decades after 2030 as they gain a more reliable electricity connection.

Figure 4.10 ⊳ Access to clean cooking by technology and related investment in the Stated Policies and Net Zero Emissions by 2050 scenarios, 2021-2030



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Half of those gaining access to clean cooking in the NZE do so with renewables, and a further 10% with electricity; investments are five-times higher than in the STEPS

Notes: Annual investments = average annual investment in the 2021-2030 period. Biogas digester investment refers to decentralised systems and includes both the biodigester and the cost of the stove.

4.3 Energy demand

4.3.1 Energy demand trends to 2030

Total energy supply grows by 1.3% per year from 2020 to 2030 in the STEPS, reaching 670 exajoules (EJ) by 2030 (Figure 4.11). Announced pledges trim the annual growth rate to 1.0% in the APS (650 EJ in 2030). Both scenarios stand in contrast to the NZE where demand declines by an average 0.7% annually to 550 EJ by 2030.

In the STEPS, the world is set to save more energy on an annual basis in the 2020s than it did in the previous decade, with annual intensity improvements averaging 2.2%.[7] In the APS, announced targets lead to annual intensity improvement rate averaging 2.5% over the next decade, which is closer to the objective championed by governments in the Three Percent Club,[8] but still below it, and far from the 4.2% annual improvement rate required in the NZE.

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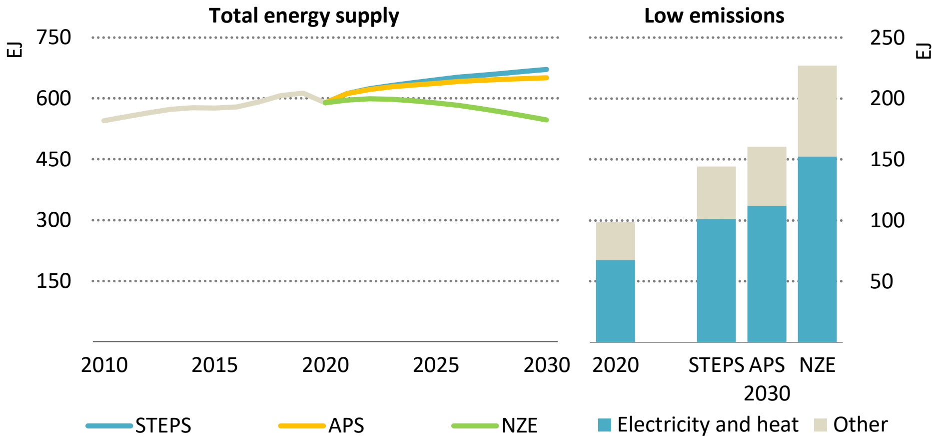
[7] Energy intensity is defined as the ratio of energy supply to GDP in purchasing power parity (PPP) terms to enable differences in price levels among countries to be taken into account. In our scenarios, PPP factors are adjusted as developing countries become richer. Global energy intensity is defined as the ratio of energy supply to GDP. Energy intensity improvement rate is defined as the annual reduction of energy intensity.

[8] The Three Percent Club is a collaboration of governments and supporting organisations committed to putting the world on a path to 3% annual energy efficiency improvements.

Figure 4.11 ▷ Global total energy supply by scenario and low emissions energy supply sources by sector, 2010-2030



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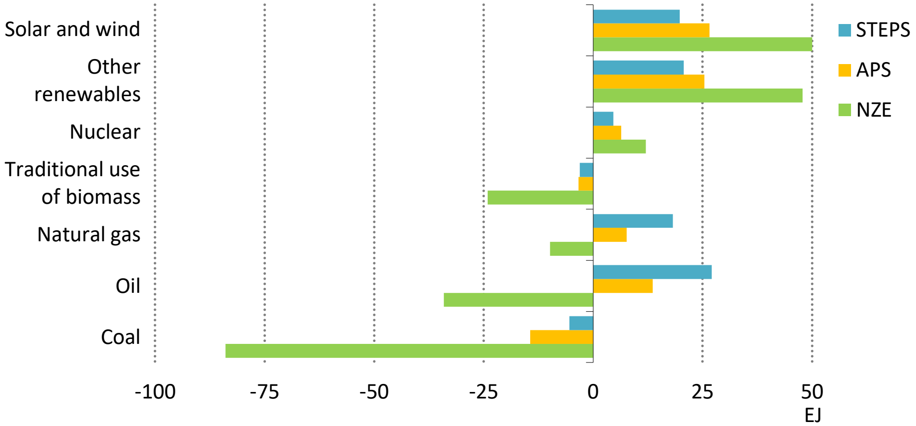
Global energy supply increases 1% per year to 2030 in the APS and 1.3% in the STEPS; the total supply gap between the APS and the STEPS reaches 20 EJ by 2030

Notes: Low emissions sources include renewables, nuclear power and fossil fuels fitted with CCUS, but exclude the traditional use of solid biomass and non-energy use of fossil fuels. Electricity and heat refer to low-carbon energy supply to provide electricity and district heat. Other refers to end-use sectors and the other energy sector.

Figure 4.12 ▷ Change in global total energy supply by fuel and scenario, 2020-2030



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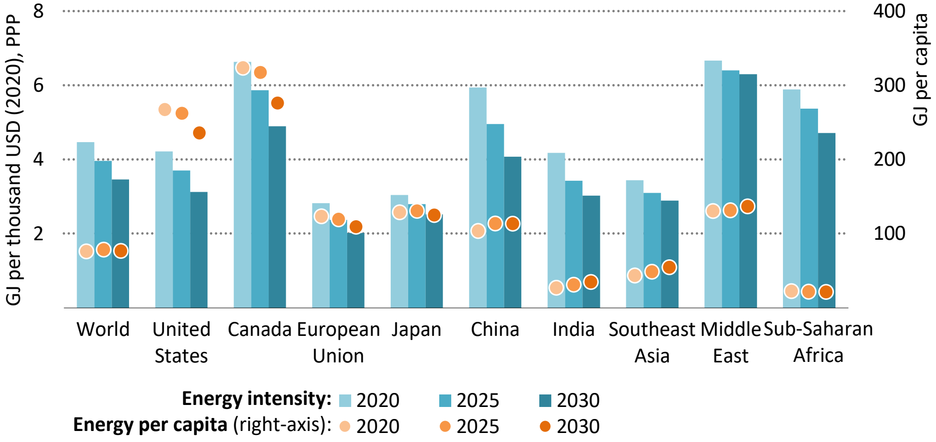
Pledges accelerate the uptake of low-carbon energy sources in the APS relative to the STEPS, but the speed and scale of the transition are well short of what is required in the NZE

Trends by fuel show more marked differences between the scenarios (Figure 4.12) (see Chapter 5). In the STEPS, coal demand rises slightly to 2025, but declines to below 2020 levels by 2030, while demand for oil and gas increases: demand growth is split roughly equally between fossil fuels and renewables, and the share of fossil fuels in the global energy mix declines only slightly from 79% today to 75% in 2030. In the APS, coal demand declines by 10% to 2030, demand for oil and gas grows at only half the rate in the STEPS, and almost 85% of demand growth is met by renewables, as a result of which the share of nuclear and renewables increases from 17% to 24% in 2030 and the share of unabated fossil fuels declines to 72% of the global energy mix.

Regional trends

In **advanced economies**, energy demand increases by 0.1% annually in the STEPS to 2030. Pledges in most major advanced economies mean energy demand in 2030 in the APS is 7% lower than in the STEPS. In the NZE it falls to almost 10% below the level in the APS. Improvements over the STEPS could come about as a result of policies to improve energy efficiency. Measures may include more stringent fuel-economy standards, building codes for new construction, deep retrofits for existing buildings, and the adoption of energy management systems in industry and buildings along with policies to accelerate the electrification of transport and heat, including through bans on new fossil fuel boilers and new ICE cars. On average, the energy intensity of gross domestic product (GDP) in advanced economies improves by 2.1% a year through to 2030 in the STEPS, by 2.8% in the APS and by around 4% in the NZE (Figure 4.13).

Figure 4.13 ▷ Energy intensity and energy demand per capita in selected regions in the Announced Pledges Scenario, 2020-2030



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Despite some significant changes in the APS over the next decade, there remain wide differences in per capita energy use among countries in 2030

Notes: GJ = gigajoules. Energy intensity is defined as the ratio of total energy supply to GDP in PPP terms. Energy per capita corresponds to the ratio of total energy supply to population.

The picture is varied in many **emerging market and developing economies**, where limited emissions reduction pledges to date mean no major implementation gap emerges to 2030: energy demand increases by almost 2% annually through to 2030 in both the STEPS and the APS. Nevertheless, the energy intensity of GDP improves by 2.8% annually in both scenarios, faster than the global average in the STEPS or the APS. Increasing the ambition of energy efficiency and electrification policies would further accelerate this improvement in energy intensity: in the NZE, the annual improvement rate to 2030 rises to 4.8%.

In many developing economies, energy demand per capita continues to increase through to 2030 in order to increase services for the billions of people who want to improve their quality of life, for example by buying refrigerators and air conditioners, motorbikes and cars, and to provide energy services to those who lack access today. This growth of energy services implies higher consumption of industrial products and increased energy demand for their production. Efficiency and/or electrification policies have an important part to play in tempering energy demand growth and helping to keep goods and services affordable (Box 4.2).

In advanced economies, most households already have access to appliances, thermal comfort and transportation, as reflected in high levels of per capita energy demand today. Therefore the focus is on tapping the energy efficiency potential of these goods and services to reduce demand, especially in the NZE. Many advanced economies are already moving in this direction. For example, as part of its Renovation Wave strategy and the Energy Performance of Buildings Directive, the European Union aims to increase retrofit rates and implementing stringent standards for new constructions.

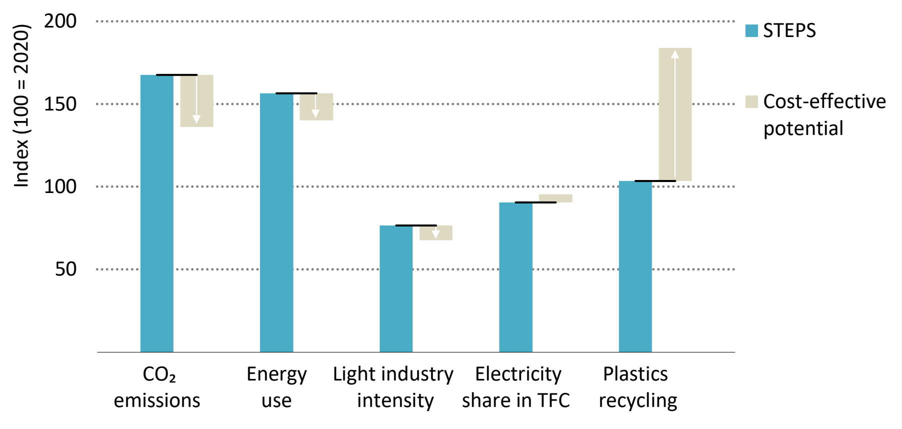
In each scenario, emerging market and developing economies increase their share of global energy demand. This shift is accentuated in the APS: many advanced economies have made pledges which involve curbing demand growth, while few emerging market and developing economies have done so.

Box 4.2 ▹ Make in India, Make Efficient

The "Make in India" programme was launched in 2014 and aims to attract foreign direct investment in industry by improving the ease of doing business, investing in infrastructure and offering fiscal incentives to manufacturers. Make in India targeted an increase in the contribution to GDP from the manufacturing sector to at least 25% by 2022. In May 2020 the announcement of the Atmanirbhar Bharat Scheme provided a further boost to the sector by setting a target for India to achieve industrial self-reliance.

Policies under the Make in India banner cover the light industry sub-sector, whose value added is set to double in the next ten years, and the chemicals sub-sector, where production is set to increase by 55% to 2030. This expected growth points to a rise of almost 70% in CO_2 emissions from light industries and of 60% from chemicals this decade. Tempering the energy demand growth linked to expanding domestic manufacturing in India would have multiple benefits: reducing energy bills for manufacturers (which have been affected by a recent removal of energy subsidies), curbing industrial electricity demand growth (which approaches 770 terawatt-hours [TWh] in the STEPS, up from 540 TWh today) and reducing emissions (Figure 4.14).

Figure 4.14 ▷ Key indicators for the chemicals and light industry sub-sectors in India in the Stated Policies Scenario in 2030 and cost-effective energy and materials efficiency potential



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Promoting cost-effective efficiency and electrification alongside "Make in India" could reduce associated energy demand by 10% and direct CO_2 emissions by 20%

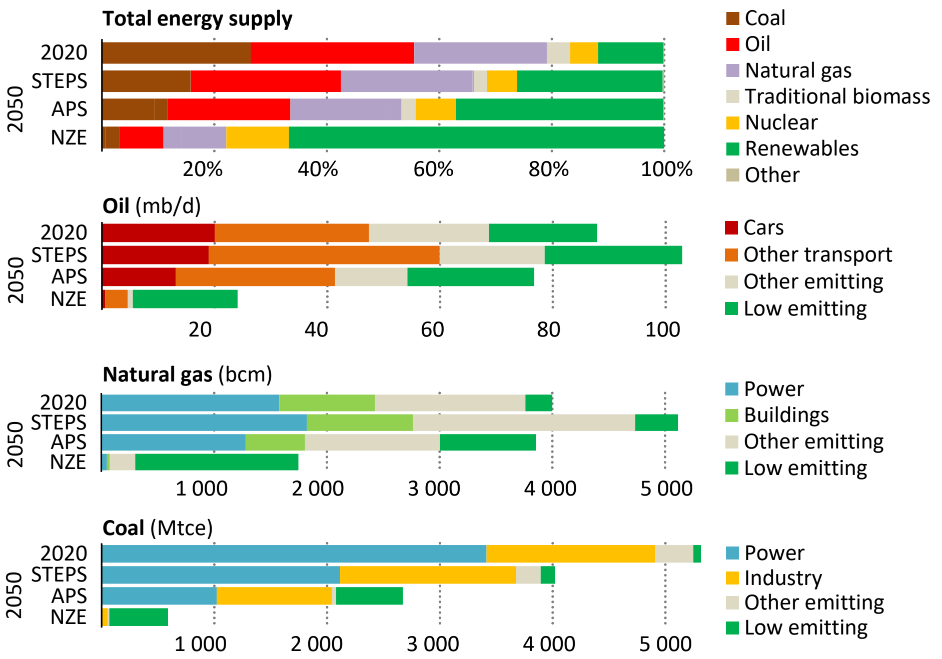
Notes: TFC = total final consumption. Energy and emissions indices are calculated for the chemicals and light industries sub-sectors.

Energy efficiency is the key to tempering demand growth and unlocking these multiple benefits. Current and announced policies would only lead to annual efficiency improvements of 2%, but pushing efficiency towards its full economic potential – including through switching to heat pumps for low-temperature process heat needs – could increase the rate of improvement to 3%. Further to energy efficiency, materials efficiency can play an important role in tempering growth. Improving plastics recycling rates reduces energy demand for chemicals by 4%. Doing so would require the implementation of more stringent and wide-ranging efficiency policies, and measures to link the policies to the Make in India programme and related benefits.

4.3.2 Energy demand trends after 2030

In the STEPS, energy demand continues to climb after 2030, while in the APS it plateaus as a result of net zero pledges that require increased energy efficiency and further electrification across all sectors, ending up almost 10% lower in 2050 than in the STEPS. Even so, the APS lags well behind what is required in the NZE, where energy demand in 2050 is an additional 20% lower than in the APS (Figure 4.15).

Figure 4.15 ▷ **Energy supply and demand by fuel and sector, 2020 and 2050**



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Announced pledges drive the share of unabated fossil fuels in the APS 17 percentage points lower than the STEPS in 2050; demand for all fossil fuels declines relative to today

Notes: mb/d = million barrels per day; bcm = billion cubic metres; Mtce = million tonnes of coal equivalent. Traditional biomass = traditional use of biomass; other = non-renewable municipal waste and other non-specified; power = electricity and heat; low emitting includes fossil fuels combusted in plants equipped with CCUS and non-combustion use of fossil fuels which includes use for non-emitting, non-energy purposes such as petrochemical feedstocks, lubricants and asphalt.

Changes in energy demand are underpinned by shifts in the equipment and fuels used to meet energy demand. Announced pledges in the APS reduce the share of unabated fossil fuels in the global energy mix to just below 50% in 2050. Demand for coal and oil declines the most, with their respective shares in the energy mix falling 15 percentage points and seven percentage points from 2020 levels by 2050. Failure to fully implement the pledges in the APS would slow the transition away from fossil fuels. In the STEPS, unabated fossil fuels still account for two-thirds of the global energy mix in 2050 underlining the need for more support policies to achieve the objectives of the APS. Both scenarios fall very far short of what is needed to deliver the NZE, where the share of unabated fossil fuels drops to around 10%, a share that falls below 5% when non-combustion uses of energy are excluded.

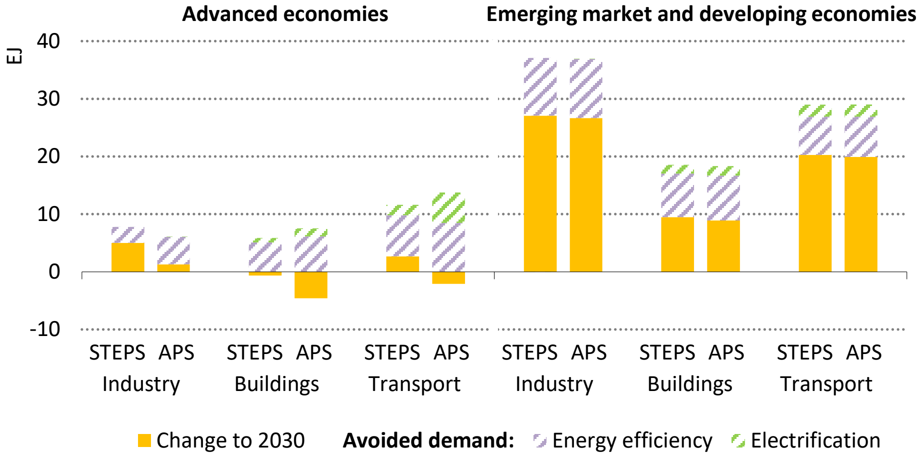
In the APS, oil demand in 2050 is more than 25 million barrels per day (mb/d) below the STEPS levels. Lower oil demand in the APS relative to the STEPS reflects reduced oil use in uses such as road passenger transport, petrochemicals, heavy trucks, aviation and shipping, but the reductions in the APS pale by comparison with what is needed in the NZE. Coal demand is affected in particular by trends in the electricity and heat sector, especially in major emerging markets such as China. China's pledge to reach net zero emissions by 2060 is realised in the APS and drives a structural decline in coal use for electricity and heat generation and industry, but the lack of targets in other major emerging market and developing economies means that coal demand in the APS is far above the levels in the NZE.

4.4 Transitions in final energy consumption

Total final consumption of energy increases by an average 1.7% per year from 2020 to 2030 in the STEPS, and by 1.4% per year in the APS. By 2030, final consumption in the APS is 3% lower than in the STEPS (it is much lower still in the NZE – 17% below the level in the APS). The differences between the STEPS and the APS are largely accounted for by energy efficiency and electrification.

Energy efficiency improvements relative to today reduce overall demand by 8% in the STEPS and 9% in the APS by 2030. Improvements in the APS are sufficient to slow final energy demand growth to 1.4% and a decline of almost 10% in demand in advanced economies. Without energy efficiency improvements in the APS global demand would grow by around 2.3% per year, resulting in a 75% increase in demand growth by 2030 in the APS (Figure 4.16). The impact is greatest in advanced economies, where both existing energy efficiency policies and emissions reductions pledges are most prevalent.

Figure 4.16 ▷ Change in energy demand to 2030 and demand avoided due to energy efficiency and electrification in the Stated Policies and Announced Pledges scenarios



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Pledges in the APS accelerate energy efficiency and electrification, but are insufficient to offset growth in emerging market and developing economies

Electrification also contributes to lowering energy demand because many electric technologies are significantly more efficient than their fossil fuel counterparts. For example, today's electric cars use on average 70% less energy to travel one kilometre than a conventional ICE car and electric heat pumps can be three- to four-times more efficient than conventional boilers. In the APS, electrification reduces energy demand in 2030 by 10 EJ equivalent to 2.5% of today's demand, compared with 1.5% in the STEPS.

4.4.1 Energy efficiency improvements

In the STEPS, energy efficiency improvements through to 2030 offset 30% of the increase in CO_2 emissions linked to expanding demand for energy services. In the APS, this rises to almost 40%. Actions to unlock direct emissions savings include renovating buildings, introducing stringent energy efficiency codes to reduce the use of fossil fuels in buildings, upgrading the efficiency of industrial processes, and improving engine performance in transport (Table 4.2). Efficiency measures that indirectly reduce emissions by reducing electricity demand or slowing growth are also important. Actions to unlock indirect emissions savings include shifting sales of appliances to more efficient models and to 100% light-emitting diodes (LEDs) in lighting sales, implementing standards to require the uptake of the most efficient electric motors and deploying building energy management systems.

In **buildings**, energy efficiency avoids 10% more demand in the APS than in the STEPS to 2030. Almost 85% of this energy efficiency implementation gap is in advanced economies where current policy frameworks are not stringent enough to deliver on announced emissions reduction pledges. In the United States, there is significant untapped potential for energy efficiency improvements in buildings, though policies that would enable emissions reductions ambitions to be realised have yet to be announced. As a result, there is an efficiency implementation gap of almost 0.7 EJ, or 3.5% of demand from the buildings sector, in the United States. The European Union Energy Performance of Buildings Directive is promoting ambitious improvements in the energy efficiency of both new and existing buildings (Box 4.3).

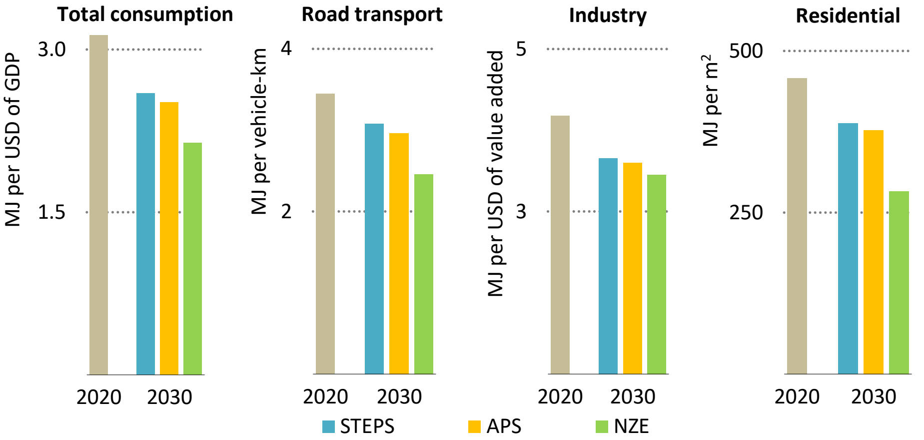
The **transport** sector sees major energy efficiency improvements in the STEPS as the efficiency of ICE vehicles improves and older vehicles are retired (Figure 4.17). Closing the gap with the NZE would require a major step up in efficiency standards as well as a shift away from ICE vehicles to EVs and fuel cell electric vehicles, and further advances in more efficient batteries, fuel cells and low-carbon fuels. The combined effect of electrification and technical efficiency gains is 50% larger in the APS than in the STEPS in advanced economies. Strict fuel economy targets, as deployed in the European Union, have a central part to play in achieving the transport outcome in the APS. The US Department of Transportation recently announced that it will propose a major tightening of corporate average fuel economy (CAFE) standards, targeting 8% fuel economy improvements annually for passenger cars and light trucks manufactured in model years 2024-26, and the APS reflects this upward revision from the previous rules as well as a 50% market share target for zero emissions car sales by 2030.

Table 4.2 ⊳ Selected energy efficiency policies in industry and buildings

Country / region	Policy / action	Description
Canada	Energy Efficiency Regulations	Industrial energy-consuming products (e.g. electric furnaces, heat pumps) need to meet federal standards to be imported, or sold or leased across provinces.
	Canada Greener Homes	Grants and interest-free loans programme to finance deep home retrofits. Dedicated funding stream available for low-income homeowners
Chile	Law on Energy Efficiency	Mandatory reporting of energy efficiency ratings for all new buildings.
European Union	A Renovation Wave for Europe	Double the annual rate of building retrofits in the European Union by 2030.
France	Multi-annual energy plan	+27% improvement of energy efficiency by 2030. Investment support for building retrofits Industry final consumption target of 269 TWh by 2028.
India	New Energy Performance Standards for Air Conditioners	Mandate a default set point temperature of 24 °C for all room air conditioners. Improve minimum performance standards.
Japan	Strategic Energy Plan	Net zero emissions on average from new buildings (residential and services) by 2030.
Korea	Green New Deal	Funding for retrofits of public service and residential buildings.
United Kingdom	Industrial Energy Transformation Fund	Support investment in energy efficiency and the use of low-carbon technologies in energy-intensive industries.
	Future Homes Standard	Fossil fuel heating systems banned from new homes by 2025.
United States	Better Plants program	Energy management plans and energy performance tracking.

Efficiency improvements in **industry** under current and announced policies lag what is required to meet announced pledges by 15%. Industry is the end-use sector with the biggest implementation gap, reflecting the current lack of policies and measures to support efficiency improvements, and almost 90% of this implementation gap is in advanced economies. The introduction of more stringent standards for boilers that provide process heat and for electric motor systems and other industrial equipment is critical to closing the gap. Electrifying industrial processes could also bring efficiency gains, for example by providing low-temperature heat through heat pumps. Increased use of less energy-intensive materials, such as wood instead of concrete for construction, could also help drive down energy intensity. In advanced economies, closing the gap between the STEPS and the APS cuts demand growth from industry by a factor of four.

Figure 4.17 ▷ Energy intensity by sector and scenario



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Energy intensity improves by more than 10% to 2030 in all sectors in the STEPS, but there remains an energy efficiency implementation gap between the STEPS and the APS

Note: MJ = megajoules.

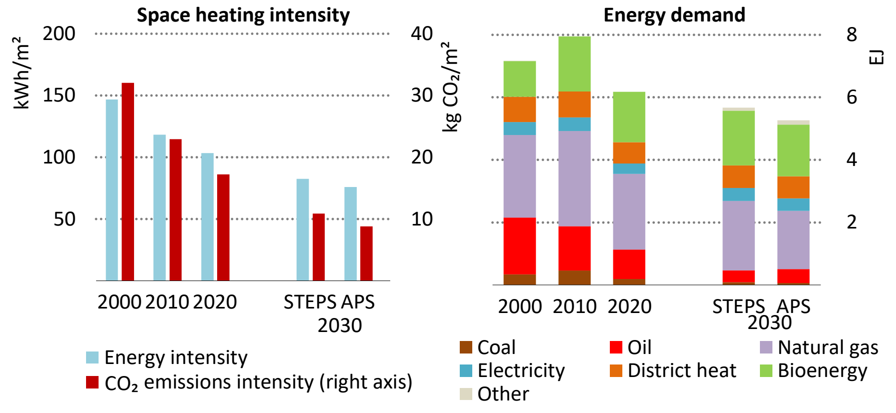
Box 4.3 ▷ Space heating in the European Union: Act now to keep the 2050 target in reach

Space heating in the European Union accounts for 60% of energy demand and 80% of direct CO_2 emissions in the buildings sector. Reducing emissions from space heating is a central pillar of its climate policy and critical to the achievement of the European Union target of net zero emissions by 2050. Progress towards this objective in the buildings sector is supported by a suite of complementary policy measures and targets, notably the Energy Performance of Buildings Directive (EPBD), Renovation Wave for Europe strategy, Energy Efficiency Directive, Renewable Energy Directive, equipment energy performance standards and national long-term renovation strategies. The EPBD requires all new buildings to be nearly zero energy buildings, which means that they must have a very high level of energy performance and meet the majority of energy demand from renewable sources. This requirement came into force at the end of 2018 for public buildings and at the end of 2020 for all other new buildings.

Decarbonisation of space heating hinges on addressing emissions from existing buildings, with the vast majority of existing buildings in the European Union expected to still be in use in 2050. The EPBD aims to support the renovation of existing buildings to achieve a highly energy efficient and decarbonised building stock by 2050. More than 90% of the existing EU building stock needs to be retrofitted to achieve this target, but current retrofit rates are far from sufficient, averaging between 0.5% and 1% of the building stock annually in recent years, and even less for deep renovations. The Renovation Wave for Europe strategy aims to kick-start progress by doubling annual renovation rates in the next ten years, while the Fit for 55 package sets the goal of retrofitting 3% of all public buildings annually. Many Member States are directing funding from the EU recovery and resilience plan toward national building retrofit programmes in an effort to accelerate action.

So far, not all EU Member States have transposed the EPBD into national building energy codes and policies that establish quantified targets in line with the EPBD, and a number of other recently announced targets and strategies have yet to be underpinned by policies and measures. In the STEPS, which reflects current legislation and concrete policy announcements, the energy intensity of residential space heating in the European Union declines from an average of just over 100 kilowatt-hours per square metre (kWh/m^2) in 2020 to 80 kWh/m^2 by 2030 (Figure 4.18), and total space heating demand declines by less than 10%.

Figure 4.18 ▷ Residential space heating energy intensity and energy demand in the European Union in the Stated Policies and Announced Pledges scenarios



Space heating demand falls 15% to 2030 with full implementation of EU policies and targets. Delay in increasing retrofit rates to 2% puts building sector targets out of reach.

Note: kg CO_2/m^2 = kilogrammes of carbon dioxide per square metre.

Full implementation of the suite of policies and targets in the European Union and its member states, as assumed in the APS, would see residential space heating energy demand intensity fall to 75 kWh/m^2, with total space heating demand declining by 15% between 2020 and 2030, and CO_2 emissions falling by 35%. Annual building retrofit rates would need to ramp up to at least 2% by 2030 and 20% of the EU building stock would need to undergo retrofitting by 2030. This is a tall order, but delaying policy action to accelerate retrofit rates by even five years risks pushing the EU climate neutrality goal out of reach.

Reducing space heating emissions in line with the EU climate objectives also depends on a switch to low-carbon heating technologies such as heat pumps or renewables together with the use of building-related digital and connected technologies for energy management and of more efficient appliances. One important milestone on the path to a decarbonised building stock is the phase-out of sales of oil and/or gas boilers for new and/or existing buildings, and several member states are already taking action on this front.

4.4.2 Electrification

Electrification options are cost-effective and commercially available in most end-use sectors today. They become an important driver of emissions reductions in each of the three scenarios.

In **buildings**, electric heat pumps offer the biggest opportunity for displacing fossil fuel boilers for heating. Electric heat pumps are an increasingly attractive technology to meet heating needs in buildings, and installations in the STEPS rise from the current 1.5 million per month to around 3 million by 2030, leading sales for new construction in many regions. In the APS, heat pump installations reach 3.5 million per month by 2030, while in the NZE they reach 5 million a month.

Thanks to significant cost declines in the last decade, heat pumps are becoming more and more competitive as the technology and market mature. They are especially attractive for the one-third of the global population living in regions requiring both space heating and cooling, since reversible heat pumps are able to deliver both services (IEA, 2020a). However, non-economic barriers commonly hinder customer adoption. For example, heating equipment is usually only replaced when the existing equipment fails, and switching to a different kind of heating system may take time and involve substantial extra work. This is compounded by split incentives in rental properties: the savings from lower utility bills often accrue to renters, while building owners pay the higher upfront costs. Some governments have created financing programmes to overcome these upfront cost barriers or have introduced bans on new fossil fuel boilers.

In **industry**, electricity is increasingly used for heat below 200 °C in the STEPS, mainly in the food, textile and chemical industries. In the APS, the switch from fossil fuel boilers to heat pumps and electric boilers is faster, and electric heat provides almost 10% more low- and medium-temperature heat by 2030 than in the STEPS. In the NZE, electric heat also makes inroads into the provision of high-temperature heat demand by 2030, for example in electric furnaces for glass production.

In **transport**, a few countries have announced and started to implement policies to end the sale of new ICE vehicles, usually focusing on passenger cars (Table 4.3). Battery electric cars typically can cost from USD 8 000 to USD 18 000 more than ICE models,[9] dissuading many customers from switching (see examples in Box 4.4). However, future cost reductions and improvements in battery performance are expected to make EVs cost competitive in the 2020s (See Chapter 3, section 3.5.2). EV sales proved to be resilient during the pandemic: around 3 million electric cars were sold in 2020, accounting for 4.6% of car sales worldwide. Sales of all types of EVs continue to accelerate in the STEPS, and there are some 135 million electric cars in the global fleet in 2030. In the APS, this figure increases to over 190 million, and EVs account for over 3% of global electricity demand in 2030. In the NZE there are over 300 million electric cars on the road in 2030, accounting for 20% of the global car fleet, and the world is on track to end the sale of new ICE cars by 2035.

Table 4.3 ⊳ Selected policies and targets to phase out sales of ICE passenger vehicles by country and automaker

Year	Countries/states	Type of vehicles
2025	Norway	Light-duty vehicles
2030	Austria, Slovenia	Light-duty vehicles
	Iceland, Ireland, Netherlands, Singapore	Passenger cars
2035	Canada, United Kingdom, California and New York (United States)	Light-duty vehicles
	Cape Verde, Denmark	Passenger cars
2040	France, Spain	Light-duty vehicles
2050	Costa Rica, Germany*, Connecticut, Maryland, Massachusetts, New Jersey, Oregon, Rhode Island, Vermont, Washington (United States)*	Passenger cars
Year	**Automaker**	**Announcement** (passenger cars)
2025	Jaguar	100% EV sales
2027	Alfa Romeo	100% EV sales
2028	Opel	100% EV sales in Europe
2030	Bentley, Fiat, Mini, Volvo	100% EV sales
	Ford	100% EV sales in Europe
2033	Audi	100% EV sales
2035	General Motors	100% ZEV sales
	Hyundai	100% EV sales in Europe
	Volkswagen	End ICE vehicle sales in Europe
2040	Honda	End ICE vehicle sales

*Country/state included based on membership of the International Zero-Emission Vehicle Alliance.

Notes: This table includes those countries and states with legislation, a target or stated ambition in place to phase out the sales of ICE passenger vehicles. Announcements with only proposals to phase out the sales of ICE vehicles such as the EU under the draft legislation in the Fit for 55 package are not included in this table.

Source: IEA analysis and ICCT (2021).

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[9] The additional upfront purchase cost of an electric car relative to an ICE depends on the size and performance of the battery, among other variables. Smaller car models have lower additional costs and in certain regions the additional cost of electric models relative to ICE vehicles is less than USD 4 000.

EVs also face non-economic barriers that are not completely overcome in the STEPS or in the APS. For instance, emerging market and developing economies rely heavily on second-hand vehicle markets where EVs will only become available with a time lag. Governments in these countries could consider instituting environmental regulations to encourage earlier uptake of EVs. Without policies of this kind, car fleets in some emerging market and developing economies may lag advanced economy efficiency and emissions standards. This is the case of Africa today, where only a few countries have emissions standards in place. Standards in countries like Nigeria or South Africa are at or below Euro 3, a level superseded by more stringent standards almost two decades ago in Europe (IEA, 2019a). Another potential barrier is that EV adoption may not be viable in regions with weak or unreliable grids. Targeted distribution grid enhancements and smart charging of EVs are likely to be the best way to address this issue. The widespread deployment of public charging infrastructure could also boost adoption, especially for electric heavy trucks.

Box 4.4 ▷ Rolling out zero emissions vehicles in North America

Road transportation currently accounts for 1.5 Gt CO_2 emissions in North America, about 30% of total emissions. With SUVs and pick-up trucks accounting for around three-quarters of all passenger light duty vehicle sales in the United States and Canada in 2019, the transition towards zero emissions will require targeted government policies and a further evolution in the strategies of traditional automakers.

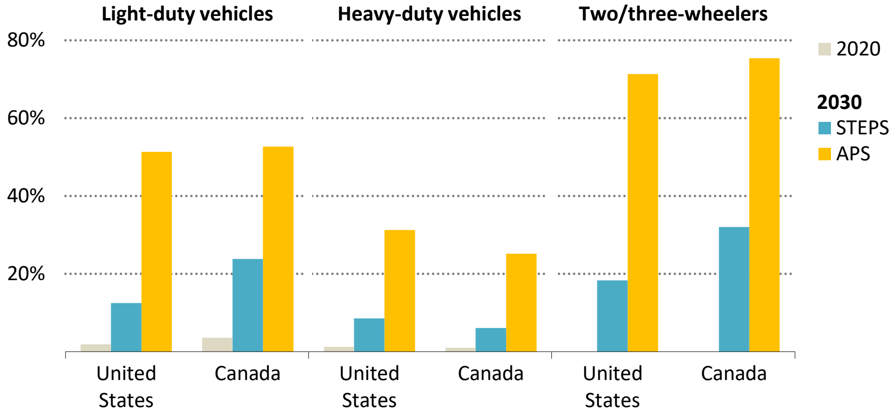
In Canada, co-ordinated, comprehensive zero emissions vehicle policy programmes are beginning to shift the market, and the share of EVs in light-duty vehicles sales reaches almost 25% by 2030 in the STEPS. In the United States, company- and state-level commitments succeed in increasing the share of EVs in light-duty vehicle sales to more than 10% by 2030 in the STEPS.

The Government of Canada has committed to ensure that all new passenger cars and light commercial vehicles are zero emissions vehicles (ZEVs) by 2035, and some provinces have translated this target into law. This target, met in full in the APS, is supported by upfront subsidies for ZEVs and public investment in charging infrastructure. The government is now creating partnerships with auto manufacturers to re-tool and produce ZEVs in Canada and to re-train current workers in the industry to work on EVs. Reflecting Canada's target, sales of ZEVs in the APS are double the level of the STEPS in 2030 (Figure 4.19).

In the United States, an executive order announced in August 2021 sets a target for 50% of all new passenger cars and light trucks to be zero emissions vehicles by 2030. The announcement came with a call to improve fuel efficiency standards (CAFE standards), and the US Department of Transportation has set a fleet-wide goal of 52 miles per gallon by 2026 for passenger cars and light trucks. At the state level, California is leading the way. It aims for 100% of passenger car and light commercial vehicle sales to be ZEVs by 2035, and for 100% of medium- and heavy-duty vehicles sales to be ZEVs by 2045.

General Motors, which accounts for over 15% of total car sales in the United States, has budgeted USD 35 billion through to 2025 to invest in both EVs and autonomous driving. The Ford Motor Company, which accounts for around 15% of total car sales in the United States, is set to spend USD 22 billion in the period to 2025 to further develop its EVs capabilities. Full implementation of the recently announced targets as modelled in the APS would increase the number of electric cars in the United States to 32 million by 2030, compared with 11 million in the STEPS.

Figure 4.19 ▻ Share of zero emissions vehicles sales in Canada and the United States in the Stated Policies and Announced Pledges scenarios, 2020 and 2030



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Policies in Canada are bringing the country closer to meet its 2035 target of 100% ZEV sales

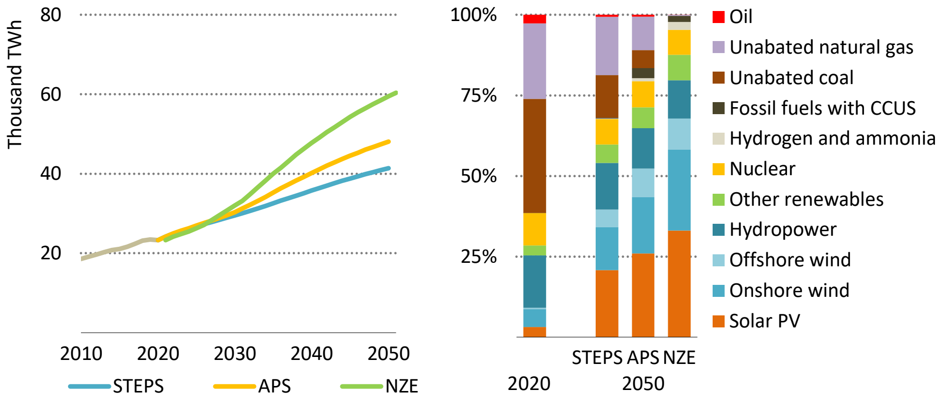
Note: Light-duty vehicles include passenger cars and light trucks; heavy-duty vehicles include medium and heavy freight trucks, and buses; ZEVs include battery electric, plug-in hybrid and fuel cell vehicles.

4.5 Electricity

The electricity sector has the potential to reshape global energy demand and supply through the electrification of end-uses and a shift towards renewables and other low emissions sources of electricity. Whether it does so, and at what speed, depends to a large extent on decisions by policy makers. Long-term visions and plans are needed to align electricity demand and supply developments, with electricity networks included as an integral part of the system, and to put in place the necessary policy and regulatory environments to achieve them.

Electricity demand increases steadily in the STEPS (Figure 4.20). There is a modest shift away from coal, and renewables rise from below 30% of generation in 2020 to over 40% in 2030. Delivery in full of announced pledges would lead to an additional 40% growth in electricity demand to 2050: it would also accelerate the move away from coal in the generation mix and increase the share of renewables to around 45% by 2030. The higher level of ambition in the NZE would double electricity demand growth compared with in the STEPS, cut coal-fired generation faster and lift the share of renewable energy to 60% by 2030.

Figure 4.20 ⊳ Global electricity demand and generation mix by scenario



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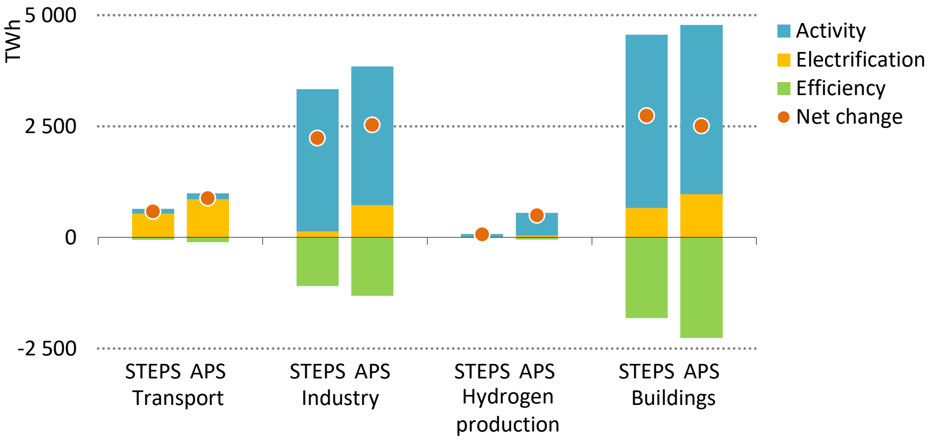
More electrification and clean electricity transitions lie ahead, and policy makers have the power to accelerate the pace of progress

4.5.1 Electricity demand

The Covid-19 crisis was a shock for the global energy system, but electricity proved to be more resilient than other energy sources. Global demand for electricity fell by only 1% in 2020. It is expected to rebound above 2019 levels in 2021 and continue to grow in 2022, as economies recover, boosted by stimulus spending.

In the years ahead, current and announced policies push electricity demand in the STEPS up by almost 30% from 23 300 TWh in 2020 to almost 30 000 TWh by 2030. Demand is projected to approach 42 000 TWh by 2050, almost 80% above today's level. Closing the implementation gap between the STEPS and APS would result in an acceleration of the average rate of annual electricity demand growth to 2030 from 2.4% in the STEPS to 2.7% in the APS, and would require an acceleration of efforts to electrify road transport, heating in buildings, and industrial processes (Figure 4.21). It would also need effective action in parallel to temper demand growth by increasing energy efficiency (see section 4.4.1).

Figure 4.21 ▷ Drivers of change in electricity demand in the Stated Policies and Announced Pledges scenarios, 2020 to 2030



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Meeting announced pledges requires new policies to accelerate efficiency improvements, electrification and the ramp up of hydrogen production

Note: Activity includes the impact of materials efficiency that reduces demand for industrial products as well as higher recycling rates.

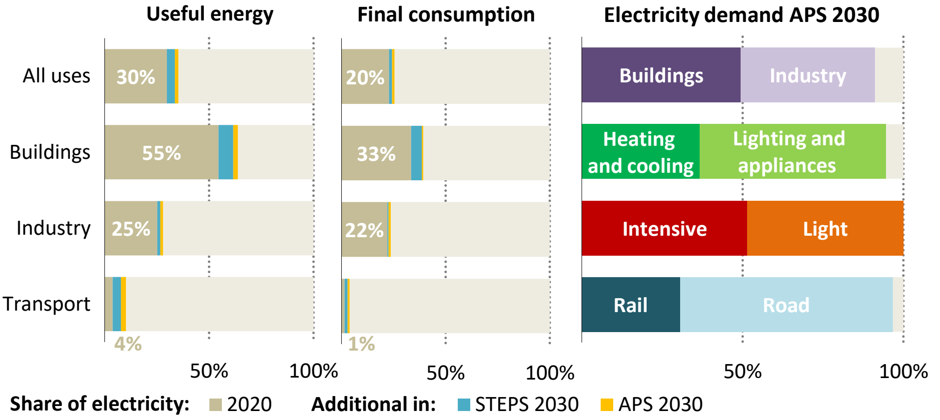
The vast majority of the increase in electricity demand between the STEPS and the APS is concentrated in **advanced economies**. They are responsible for most of the net zero and other emissions reduction pledges which have been made, and those pledges lead to faster electrification of end-uses in the APS. Electricity demand in advanced economies increases by almost 2% per year in the APS compared to only 1.2% in the STEPS to 2030, and demand is 7% higher in the APS than in the STEPS by 2030. The biggest drivers of the additional 7% of demand are faster growth in electrolytic hydrogen production and more rapid electrification of transport in the APS.

Emerging market and developing economies, led by economies in developing Asia, account for over 80% of electricity demand growth in the STEPS to 2030. However, their limited pledges mean that there is little difference in the level of their electrification between the APS and STEPS, and therefore not much of an implementation gap.

Improving the **efficiency** of electricity use is critical to tempering demand growth as economic activity increases and energy use is increasingly electrified. It decreases the overall amount of capacity needed, reduces costs and facilitates the transition to low-carbon generation. The biggest efficiency savings to 2030 in the STEPS are in the buildings sector, where demand is reduced by more than 1 800 TWh (largely due to efficiency improvements in appliances and lighting), and in the industry sector, where demand is reduced by 1 000 TWh (largely due to greater uptake of more efficient motor systems and heat pumps for low-temperature process heating). The APS sees further efficiency gains from buildings and a 20% increase of efficiency savings in industry.

At an economy-wide level, increased **electrification** offsets almost 50% of the demand savings from energy efficiency improvements in the STEPS to 2030, and more than 70% of the demand savings in the APS, which sees a faster shift to electric technologies than the STEPS. The electrification of transport alone increases demand by almost 900 TWh in the APS. Although the share of electricity in final energy demand increases to 22% in the APS by 2030 compared to 20% today, looking at the share of electricity in meeting demand for energy services provides a more accurate picture of its growing role because its high conversion efficiency means that one unit of electricity can provide more energy services, or useful energy[10], than fossil fuels in almost all cases. To take one example, electric cars are more efficient than their fossil fuel-powered counterparts, and the result is that, while electricity accounts for around 3% of passenger car energy demand in 2030, it accounts for over 10% of kilometres travelled. Electricity meets an average 30% of useful energy demand today across all sectors, and this increases to 34% in the STEPS and 35% in the APS by 2030 (Figure 4.22).

Figure 4.22 ▷ Share of electricity in useful energy demand and final consumption by sector and scenario



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Electricity is more efficient than fossil fuels in providing energy services, so its share of final consumption understates its contribution to the supply of useful energy

Notes: All uses refers to all end-use sectors, i.e. industry, transport, buildings, agriculture and non-energy use. Percentage values shown are for 2020.

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[10] Useful energy is that available to end-users to satisfy their need for energy services. It is also referred to as energy service demand. As a result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

4.5.2 Electricity supply

Record amounts of solar photovoltaics (PV) and wind capacity were added to global electricity supply in 2020, while demand fell slightly related to the pandemic. As a result, the share of fossil fuels in electricity generation fell to a 20-year low, and coal-fired generation dropped to its lowest share in the past 50 years. Recovery plans unveiled in recent months have committed huge funds to spur economic growth, but the amounts directed towards clean energy and electricity networks fall well short of the levels suggested in the Sustainable Recovery Plan (IEA, 2020b), and the continued expansion in renewables has not been sufficient to offset the increase of fossil fuels to meet electricity demand growth: the upshot is that CO_2 emissions from electricity generation are set to rebound in 2021.

Over the next decade, the strong growth of **renewables** is set to continue in all scenarios. Solar PV and wind power lead the way with capacity increases that far outstrip those for other sources of electricity (Figure 4.23). This reflects policy support in over 130 countries and the success of solar PV and wind in becoming established as the cheapest and most competitive sources of new electricity in most markets.[11] Current policies lead to an increase in combined capacity additions from a record 248 GW in 2020 to 310 GW in 2030 in the STEPS. Additional implementation measures (such as securing more capacity through auction schemes, streamlining permitting and approval processes, raising minimum share requirements, bolstering tax credits or strengthening carbon pricing) are needed to expand deployment to almost 470 GW in 2030 in the APS. The increase needs to be achieved mostly outside of China – today's largest market for solar PV and wind – as it faces a relatively small implementation gap. China's current policies are consistent with announced targets to 2030. The implementation gap is largest in advanced economies, including the United States, Canada, Australia and the European Union. The net zero pathway set out in the NZE requires wind and solar PV capacity additions in 2030 of over 1 000 GW. Ambitions would need to be raised significantly in emerging market and developing economies in particular to make this happen.

Solar PV and wind alone meet three-quarters of electricity demand growth to 2030 in the STEPS and 90% in the APS: they easily exceed demand growth in the NZE. This means that the share of solar PV and wind in electricity supply in 2030 rises from under 10% in 2020 to 23% in the STEPS, 27% in the APS and 40% in the NZE. Hydropower, bioenergy, geothermal and concentrating solar power see much smaller increases to 2030 across the scenarios, as they often have longer project lead times and require favourable site conditions and resources, but they match the pace of electricity demand growth and continue to provide about 20% of electricity generation worldwide.

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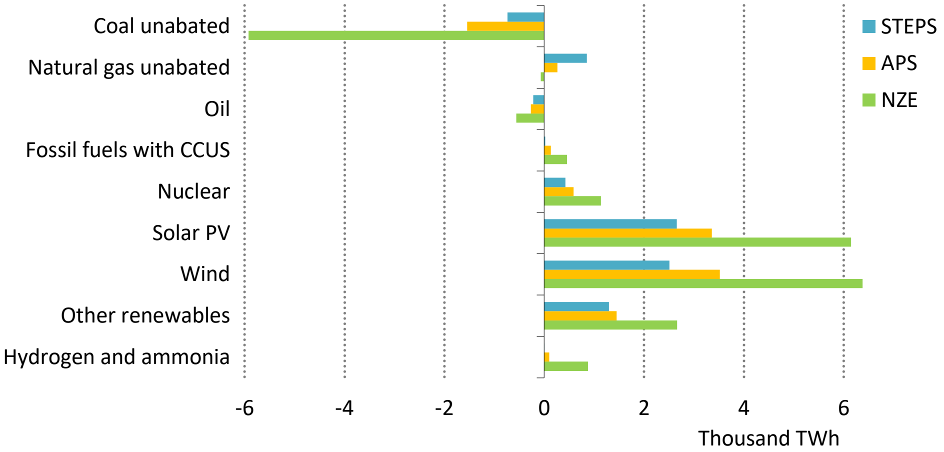
[11] Competitiveness of power generation technologies is evaluated in the IEA World Energy Model by combining technology costs and system value through the value-adjusted levelised cost of electricity (IEA, 2018). It does not include grid-related integration costs.

Figure 4.23 ▷ Change in electricity generation by source and scenario, 2020 to 2030



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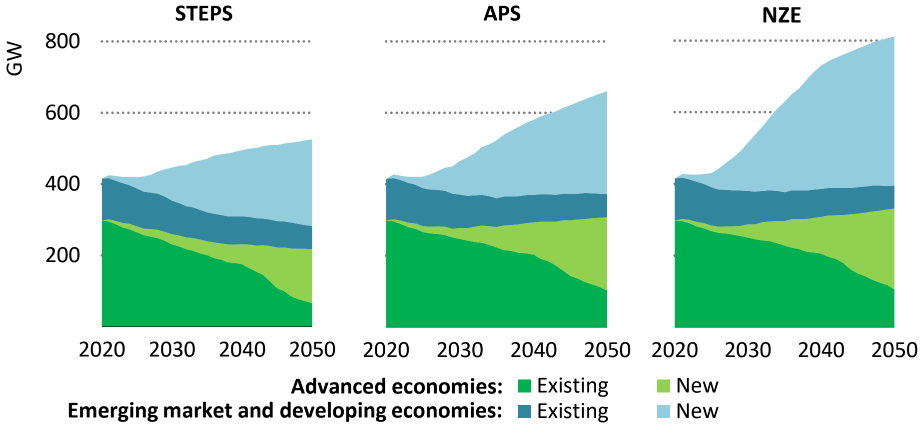
Solar PV and wind take the lead in each scenario by 2030, but their strong growth at the expense of coal in the APS falls short of what is needed for net zero emissions by 2050

The outlook for **nuclear power** depends on decisions yet to be made about both existing reactors and new construction. Over the next decade, the expansion of nuclear power is largely determined by the nearly 60 GW of capacity under construction in 19 countries at the start of 2021. China, Russia and Korea have successfully constructed many recent projects in five to seven years both at home and abroad, so it is possible that some additional reactors that start construction before 2025 could be completed by 2030. Beyond 2030, there are over 100 GW of planned projects that have not yet broken ground and several times that proposed individually or through policy targets. There is more uncertainty about the pace of retirements for existing reactors, with many ageing reactors in the United States, Europe and Japan in need of additional investment (and new regulatory approvals in some cases) to extend their operational lifetimes. Lifetime extension decisions also face challenging market conditions, rigorous safety checks and social acceptance issues.

In the STEPS, over 65 GW (23%) of the existing nuclear fleet in advanced economies is retired by 2030, compared with 50 GW in the APS (Figure 4.24). Even though lifetime extensions offer a cost-effective way of providing more low emissions electricity over the next decade, there is a risk that reactors in advanced economies could be retired at an even faster pace, eroding the low-carbon foundation for electricity supply provided by nuclear power (IEA, 2019b). By 2040, about three-quarters of the current nuclear fleet in advanced economies will exceed 50 years of operations, and currently this looks very likely to lead to a wave of retirements in each of the scenarios. Innovative nuclear power technologies, such as small modular reactors, could offer shorter construction and approval times for new capacity, as well as expanding opportunities for nuclear power beyond electricity, for example for heat and hydrogen production, but innovation efforts need to be accelerated to improve their prospects.

Figure 4.24 ▷ Nuclear power capacity by scenario, 2020-2050



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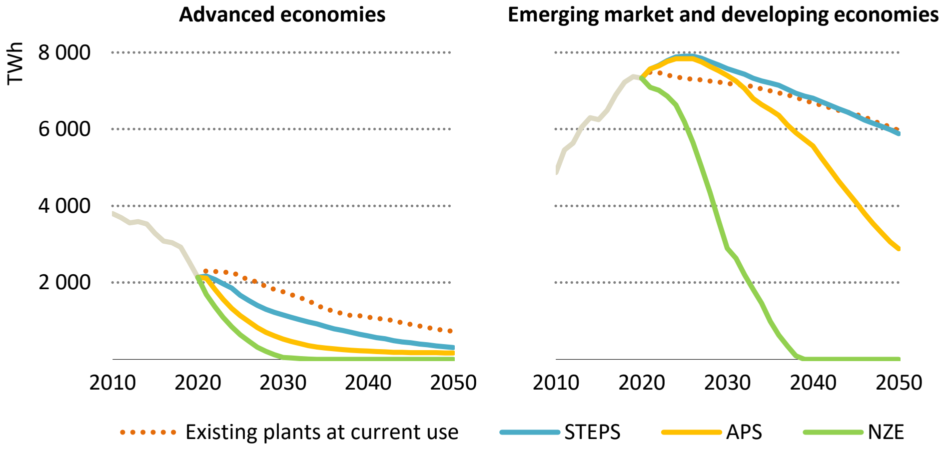
Nuclear power can help clean energy transitions through lifetime extensions for existing reactors where safe, and the acceleration of new construction where acceptable

The technologies needed to equip **power plants with carbon capture technologies or to co-fire ammonia and hydrogen** in high shares in coal- or natural gas-fired power plants are currently at pre-commercial stages of development. Concerted efforts need to be made to drive down their costs if they are to make inroads by 2030. These technologies are important because they can provide a low emissions source of generation and flexibility, and because they help to extend the use of existing assets. They are not deployed on a significant scale in the STEPS at any stage through to 2050. Meeting announced pledges in the APS calls for some development of these technologies, while the path to net zero emissions in the NZE calls for several projects using these technologies to be completed by 2030 and for many more to be under development at that point, putting them on course to make a larger contribution between 2030 and 2050.

The outlook to 2030 for **coal** varies widely across the three scenarios. It was the leading source of electricity in 2020, but it was also responsible for three-quarters of total CO_2 emissions from electricity generation. In advanced economies, coal continues its recent decline in all scenarios, but emerging market and developing economies face the challenge of slowing and stopping its growth before it can begin a long-term decline. Underscoring this challenge is the 140 GW of coal-fired capacity currently under construction and the over 430 GW at the planning stage. Financing coal has become increasingly difficult in some regions, including Southeast Asia, developing Asia and Africa, as international pressures related to climate change mount and erode the expected profitability of new coal plants.

The implementation gap for unabated coal is sizeable in advanced economies, where generation falls by almost 50% in the STEPS from 2020 to 2030 but by 75% in the APS (Figure 4.25), underlining the case for accelerating renewables growth. In emerging market and developing economies, unabated coal peaks in 2025 in both the STEPS and the APS (and is higher at that point than in 2020) before declining rapidly, whereas the NZE calls for immediate reductions and 60% reductions of unabated coal-fired generation by 2030. Over the next 30 years, pledges announced in China and elsewhere close only one-quarter of the gap between the STEPS and the NZE in terms of cumulative unabated coal-fired generation and related CO_2 emissions.

Figure 4.25 ▷ Unabated coal-fired electricity generation by scenario, 2010-2050



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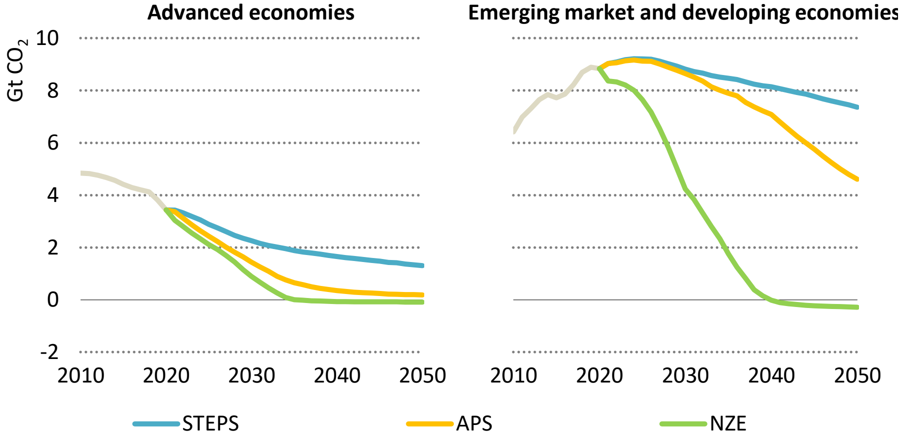
Unabated coal is set to decline, but even in the APS it continues to be used widely: this puts the world off track to reach net zero emissions by 2050

Existing coal-fired power plants present a significant challenge. If they were to continue recent operations for the remainder of their technically viable lives, it is very hard to see how net zero emissions could be reached by 2050. Efforts to tackle these emissions, including those from the large fleet of young coal plants in emerging market and developing economies, are therefore essential. In many cases, coal-fired plants were traditionally the cornerstone of power systems, providing electricity along with stability, flexibility and other grid services. Phasing down and ultimately replacing coal in these systems in a secure and affordable manner requires a number of regulatory and operational changes, including actions to tap a wider set of smaller and more distributed sources for grid services, in systems that often face financial difficulties. International collaboration and knowledge sharing of past experiences and best practices are important ingredients to build the confidence needed to raise ambitions.

Natural gas use in the electricity sector worldwide increases between 5% and 15% to 2030 in the STEPS and the APS, though its share of generation declines. It also provides essential system flexibility and grid services in both these scenarios. Natural gas is the largest source of electricity in advanced economies and its level of use remains broadly stable in those economies over the next decade, while it increases by about one-third in the emerging market and developing economies, helping to moderate the use of coal. In the NZE, natural gas provides a bridge to deeper CO_2 emissions reductions by displacing the need for coal-fired power, but it then begins a long-term decline before 2030.

Beyond 2030, electricity sector transitions continue to shift away from coal and towards renewables. Unabated coal-fired generation declines after 2030 in each scenario, but it remains a major source of electricity in the STEPS through to 2050, whereas its use falls by 60% from 2030 to 2050 in the APS, and it is phased out entirely by 2040 on the net zero pathway set out in the NZE. The share of renewables in electricity generation reaches 60% by 2050 in the STEPS, 70% in the APS and nearly 90% in the NZE. Wind and solar PV continue to lead, with hydropower and other renewables accounting for about 20% of generation in 2050 in each scenario, while nuclear power, fossil fuel plants equipped with CCUS, and hydrogen and ammonia combined contribute about another 10% of generation. The additional demand for electricity embodied in the APS, and still more in the NZE, means that substantially more growth is required to keep pace with electricity demand in these scenarios. Unabated natural gas for electricity generation varies most between 2030 and 2050 across the scenarios: in the STEPS, it grows almost 20%; in the APS, it declines by almost 15%; and in the NZE it declines by over 95%.

Figure 4.26 ▷ Electricity sector CO_2 emissions by scenario, 2010-2050



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In the APS, CO_2 emissions from electricity decline steadily to 2030 in advanced economies but rise until a peak in the mid-2020s in emerging market and developing economies

The electricity sector is the largest source of global **CO_2 emissions** today and these emissions are set to decline in each scenario over the coming decades. However, the reductions by 2030 are 10% in the STEPS and nearly 20% in the APS compared with close to 60% in the NZE where electricity leads the way and enables reductions in other sectors through electrification (Figure 4.26). The difference between the APS and the NZE highlights the large ambition gap in the electricity sector. In advanced economies, the announced pledges that are incorporated in the APS close about 70% of the gap between the STEPS and the NZE in terms of cumulative emissions savings to 2050. In emerging market and developing economies, the pledges in the APS reduce electricity sector CO_2 emissions starting in the mid-2020s and close about 15% of the gap between the STEPS and the NZE.

4.5.3 Electricity system flexibility

Electricity system flexibility is becoming increasingly central to electricity security, and systems are going to need greater flexibility from minute-to-minute, hour-to-hour and season-to-season over the coming decades.[12] In India, the emphasis on scaling up solar PV and other renewables drives the largest increase in hour-to-hour flexibility needs over the next decade (Figure 4.27). In the United States, the European Union and China, average flexibility needs rise by over 40% in the STEPS from 2020 to 2030. Some countries in Europe and some states in the United States, Australia and India already have high shares of variable renewables (NITI Aayog and IEA, 2021), and others may find it useful to draw on their experiences.

By 2050, global average flexibility needs triple in STEPS, increase 3.5-times in the APS and quadruple in the NZE. The growth in flexibility needs outpaces electricity demand growth in each scenario. In the United States, for example, hour-to-hour flexibility needs double over the next decade in the APS.

The main drivers of increasing short-term flexibility needs are the rising shares of variable wind and solar PV in electricity generation and the changing nature of electricity demand patterns. (See Box 4.5 and the wider flexibility and electricity security discussion in Chapter 6). Solar PV and wind are set to more than double their combined current share of electricity generation (nearly 10%) over the next decade in the STEPS and APS, and to quadruple it in the NZE. The non-dispatchable and variable nature of these renewable energy technologies requires additional system flexibility to continuously balance electricity supply and demand and maintain grid stability. To date, dispatchable thermal generators like coal and gas plants have been the main sources of electricity, but this is rapidly changing as their market share declines.

Beyond 2030, the amount of flexibility needed by scenario continues to widen based primarily on the contributions of wind and solar PV. At the same time, increased

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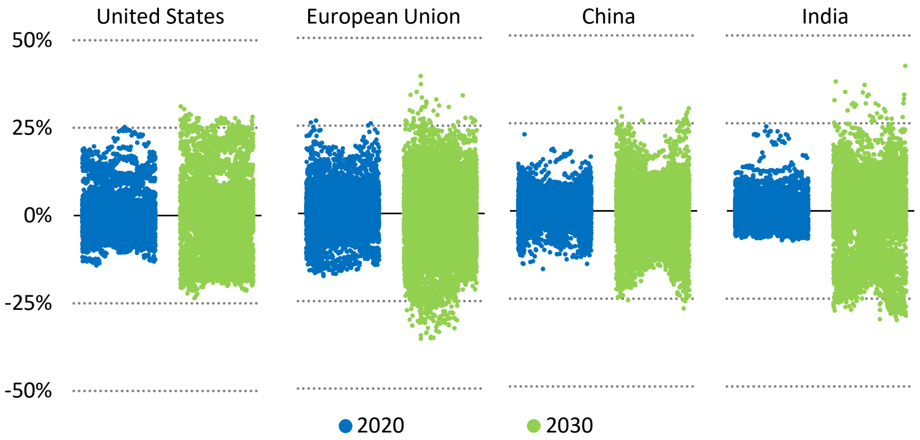
[12] Flexibility is defined as the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply.

electrification (including road transport, heating in buildings and industrial processes) and an expansion of electrolytic hydrogen production together reshape electricity demand, raising peaks and increasing variability throughout the day and as a result pushing up overall electricity system flexibility needs.

Figure 4.27 ▻ Hour-to-hour flexibility needs in the United States, European Union, China and India in the Stated Policies Scenario, 2020 and 2030



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Even with the relatively modest clean electricity transitions in the STEPS, electricity system flexibility needs to rise by two-thirds over the next decade

Note: Flexibility needs are represented by the hour-to-hour ramping requirements after removing wind and solar production from electricity demand, divided by the average for the year.

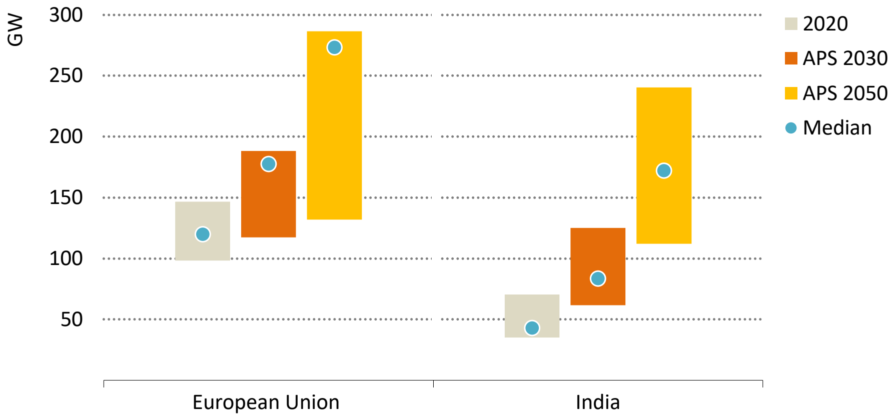
Box 4.5 ▻ Changing shape of electricity demand

The electrification of road transport, heating in buildings, industrial processes and the emergence of electrolytic hydrogen production have the potential to reshape electricity load curves and compound the challenges for electricity systems in transition. By 2030 these emerging end-uses are set to increase their share of electricity demand to 14% in the STEPS, 16% in the APS and 25% in the NZE.

Electricity demand peaks are influenced by annual variations in demand for certain end-uses, such as heating and cooling, and daily variations in demand corresponding to patterns of activity. For this *World Energy Outlook*, the IEA has added further detail to its modelling of hourly heating, cooling and lighting electricity demand across the year, using deep learning algorithms, in order to provide detailed insights into the contributions of these end-uses to peak demand today and in the future.

Recent cold snaps and heat waves have underlined the impact that weather can have on electricity demand variation and the importance of understanding and preparing for these impacts. The rapidly increasing deployment of heat pumps and air conditioners will increase the temperature sensitivity of demand, while uncontrolled charging of the EV fleet presents an additional risk of rapid variations in demand. Daily electricity demand today varies by around 120 GW in the European Union and 40 GW in India, or more than 40% and 30% of annual average demand respectively. Without effective planning and deployment of demand-side response, the daily variation of demand is expected to increase to as much as 270 GW in the European Union and some 170 GW in India by 2050 in the APS (Figure 4.28).

Figure 4.28 ▷ Range of maximum variation in daily electricity demand in the European Union and India in the Announced Pledges Scenario, 2020, 2030 and 2050



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Daily demand becomes more changeable as demand for EV charging, digital appliances, heating and cooling and other highly variable end-uses increases

Note: The range of variations in daily demand is based on the difference in the minimum and maximum hourly demand for each day of the year.

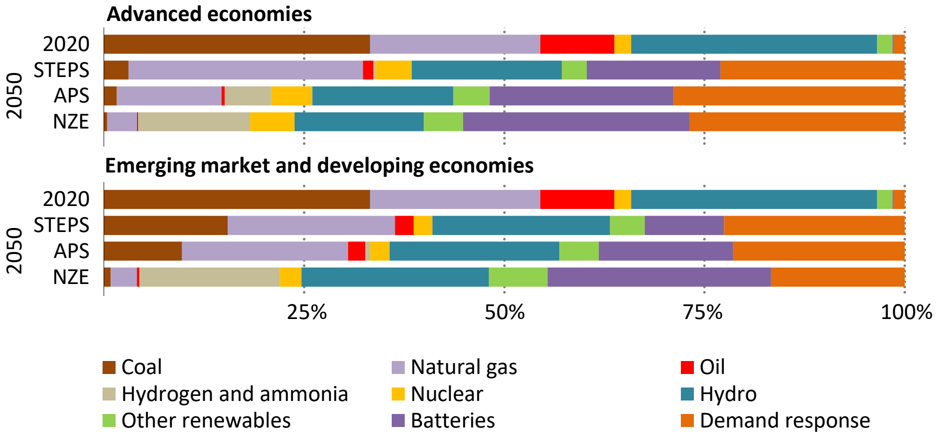
These changes are happening in parallel with a rapid increase in the share of electricity being generated from variable renewables in each of the scenarios. Additional flexibility resources need to be deployed in order to successfully integrate these increasing shares of variable renewables and maintain security of supply. With the right control technology and incentives, around 15% of electricity demand could be shifted in time to some extent by 2030 so as to provide flexibility in the APS, increasing to 40% by 2050. For example, electric cars could be smart charged and used in a vehicle-to-grid configuration, grid-connected hydrogen electrolysers could be switched on and off in line with system needs, and well insulated homes and some appliances could shift heating and cooling demand in line with system needs.

Policy action is required to ensure that demand-side response resources can participate in flexibility markets and that incentives to shift demand are available to consumers through models such as time-of-use and dynamic electricity pricing. The right frameworks and incentives could do much to help maximise the system utility of emerging end-uses such as EV charging and electrolytic hydrogen production, encourage consumer behavioural change and support the innovations needed to integrate ever higher shares of variable renewables.

A transition is also underway in electricity system flexibility. There are four main sources that contribute to ensure the balance of electricity demand and supply at all times: power plants, energy storage, demand-side response and electricity networks.

Power plants have always played an important role in providing flexibility, but that role changes in the future, with the extent of change varying by scenario. In the STEPS, transitions are limited in most regions, with unabated coal and natural gas playing an important role through to 2050, and the changes needed in the way systems are managed are similarly limited. With more vigorous action to phase out coal in the APS and the NZE, dispatchable low emissions sources – including hydropower, bioenergy and nuclear power – become more central to system flexibility, although natural gas-fired power plants continue to be a primary source of flexibility to 2050 in all but the NZE (Figure 4.29).

Figure 4.29 ▷ Electricity system flexibility by source and scenario, 2020 and 2050



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Coal and natural gas remain cornerstones of electricity flexibility in the STEPS, but the mix of flexibility sources shifts dramatically on the path to net zero emissions by 2050

Storage technologies are set to play a much larger role in system flexibility in all scenarios. Battery storage systems have become an attractive option to address flexibility needs measured in seconds up to hours because they are capable of near-instantaneous charging or discharging to suit system needs. Although batteries are usually designed to store limited amounts of energy, other energy storage technologies are better suited to address longer duration flexibility needs, even across seasons: they include pumped hydro, which looks set for strong growth over the next decade (IEA, 2021c), as well as compressed air energy storage, gravity storage, hydrogen and ammonia.

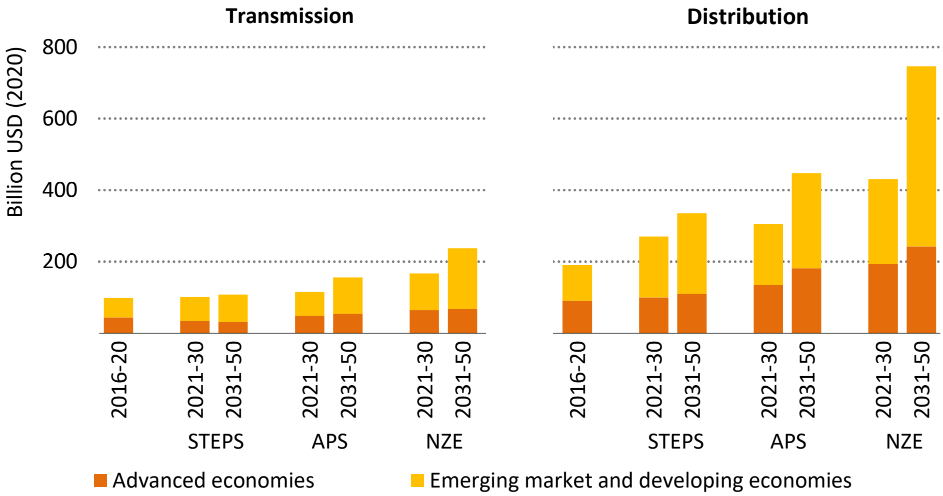
Demand-side response has the potential to play a large role in system flexibility, but its ability to do so hinges critically on the regulations and digital infrastructure in place. By shifting the times when energy is consumed, demand-side response helps to align demand with available supply, thereby lowering stress on the system. In each scenario, there are rapid increases in electricity demand from air conditioners, heat pumps, EVs and other potentially flexible sources of demand. Price signals are a powerful means of determining when and where flexibility is needed, and are best applied equally to all sources of flexibility, whether they are large or small and whether they come from the supply side or demand side.

Electricity networks pool the potential of flexibility sources and bolster overall system flexibility. Large transmission lines assist the balancing of electricity demand and supply within and between regions, for example by linking into hydro-rich systems to help manage the integration of wind and solar PV, thereby increasing system resiliency. Strengthened distribution lines connect decentralised sources, including distributed solar PV and battery systems, enabling more localised electricity usage and decreasing demand on a main network. Smart grids add further resiliency by dispatching energy more accurately and rapidly relaying data on optimised load balancing.

4.5.4 Networks

Electricity networks are the foundation of reliable and affordable electricity systems, making them critical infrastructure in all modern economies. There are around 80 million kilometres of networks in the world today. Over the next decade, investment in these networks needs to increase substantially in order to maintain and improve grid reliability, support clean energy transitions and provide access to electricity to all. In the STEPS, investment in transmission and distribution grids climbs from less than USD 300 billion on average per year over the past five years to over USD 370 billion on average over the next decade, with most of the increase going to distribution (Figure 4.30). The APS calls for only marginally higher grid investment to 2030, but the level of investment needed rises significantly after 2030 in line with the pace of overall decarbonisation. In the NZE, grid investment to 2030 averages USD 630 billion per year, a major increase in an area where new projects often span a decade or more.

Figure 4.30 ▷ **Average annual electricity network investment by scenario, 2016-2050**



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Grid investment needs to scale up as electricity demand and variable renewables increase, making long-term visions for grids essential for energy transitions

The main catalyst for investment to reinforce and extend electricity networks is electricity demand growth. By 2030, electricity demand rises by about 30% in both the STEPS and APS, while it increases by almost 45% in the NZE. However, network expansion and modernisation also play a crucial role in decarbonisation, paving the way for rising shares of renewables and universal access to electricity, and this needs to be supported by investment too. Modernising and extending electricity network infrastructure – from transmission and distribution lines to substations and other equipment – constitutes a major challenge for owners and operators. New transmission lines are needed to connect utility-scale wind and solar PV to demand centres, sometimes over long distances; new distribution lines are needed to handle distributed solar PV capacity, which globally grows nearly fourfold by 2030 in the APS and nearly sixfold in the NZE; and new offshore substations and dynamic cabling are needed to connect offshore wind to the mainland. In addition to new and replacement sections of networks, investment is needed in smart grids and digitalisation components, not least to help ensure that expanding volumes of solar PV and wind can be accommodated in a way that ensures network stability and reliability. Cities all over the world have a particular opportunity to accelerate progress towards net zero emissions by taking advantage of the new opportunities presented by digitalisation (IEA, 2021d). Early action is essential to keep pace with transitions: grid projects generally take years longer than most renewable energy projects, and inadequate progress has the potential to create bottlenecks in the uptake of renewables.

In all scenarios, at least 60% of investments to 2050 are in emerging market and developing economies, where millions of new customers continue to be connected to the network and end-uses are increasingly electrified. In advanced economies, investments are largely focused on ensuring network reliability throughout the transition to a decarbonised power sector facing higher demand. Interconnections have a part to play in all regions in meeting rising flexibility needs, maximising the use of available resources and ensuring overall system reliability.

Policy makers have a crucial role to play in setting long-term visions and plans for electricity aimed at ensuring that electricity network expansion and modernisation keep pace with expanding renewables deployment and new sources of demand. Clear visions and plans will limit uncertainty for regulators, investors and project developers in terms of system needs and market conditions, and in so doing will help to minimise the costs of transitions.

Regulators have the important task of ensuring electricity network development while maintaining system stability and adequacy. With the rapid growth of grid-connected variable renewables and storage, avoiding grid congestion and modernising ageing equipment are likely to be primary concerns, and these are likely to be easier to manage where network planning provides timely signals to invest in new sources of electricity. Greater integration of renewables also increases the complexity of grid operations, not least in terms of grid-forming capabilities for maintaining power quality, and may give rise to new questions about asset ownership and the allocation of responsibilities. Regulators need to examine whether electricity market designs are still fit for purpose, which will involve reviewing cost allocation frameworks and ensuring fair remuneration to system operators and investors. They also need to ensure the resilience of power systems in the face of growing cybersecurity and climate risks (IEA, 2021e).

With all these considerations, network-wide oversight can help to ensure that the grids of tomorrow will be able to meet the needs of accelerated clean energy transitions. This includes coordinating long-term grid planning and, where necessary, clarifying the roles and responsibilities of regulators, transmission system operators (TSOs) and distribution system operators (DSOs). The importance of network-wide co-ordination has already been recognised in countries such as Australia and Japan, and steps to enhance the role of TSOs and DSOs to support this are being considered in the United States and the European Union. Given lead times of a decade or more to build new lines, it would be helpful to have entities responsible for co-ordination that are able to take an overall view of retirements of conventional generators, new renewable energy projects, opportunities for demand-side response and cross-border trade, and the state of domestic grids. Long-term planning and co-ordination could also help address other potential bottlenecks, including land availability.

Chapter 5

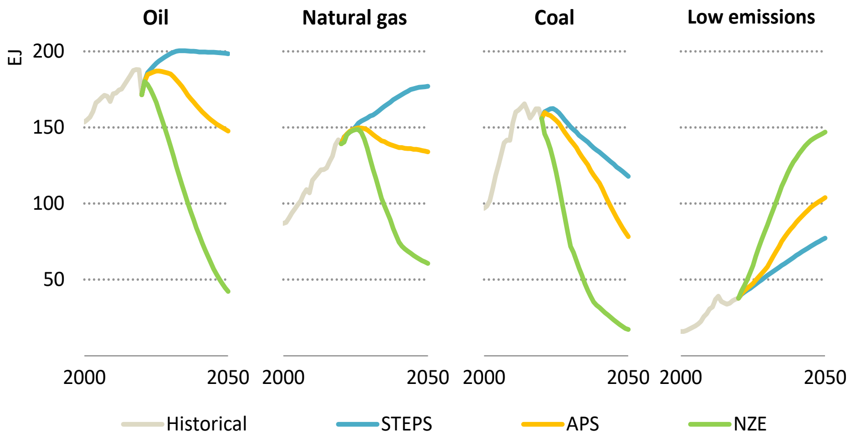
Exploring multiple futures: fuels

Only fuels rush in?

SUMMARY

- For the first time, each of the scenarios examined in this *World Energy Outlook* shows an eventual decline in global oil demand, although the timing and sharpness of the drop vary widely. Today's policy settings, as set out in the Stated Policies Scenario (STEPS), see oil demand level off at 104 million barrels per day (mb/d) in the mid-2030s and then decline very gradually to 2050. In the Announced Pledges Scenario (APS), oil peaks soon after 2025 at 97 mb/d and starts to decline thereafter. Rapid action in the Net Zero Emissions by 2050 Scenario (NZE) to get on track to meet the world's climate goals sees oil demand fall sharply to 72 mb/d in 2030 and continue falling to 24 mb/d by 2050.

Figure 5.1 ⊳ Oil, natural gas, coal and low emissions fuel use to 2050



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Fuels are an integral part of the energy system in each scenario, but reaching net zero requires a transformation in their production, use and supply chain emissions

Note: Low emissions fuels include low-carbon hydrogen, hydrogen-based fuels and modern bioenergy.

- Natural gas demand increases in each scenario over the next five years, but there are sharp divergences afterwards. Demand in advanced economies declines from the mid-2020s in each scenario, but it falls faster in the APS than in the STEPS and fastest in the NZE. Demand in emerging market and developing economies rises to well above today's level through to 2050 in the APS and still higher in the STEPS, but is kept in check in the NZE. The share of natural gas in the global energy mix remains around 25% to 2050 in the STEPS, while it falls to 20% in the APS and to 11% in the NZE. Around 70% of natural gas use in 2050 in the NZE is equipped with carbon capture, utilisation and storage (CCUS).

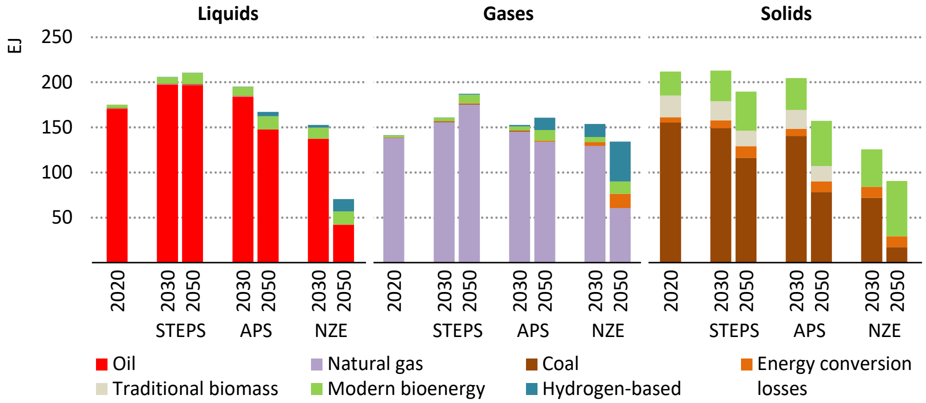
- Coal faces structural decline in each of the three scenarios. The main question is how quickly demand falls in emerging market and developing economies, which account for more than 80% of current global demand. In the STEPS, global coal demand rises slightly to 2025, but then starts a slow decline to 2050. In the APS, coal use falls significantly after 2030, notably in China, and global demand in 2050 is half of 2020 levels. In the NZE, global coal demand drops by 90% to 2050 and 80% of coal use in 2050 is equipped with CCUS.
- The drive for net zero naturally has strong implications for fossil fuels, but there are nuances across sectors. By 2030, the NZE shows a fall in the use of coal to generate power in advanced economies (90% decline), a fall in oil use in passenger cars globally (40% decline) and a fall in the use of natural gas in buildings globally (35% decline). Yet there are many areas where fossil fuel use remains resilient. These include: coal use in iron and steel production (20% decline to 2030 in the NZE), oil use in aviation (30% increase), and natural gas use in cement production (40% increase).
- Minimising methane leaks and flaring should be a top priority in the quest to reduce greenhouse gas emissions from fossil fuel operations. On average, we estimate that 8% of natural gas and natural gas liquids entering flares are not combusted and leak into the atmosphere; this is more than double previous estimates. Flaring resulted in more than 500 million tonnes of carbon-dioxide equivalent (Mt CO_2-eq) emissions in 2020, which is more than annual CO_2 emissions from all cars in the European Union.
- Countries with net zero pledges need to introduce policies and measures to close the implementation gap between the STEPS and APS, including to reduce demand for fossil fuels, and stimulate demand and production of low emissions fuels. In the NZE, a rapid rise in low emissions fuels is a key reason why no new oil and gas fields are required beyond those already approved for development.
- Around 2 mb/d of biofuels were used in 2020: volumes approximately double to 2030 in the STEPS, increase two-and-half-times in the APS and triple in the NZE. The use of modern forms of solid bioenergy increases by 30-70% across the scenarios to 2030. In the NZE, biogas provides clean cooking access for 400 million people in 2030, while 2.5 exajoules (EJ) of biomethane is consumed and total biogas demand rises to 5.5 EJ.
- The STEPS sees small increases in the use of low-carbon hydrogen to 2030. In the APS and the NZE, demand rises more rapidly as low-carbon hydrogen replaces the current use of hydrogen in industry, low-carbon hydrogen and hydrogen-based fuels are used to provide flexibility in the power sector and new end-uses emerge. The pipeline of planned low-carbon hydrogen production projects is insufficient to meet the levels of use implied by current pledges (2 EJ in the APS) and far short of the levels required in the NZE (17 EJ in 2030). Shipping and aviation drive large increases in the use of low-carbon hydrogen-based liquid fuels in the APS and NZE after 2030.

5.1 Introduction

A commonly-heard rallying cry for clean energy transitions is to “electrify everything”. But not everything can be electrified: only in the Net Zero Emissions by 2050 Scenario (NZE) does electricity approach even an equal share of final energy consumption with fuels. This speaks both to the enduring importance of liquid, gaseous and solid fuels in global energy and to the need to transform their production and use as part of the drive for net zero emissions. In all of the *World Energy Outlook-2021* (*WEO-2021*) scenarios, ensuring adequate supplies of both fossil fuels and low emissions fuels is essential to maintain energy security and reduce price volatility during energy transitions.

Efforts to accelerate clean energy transitions present a new and pervasive set of risks for fossil fuel markets, in particular over the outlook for demand and prices. In the Stated Policies Scenario (STEPS), oil and natural gas demand grow to 2030 while coal demand falls only marginally. In the NZE, demand to 2030 falls by nearly 10% for natural gas, 20% for oil and 55% for coal. These variations in demand are matched by differences in prices. The oil price in 2030 in the NZE (USD 35/barrel) is less than half the level in the STEPS (USD 77/barrel).

Figure 5.2 ⊳ Consumption of liquid, gaseous and solid fuels by scenario



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Fuels remain an integral part of the global energy mix to 2050, but there are differences in the outlooks for both fossil and low emissions fuels between scenarios and over time

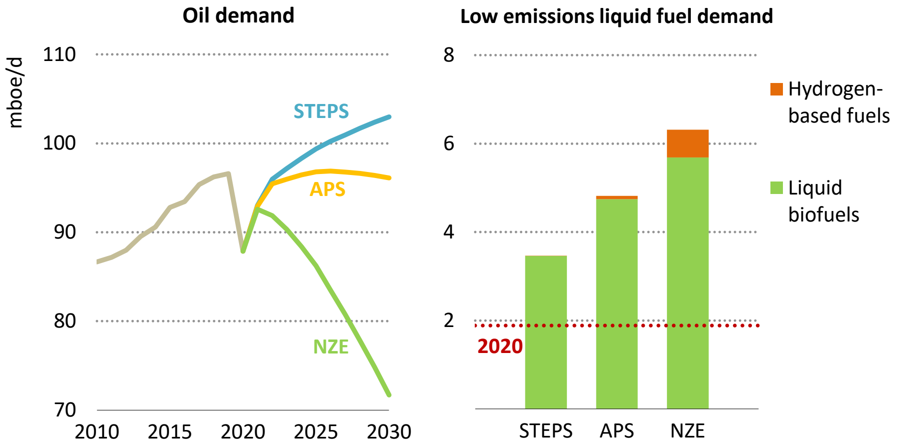
Notes: APS = Announced Pledges Scenario; traditional biomass = traditional use of biomass. Conversion losses = fuel consumed in the transformation process to produce other liquid, gaseous or solid fuels for final consumption.

Yet clean energy transitions also provide new opportunities for fuels, which continue to comprise a large share of total final consumption in each scenario. In the NZE, the share of fossil fuels in final energy consumption drops from 66% in 2020 to just over 20% in 2050, but there is a growing role for alternative low emissions fuels, such as hydrogen-based and modern bioenergy, meaning that the overall drop in fuel demand is much smaller

(Figure 5.2). Policy support for low emissions fuels varies significantly among countries, but they play a key role in the achievement of net zero targets, especially in sectors where direct electrification is most challenging.

5.2 Liquid fuels

Figure 5.3 ⊳ Oil demand over time and low emissions fuel demand in 2030



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A 31 mboe/d difference in oil demand emerges between the STEPS and NZE by 2030. Biofuels remain the largest low emissions fuel but hydrogen-based fuels increase in the NZE

Note: mboe/d = million barrels of oil equivalent per day.

Activity changes, technology deployment, consumer choices and policy ambition in transport and petrochemicals largely determine the long-term trajectory of global oil demand. In the STEPS, global oil demand exceeds 2019 levels by 2023 before reaching its maximum level of 104 million barrels per day (mb/d) in the mid-2030s and then declining very gradually to 2050 (Figure 5.3). In the APS, global oil demand peaks soon after 2025 and then falls by around 1 mb/d per year to 2050. In the NZE, demand falls by more than 2 mb/d per year between 2020 and 2050.

There has been a strong rebound in oil demand to date in 2021 that has not been matched by a rebound in investment in supply (see Chapter 6). Despite upward pressure on prices, upstream spending in 2021 is set to remain well below 2019 levels. Major international companies are under pressure to diversify spending, while the tight oil industry is demonstrating a new-found commitment to capital discipline, with a number of companies choosing to pay down debt and return money to shareholders. Many national oil companies face severe budgetary constraints and only a handful (including Saudi Aramco and the Abu Dhabi National Oil Company) are in an expansive mode. The differences in demand and price outlooks across our scenarios present a new set of challenges for the industry and will test all of these stances.

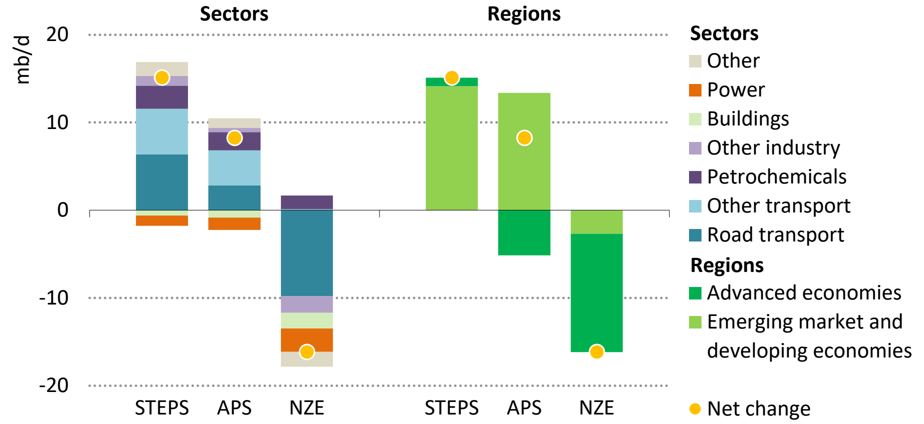
Traditional oil markets could also be challenged by the rise of alternative liquid fuels. Nearly 98% of liquid fuel demand today is met by oil; the remainder is met mainly by conventional liquid biofuels, and by very small quantities of advanced biofuels[1] and hydrogen-based liquid fuels. Biofuel demand increases to 2030 in all scenarios, with a tripling of demand in the NZE. Hydrogen-based fuels are expensive to produce today (e.g. synthetic kerosene costs at least USD 300 per barrel of oil equivalent), and new market frameworks together with major investments in innovation and new large-scale production facilities, will be needed in the 2020s if they are to play a role in the future.

In the APS, consumption of hydrogen-based fuels reaches material levels in the 2030s in countries with net zero pledges. In the NZE, progress is more rapid and more global. These fuels are particularly important in some of the sectors where emissions reductions are likely to be most challenging. In the NZE, for example, hydrogen-based fuels meet 45% of shipping energy demand and 30% of total aviation fuel demand by 2050.

5.2.1 Oil trends to 2030

Demand

Figure 5.4 ⊳ Change in oil demand by scenario between 2020 and 2030



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The global oil outlook pivots on changes in road transport. Oil use for petrochemicals grows in all scenarios mainly as a result of large increases in the Middle East, China and India

Note: Other includes agriculture and other energy sector.

Passenger cars use the largest volume of oil of any sector today and in 2020 they consumed around 20 mb/d. In the STEPS, demand by passenger cars increases by around 2 mb/d through to 2030, with a particularly sharp rise in 2021 due to the gradual relaxation of

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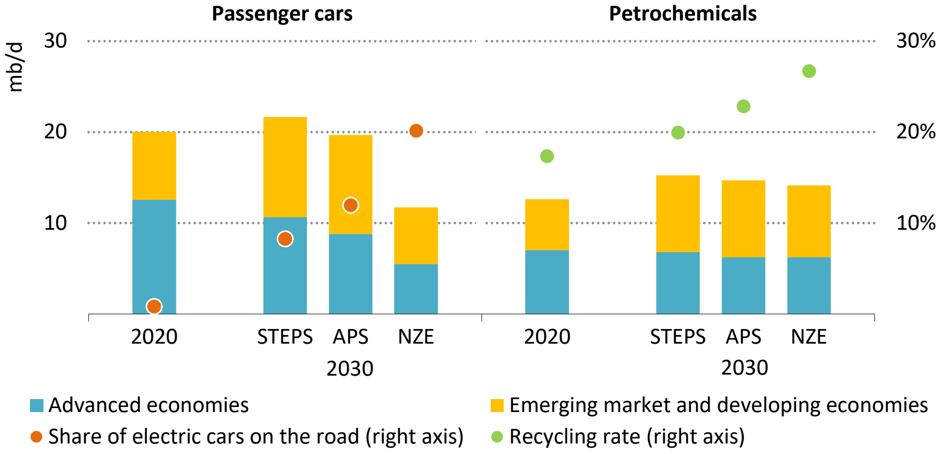
[1] Advanced biofuels are produced from non-food crop feedstocks, result in significantly fewer greenhouse gas emissions than fossil fuels, do not compete with food for agricultural land and do not adversely affect sustainability.

Covid-19 restrictions (Figure 5.4). Around 8% of cars on the road are electric in 2030, but a rise in the number of heavier cars sold – especially sports utility vehicles – offsets some of the reductions in oil use from the rise of electric cars. In the APS, in countries with net zero pledges, more than 15% of passenger cars on the road in 2030 are electric, and the implementation gap between the STEPS and the APS is closed through measures such as specific phase-out plans for internal combustion engine vehicles, strict fuel-economy standards, support for the deployment of alternative fuels infrastructure, and enhanced investment in walking and cycling infrastructure and public transport. Globally, oil use in cars falls by 0.4 mb/d in the APS between 2020 and 2030 (Figure 5.5). In the NZE, major efforts are made across the world to reduce the number of car journeys and to shift passengers towards other modes of transport, and 20% of cars on the road are electric in 2030. As a result, oil demand for passenger cars falls by 8 mb/d to 2030.

Figure 5.5 ▷ Oil use in passenger cars and petrochemicals by scenario between 2020 and 2030



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The NZE sees 300 million electric cars on the road in 2030 that displace more than 3.5 mb/d of oil. Plastic recycling rates increase in all scenarios as does oil use in petrochemicals

Heavy trucks (both medium- and heavy-freight trucks) used 10 mb/d of oil in 2020. Electrification and fuel efficiency improvements play a central role in displacing oil use in freight trucking and there is also a potential role for alternative liquid fuels, especially for trips longer than 400 kilometres (km). In the STEPS, electric and fuel cell heavy trucks struggle to gain market share and oil demand increases by around 4 mb/d to 2030. In the APS, 3.5% of heavy trucks on the road in countries with net zero pledges are electric or fuel cell in 2030 and global oil demand for heavy trucks increases by around 3 mb/d to 2030. In the NZE, nearly 10% of heavy trucks on the road globally are electric or fuel cell vehicles by 2030, there is a large uptake in the use of biofuels, and oil demand rises by less than 0.5 mb/d between 2020 and 2030.

Aviation and shipping activity grows markedly in the STEPS, with a strong rebound as restrictions on international travel unwind. Oil demand increases by more than 5 mb/d to 2030 (reaching just over 14 mb/d in 2030). Liquid biofuels are the main alternative fuel choice to 2030, but there are few policies and measures to encourage their use. In the APS, the focus on delivering on domestic net zero pledges means that there are limited efforts to reduce emissions from international aviation and shipping, and global oil demand for aviation and shipping grows by more than 4 mb/d to 2030. In the NZE, the global effort to tackle emissions means that there are widespread efforts to reduce emissions from international aviation and shipping, and total oil use for aviation and shipping in the NZE is flat between 2020 and 2030.

The **petrochemical** sector was the only segment that saw an increase in oil use in 2020. An increasing number of countries have recently announced or introduced policies to scale up recycling and limit single-use plastics, and investment in waste management and recycling featured in a number of stimulus packages.[2] In the STEPS, this translates into a small rise in global average plastic recycling rates from 17% today to 20% in 2030. This is not enough to offset increased consumer demand for packaging and oil use for petrochemicals, and oil demand increases by around 2.5 mb/d between 2020 and 2030 (to 15 mb/d). In the APS, recycling rates increase in countries with net zero pledges to 32% in 2030. Measures to ensure that pledges are achieved include regulatory action to tackle plastic use and the development of an international secondary waste market. However, the absence of significant efforts to boost recycling in countries without net zero pledges means that recycling rates globally only rise to 23% and oil demand increases by just over 2 mb/d to 2030. In the NZE, the global average recycling rate rises to 27% in 2030. Some use is made of bio-based petrochemical feedstocks, but these compete for sustainable feedstock with other sectors and only around 5% of total plastics feedstock in the NZE in 2030 is sourced from bioenergy and oil demand increases by 1.5 mb/d to 2030.

Supply

In the STEPS, tight oil operators choose to prioritise returns over aggressive production growth, even as annual average prices rise to 2030. Tight oil production satisfies around 20% of global oil demand growth between 2020 and 2030 (compared with the 2010-2019 period when it provided 70%). Total oil production in the United States rises by around 3.5 mb/d to 2030 (reaching 20 mb/d in 2030) while Canadian production increases by 0.7 mb/d as long lead time projects approved for development in the mid-2010s start to ramp up (Figure 5.6). Brazil maintains deep water production levels through the 2020s, while emerging producers, including Guyana and Senegal, increase production by around 1 mb/d between 2020 and 2030. Organization of the Petroleum Exporting Countries (OPEC) production increases by around 6 mb/d to 2030, with Iraq, Iran and Kuwait providing over 40% of this growth as new fields come online and production increases at existing fields. OPEC and Russia together

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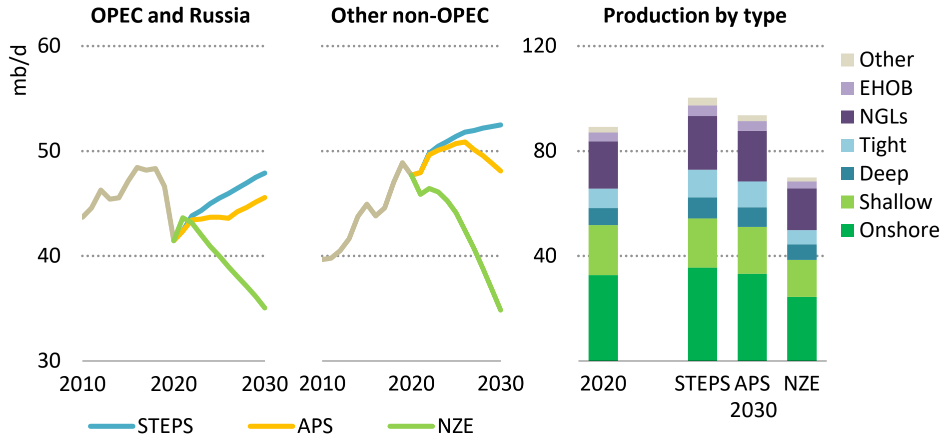
[2] Examples include: a new plastic tax in the European Union, which took effect in January 2021; a law in California in the United States that requires beverage containers to contain a minimum of 15% recycled plastic by 2022: and a ban on some single-use plastics in China.

provide 48% of total oil production in 2030, an increase from 2020, but well below their share during much of the last decade.

Figure 5.6 ▷ Oil supply by scenario



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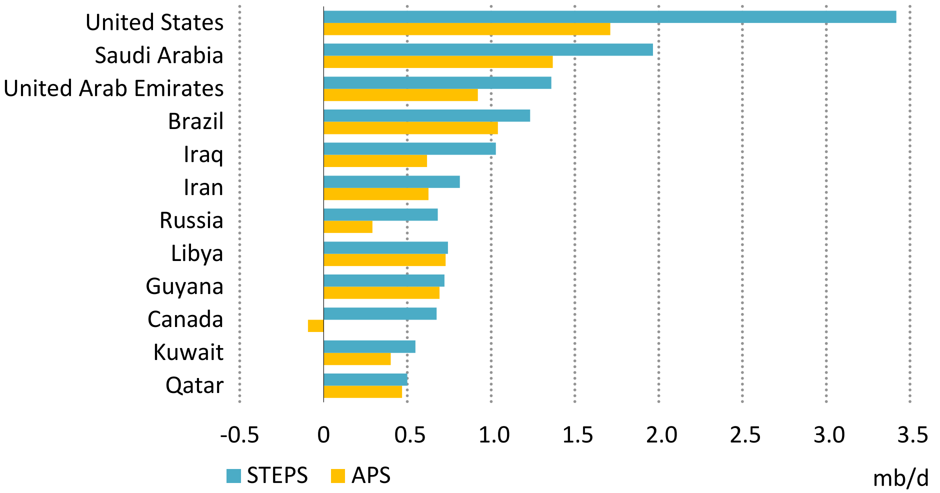
More restrained investment in tight oil means that OPEC and Russia comprise an increasing share of supply to 2030, although this remains below the levels seen in the 2010s

Note: EHOB = extra heavy oil and bitumen; onshore = onshore conventional crude oil; shallow = offshore conventional crude oil from water depths less than 450 metres (m); deep = offshore conventional crude oil from water depths more than 450 m.

In the APS, the peak in global oil demand means that prices are just over USD 65/barrel in 2030. No net zero pledges made by major oil producing countries include explicit targets to curtail production. These countries do however pursue efforts to minimise emissions from oil and gas operations in the APS: this increases their production costs relative to other producers and in many cases also involves additional financing costs. In some of the higher cost producers with net zero pledges, including in Europe and Canada, increased costs and lower prices in the APS mean there are no or very limited investment into new projects from the mid-2020s and production is markedly lower than in the STEPS (Figure 5.7). Projects with lower costs and shorter payback periods that can limit emissions from production and processing activities at low cost are less affected. Demand falls faster than supply in some countries with net zero pledges, allowing them to export more, for example, in 2030 the United States exports 3.5 mb/d in the APS, compared with less than 2.5 mb/d in the STEPS. This puts downward pressure on prices and limits export opportunities for a number of new and emerging producers.

In the NZE, the fall in oil demand and prices does not justify investment in new fields after 2021. Any such investment would be surplus to requirements in the NZE and could struggle to return the capital invested. There is still investment in existing fields to minimise the emissions intensity of production and there are also some low cost extensions of existing fields to maintain or support production. This support includes the use of in-fill drilling and improved management of reservoirs as well as some enhanced oil recovery and tight oil drilling to avoid a sudden near-term drop in supply. Supplies become increasingly concentrated in a small number of low cost producers and the share of Russia and members of OPEC rises to 50% in 2030.

Figure 5.7 ⊳ Changes in oil supply in selected countries in the Stated Policies and Announced Pledges scenarios, 2020-2030



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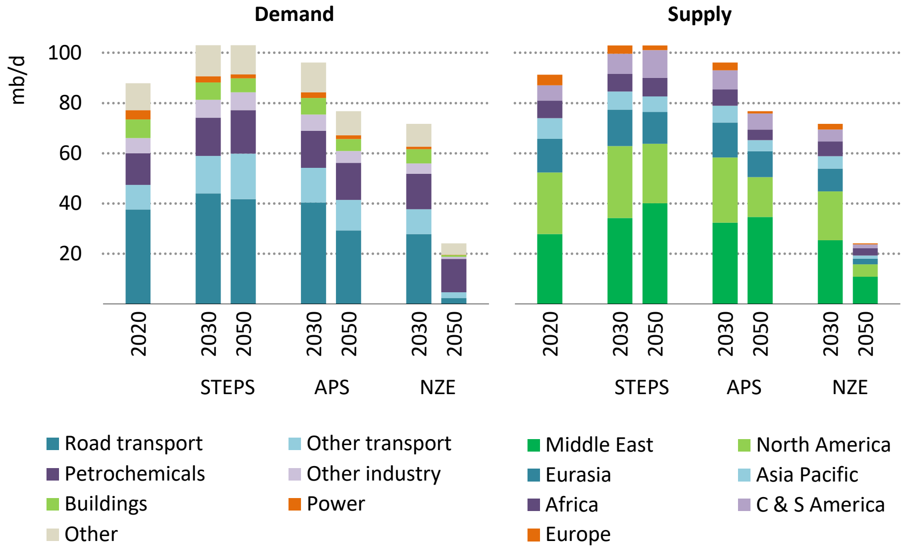
All countries produce less oil in the APS than the STEPS but changes are largest in higher cost countries with net zero pledges as they look to limit emissions from oil activities

The demand trajectories in the APS and the NZE inevitably look challenging from the perspective of the countries and companies that produce oil. High cost assets and those with high emissions intensities would likely struggle to continue producing economically. Efforts will be needed to minimise emissions from traditional operations, including tackling methane emissions. There could also be new opportunities. The skills, competencies and resources of the oil and gas industry could provide it with a competitive advantage when it comes to accelerating innovation and to the deployment of critically important clean energy, such as carbon capture, utilisation and storage (CCUS), hydrogen, bioenergy and offshore wind.

5.2.2 Oil trends after 2030

In the STEPS, oil demand levels off at 104 mb/d in the mid-2030s and then drops very slightly through to 2050. Between 2030 and 2050, oil demand for road transport declines by more than 2 mb/d globally: 30% of passenger cars on the road globally in 2050 are electric and just under 5% of heavy trucks are electric or fuel cell vehicles. Electricity generation and the buildings sector also use less oil. Demand reductions, however, are broadly matched by increases in demand for aviation, shipping and petrochemicals. Non-OPEC (excluding Russia) production declines by close to 6 mb/d between 2030 and 2050 as resource bases become increasingly mature, although production using enhanced oil recovery offsets some of the drop in supply. OPEC and Russia provide 53% of global oil production in 2050, up from 47% in 2020.

Figure 5.8 ⊳ **Oil demand and supply in 2030 and 2050**



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Demand in the STEPS levels off in the mid-2030s and falls marginally to 2050; demand falls by 1 mb/d each year from 2030 to 2050 in the APS and by 2.4 mb/d each year in the NZE

Notes: C & S America = Central and South America. Other includes agriculture and other energy sector.

In the APS, demand in countries with net zero pledges falls by nearly 30 mb/d between 2030 and 2050 while it increases by close to 10 mb/d in countries without pledges. By 2050, almost half of the cars on the road globally are electric, and more than one-quarter of heavy trucks are electric or fuel cell vehicles. After 2030, additional costs become necessary to minimise emissions from oil and gas production and there is limited investment in new fields in many countries with net zero pledges (Box 5.1). This means that non-OPEC production takes a smaller market share, and OPEC and Russia provide 58% of global oil production by 2050.

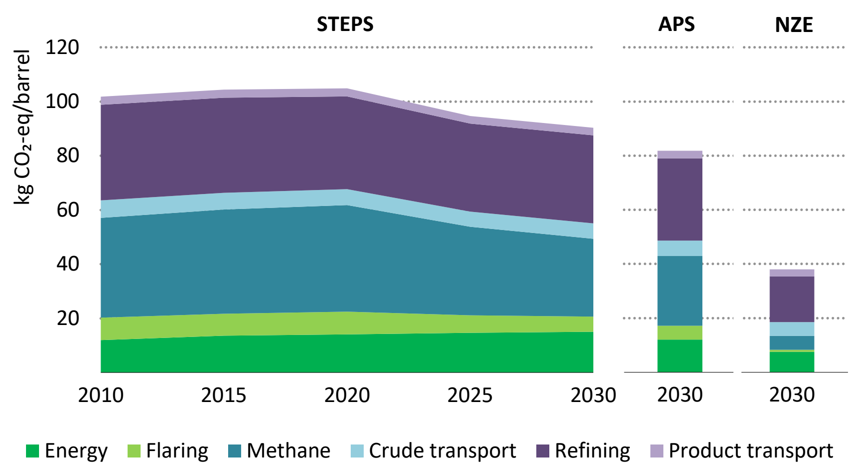
In the NZE, oil demand falls by 48 mb/d between 2030 and 2050 (a 5.3% average annual decline) (Figure 5.8). No new passenger cars with internal combustion engines are sold anywhere after 2035 and the use of oil as a feedstock falls by around 1 mb/d as plastic recycling rates rise globally to more than 50% in 2050 (and to 60% in advanced economies). Production is increasingly concentrated in resource-rich countries due to the large size and slow decline rates of their existing fields. OPEC and Russia account for more than 60% of the global oil market in 2050.

Box 5.1 ▷ Strategies to get the most from existing sources of supply

Investments in existing fields rose from less than half of capital spending on oil between 2010 and 2019 to around 55% in 2021 (IEA, 2021a). Although reductions in demand mean that no new oil fields need to be developed in the NZE after 2021, further investment is required in existing fields to reduce the emissions intensity of operations and to combat natural production declines. In the STEPS and the APS, new fields are needed to meet oil demand levels, but action to get the most from existing operations may still be a pragmatic and cost-effective approach. Such actions could take various forms:

- **Reduce emissions from existing sources of supply.** Oil and gas operations are responsible for around 15% of global energy sector GHG emissions today (IEA, 2020a). Options to reduce these emissions include tackling methane leaks (including intentional methane venting), minimising flaring, switching to low-carbon options to power operations, incorporating energy efficiency improvements across the supply chain and using CCUS for large centralised sources of emissions. All of these play a role in the NZE in reducing the emissions intensity of oil and gas production, which falls from a global average of just over 100 kilogrammes of carbon dioxide equivalent (kg CO_2-eq) per barrel in 2020 to less than 40 kg CO_2-eq/barrel in 2030 (Figure 5.9).

Figure 5.9 ▷ Global average emissions intensity of oil production



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Action to minimise supply chain emissions plays an important part in clean energy transitions. In the NZE, the global average emissions intensity falls by 65% to 2030

- **Minimise flaring and methane leakage from flaring.** Around 140 billion cubic metres (bcm) of natural gas was flared worldwide in 2020, which is equivalent to total natural gas use in Central and South America. Flaring is a wasteful practice that causes emissions of CO_2, methane and black soot, and is damaging to health (World Bank, 2021). There should be minimal methane emissions if a flare is designed, maintained and operated correctly, but higher emissions can occur as a result of factors such as weather and changes in production rates (Johnson, 2001; Kostiuk, 2004). Occasionally a flare may be totally extinguished, resulting in direct venting to the atmosphere of gas that should be combusted. Globally, we estimate that flares in 2020 leaked around 8% of the natural gas and natural gas liquids (NGLs) that should have been combusted, more than double previous estimates.[3] This resulted in nearly 8 million tonnes (Mt) of methane emissions which, when combined with CO_2 emissions from combustion, resulted in more than 500 Mt CO_2 equivalent GHG emissions. A rapid reduction in flaring and methane emissions occurs in both the APS and the NZE.
- **Reduce natural production declines.** In the absence of any investment in existing oil fields, supply would fall by around 8-9% per year, which is faster than the rate of decline in oil demand even in the NZE. This rate of decline can be slowed by supporting production from existing fields, for example with improved well reservoir management and in some cases enhanced oil recovery. There are also options to increase production from existing fields through well interventions or workovers, for example by re-perforating existing wells (Kitsios, Shields and Vroemen, 2013). Not all of these opportunities will exist across all fields, but we estimate that adopting these technologies at all applicable conventional oil fields could boost global production by at least 2 mb/d in 2030.
- **Digitalise operations.** Emerging digital technologies could help improve efficiency, reduce costs and reduce the emissions intensity of oil and gas production. They could for example be used to enhance models of the subsurface to identify new production sources (Hafez, et al., 2018), integrate remote surveys and automated robotics to detect and measure emissions levels, and optimise the transport and trade of oil and gas. Digital technologies that optimise fuel usage and reduce emissions for liquefied natural gas (LNG) carriers have been shown to reduce CO_2 emissions by around 7% per cargo delivered (Brown, et al., 2020).

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[3] The leakage rate is the proportion of natural gas and NGLs directed into a flare that is not combusted; here it includes volumes not combusted when a flare is operating normally and when it may have been temporarily extinguished. Our estimate is based on a detailed bottom-up assessment of production types, facility and flare design practices, operators, changes in produced volumes over field lifetime, local crosswind variability, and the strength of regulation, oversight and enforcement. In previous *Outlooks*, we estimated that flares released around 3.5% of natural gas and NGLs directed into flares. One tonne of methane is assumed to be equal to 30 tonnes of CO_2 equivalent, based on the 100-year global warming potential (IPCC, 2021).

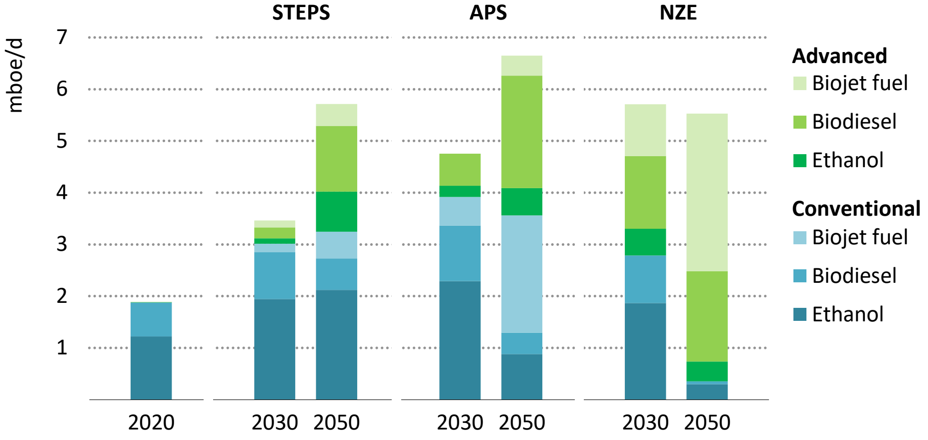
5.2.3 Biofuels and hydrogen-based fuels

Biofuels

A key advantage of biofuels is that they can often be adopted with minimal retrofit costs by end-users. However, biofuels have high costs and there is a limited supply of affordable and sustainable feedstocks. It currently costs USD 70-130 per barrel of oil equivalent (boe) to produce conventional biofuels and USD 85-160/boe to produce advanced biofuels. One major challenge for the future is to mobilise investment to develop multiple new large-scale facilities to lower production costs; another is to develop new sustainable biomass supply chains.

Between 2020 and 2030, biofuel demand increases by nearly 1.5 million barrels of oil equivalent per day (mboe/d) in the STEPS, and conventional ethanol, mostly used in passenger cars, comprises more than half of biofuel consumption in 2030 (Figure 5.10). In the APS, demand increases by more than 2.5 mboe/d to 2030. The implementation gap between the APS and STEPS is closed through blending mandates for biodiesel (mainly in Asia and Latin America) and for biojet fuel (mainly in the United States and China). Existing production facilities are upgraded and retrofitted, and a number of new production facilities are constructed. In the NZE, total biofuel demand increases by more than 3.5 mboe/d to 2030. Conventional biofuels contribute to some of this growth but most of it comes from advanced biofuels, which comprise almost half of total biofuel production in 2030, mainly for use in trucks and for aviation: biojet fuel accounts for 15% of total aviation fuel in 2030 in the NZE.

Figure 5.10 ▷ Liquid biofuel demand by type and scenario



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Production routes and end-uses differ, but biofuels increase strongly in all scenarios to 2030. Advanced biofuels are key to meeting net zero targets, especially for trucks and aviation

Note: mboe/d = million barrels of oil equivalent per day.

In the STEPS, advanced biofuels are responsible for most of the 2.2 mboe/d increase between 2030 and 2050, but conventional ethanol remains the largest single biofuel produced in 2050. In the APS, the electrification of road transport in countries with net zero pledges means ethanol use falls. Biojet fuel and advanced biodiesel increase substantially and total biofuel use rises to 6.5 mboe/d in 2050. In the NZE, biofuel use remains at around 5.5 mboe/d through to 2050 and is increasingly focused on heavy trucks, shipping and aviation. Biojet fuel accounts for around 40% of all aviation fuel in 2050, and advanced biofuels comprise nearly 90% of total biofuel use globally.

Hydrogen-based liquid fuels

Low-carbon hydrogen-based fuels, including ammonia, methanol and other synthetic liquid hydrocarbons made from hydrogen with a very low emissions intensity, offer an alternative to the use of oil.[4] Ammonia, which can be easily stored as a liquid, can also be used for power generation without CO_2 emissions, including via certain fuel cells. However, hydrogen-based fuels will need to overcome a number of hurdles in order to play a major role as liquid fuels. They currently have high costs of production, suffer from limited enabling infrastructure, can involve large energy losses from production to consumption,[5] and, in most cases, must be handled more carefully than traditional liquid fuels.

There are six demonstration projects under construction today that will produce low-carbon liquid synthetic hydrogen-based fuels and a further 38 pilot and demonstration projects are at the planning stage. There are also a large number of projects looking to produce ammonia, mainly for use as a fertiliser but also as a fuel, including some that aim to export the ammonia to overseas markets. A number of countries are exploring options to expand support for hydrogen-based fuels. For example, Germany has a requirement for 2% of fuel use in aviation to be hydrogen-based by 2030 (BMU, 2020); the European Commission has proposed a target for hydrogen and hydrogen-based fuels (derived from renewable energy) to provide 2.6% of energy for transport by 2030 (European Commission, 2021); and Japan has released an interim report on ammonia use in electricity generation and shipping (METI, 2021). Ammonia and methanol-fuelled ships are not commercially available today, although Maersk has ordered eight methanol-powered container ships for delivery in 2024 and around five ammonia-fuelled vessels are in the design phase or have been ordered (Getting to Zero Coalition, 2021). Plans to offer ammonia retrofit packages for existing ships by 2025 have also been announced.

To 2030, in the STEPS, the uptake of hydrogen-based fuels globally is limited because there are few policies supporting their use. In the APS, 0.15 EJ (0.07 mboe/d) of hydrogen-based

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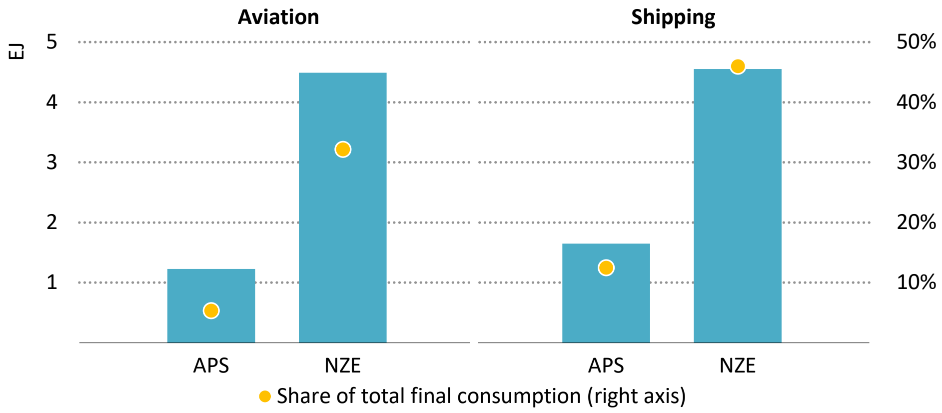
[4] These fuels can replace liquid hydrocarbons in engines and turbines, especially in transport. It is uncertain which specific low-carbon hydrogen-based fuel will be the most cost competitive and attractive to users and so they are generally presented in aggregate in our analysis. The use of low-carbon hydrogen as a gas, including as an input to hydrogen-based fuels, is described in section 5.3.3.

[5] For example, including the energy required to capture CO_2 from the air to provide the carbon inputs for the manufacture of non-fossil synthetic hydrocarbons, well-to-wheel losses could reach over 90% of the initial electricity input. Non-fossil synthetic hydrocarbons can also be made using carbon from biomass where it is available in sufficient quantities.

fuels are consumed globally for transport in 2030, mostly in the form of ammonia in shipping. This is a relatively small amount, but progress to 2030 will be critical to the later success of hydrogen-based fuels. Closing the implementation gap between the STEPS and APS will depend on major investment in innovation to lower the costs of production and transport and to ensure that new end-user equipment and vehicles are readily available on the market. There are likely to be large regional variations in production costs for hydrogen-based fuels; imports could be more economically attractive than domestic production in some countries. International trade will require co-operation on standards to ensure low emissions intensity throughout the value chain. In the NZE, consumption of liquid hydrogen-based fuels in the transport sector increases to 1.3 EJ (0.6 mboe/d) in 2030, most of which is used in shipping (representing just under 10% of total fuel use in shipping at that time).

Beyond 2030, in the STEPS, deployment remains at very low levels. In the APS and NZE, concerted policy and regulatory interventions in the 2020s help bring down production costs and increase use after 2030, with the more global efforts in the NZE having a greater impact than those in the APS. Large production facilities are developed in renewable-rich locations far from electricity demand centres, and hydrogen-based fuels are used in increasing volumes for shipping and aviation (Figure 5.11). They are also used to a lesser extent for heavy trucks, but electrification and the use of gaseous hydrogen in fuel cells are the main mechanisms to reduce emissions from heavy trucks. In shipping, the roll-out of ammonia production facilities and ammonia-fuelled ships increases substantially in the 2030s. Ammonia accounts for almost half of shipping energy demand in the NZE in 2050. In aviation, synthetic kerosene use grows substantially from 2030 and meets about 30% of total aviation fuel demand in 2050 in the NZE.

Figure 5.11 ▷ Low-carbon hydrogen-based fuel consumption in aviation and shipping, 2050



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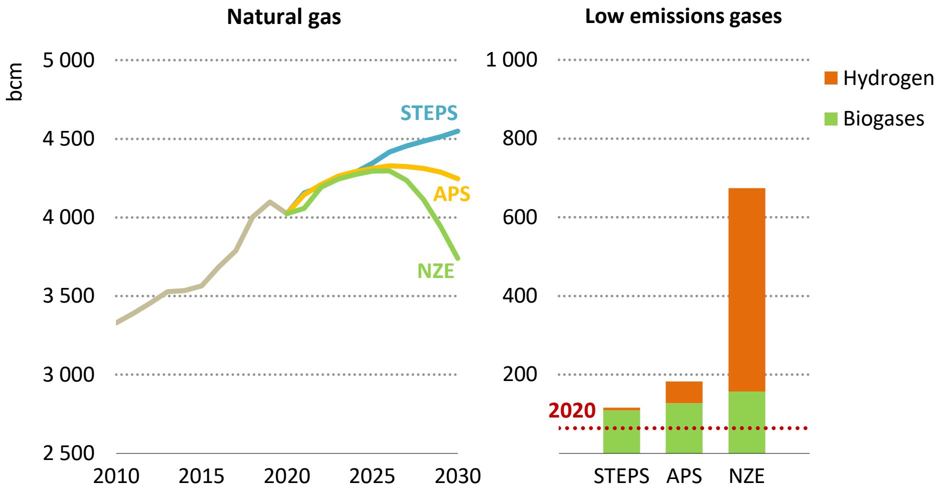
There is limited hydrogen-based fuel use before 2030, but it has a large role in the APS and NZE after 2030. Hydrogen-based fuels provide 45% of fuel use in shipping in the NZE in 2050

5.3 Gaseous fuels

Figure 5.12 ▷ Natural gas use over time and low emissions gas supply in 2030



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Natural gas use increases in each scenario to 2025 with sharp divergences thereafter. Biogas use grows rapidly in each scenario. There is a large role for hydrogen in the NZE

Note: Hydrogen gases include low-carbon gaseous hydrogen and synthetic methane with 1 EJ = 29 bcm.

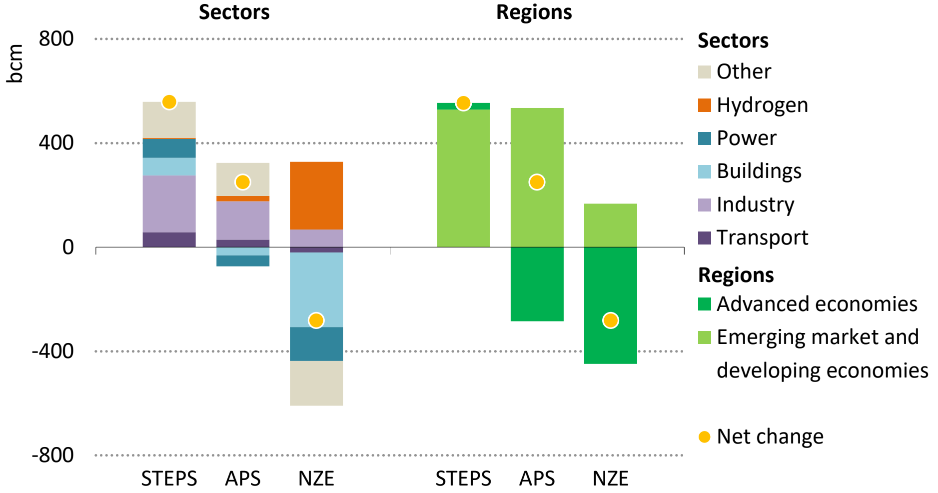
The record highs in spot natural gas prices in 2021 have refocused attention on the role of natural gas, and raised new questions about the extent to which, and for how long, it can retain a place in the energy mix as clean energy transitions accelerate. There is no single storyline. In the power sector, natural gas use could increase in countries with rising electricity demand or declining coal and nuclear capacity or indeed both, but it faces stiff competition from renewables. In industry, natural gas is well suited to provide heat, but it faces a challenge in other areas from electrification. In countries that use natural gas for space heating, building retrofits and other efficiency improvements could lead to large reductions in natural gas use. In emerging market and developing economies, increases in demand are contingent on the affordability of gas, development of new infrastructure, strength of policy measures to improve air quality, and the pace of reductions in coal and oil use in energy-intensive industries. Also looming in the background is the potential role of low emissions gases such as hydrogen, biomethane and synthetic gases.

Natural gas demand increases in all scenarios over the next five years, but there are sharp divergences thereafter (Figure 5.12). In the STEPS, natural gas demand continues to rise after 2025 and demand is around 15% higher in 2030 than in 2020. In the APS, demand reaches its maximum level soon after 2025 and then declines slowly. In the NZE, demand drops sharply after 2025 and falls well below 2020 levels by 2030. The post-2025 drop in natural gas demand in the NZE, however, is partly offset by growth in demand for low emissions gases (including low-carbon hydrogen produced from natural gas with CCUS). Total demand for gases in the NZE in 2030 is around 5% higher than today.

5.3.1 Natural gas trends to 2030

Demand

Figure 5.13 ⊳ Changes in natural gas demand between 2020 and 2030



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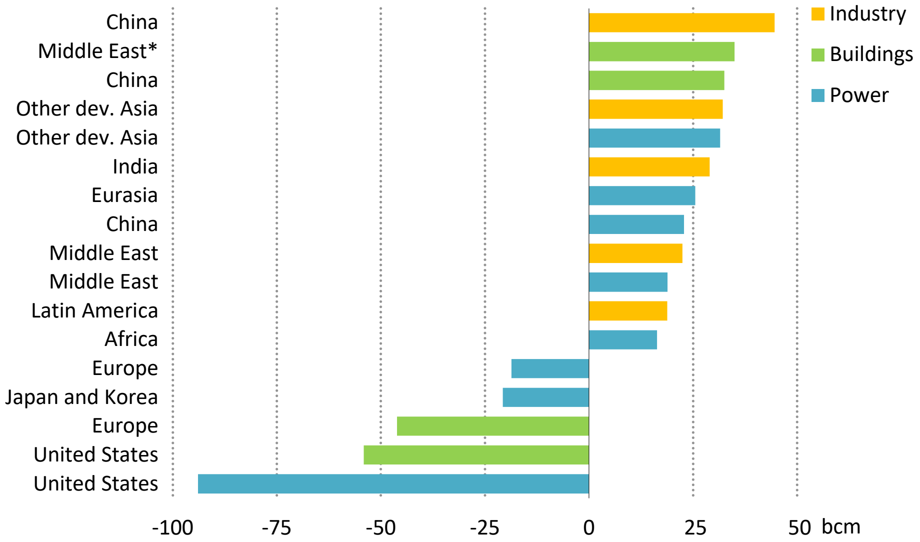
There is not a single storyline for natural gas with large differences across scenarios and sectors

Note: Other includes agriculture and non-energy use.

In the STEPS, nearly all of the 15% global increase in natural gas demand to 2030 comes from emerging market and developing economies (Figure 5.13). Demand in China is 40% higher in 2030 than in 2020. There are declines in a number of established markets, including Japan (down by 25%) and Europe, while North America and Korea see demand peak in the mid-2020s. Industry accounts for nearly 40% of overall demand growth to 2030, led by increases for light manufacturing in China and India, and from the chemical sub-sector in China.

In the APS, the 5% increase in global demand between 2020 and 2030 masks large differences between regions and sectors (Figure 5.14). This includes differences between countries with net zero pledges: in China and Korea, gas consumption increases to 2030 and is used largely to replace more polluting fuels, while in Brazil, Canada, European Union, Japan and United States, demand reduces by 20-35% (though there is considerable variation between various European Union member states). Natural gas demand tends to grow more consistently in countries without net zero pledges.

Figure 5.14 ▷ Key changes in natural gas demand in the Announced Pledges Scenario, 2020-2030



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Most of the growth in natural gas demand is for industry and power in emerging market and developing economies: this is partially offset by declines in advanced economies

* Demand mainly related to desalination.

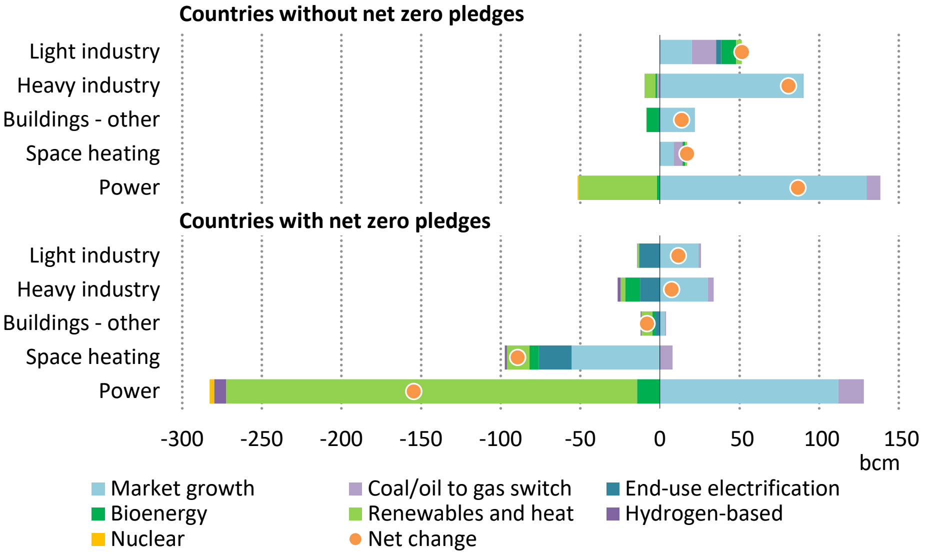
Note: Other dev. Asia = other developing Asia.

In the NZE, natural gas demand falls in nearly all regions, except those that are currently heavily reliant on coal, where it largely displaces coal. There is some upside for natural gas demand in the NZE as a result of its role in scaling up low-carbon hydrogen production: by 2030, around 250 bcm is used in steam methane reformers equipped with CCUS.

The degree of coal-to-gas switching is a key determinant of the outlook for natural gas. Its potential varies between sectors and regions, and depends for a given country on the pace and scale of emissions reductions being sought. Coal-to-gas switching since 2010, primarily in the power sector in the United States and Europe as well as in buildings and industry in China, means that global emissions were around 750 Mt CO_2 lower in 2020 than they otherwise would have been. In the APS, coal-to-gas switching continues in many of these regions. Around 100 bcm of additional gas is used to replace coal in 2030, which avoids around 180 Mt CO_2 of emissions in that year. At a global level, these increases in natural gas demand are partly offset by the drop in demand due to renewables, efficiency and electrification. There is also a modest but important shift away from natural gas to nuclear, modern bioenergy and hydrogen-based fuels, mostly in the United States, Japan and the European Union (Figure 5.15).

In the NZE, additional gas use for switching is even higher at 185 bcm, and oil-to-gas switching becomes an important part of transition strategies, particularly in the power sector in parts of the Middle East and in light industry and manufacturing in emerging market and developing economies in Asia. These increases for gas demand are offset by a switch away from gas to renewables, especially in advanced economies where overall gas demand falls by 20% between 2020 and 2030.

Figure 5.15 ⊳ Drivers of change in natural gas demand in selected sectors in the Announced Pledges Scenario between 2020 and 2030



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Renewables, electrification and efficiency reduce gas demand in countries with net zero pledges; coal-to-gas switching increases gas demand across the board

Notes: Market growth includes underlying drivers of energy service demand (e.g. population or economic growth or structural variables such as floor area increases), net of efficiency gains. Other includes water heating, cooking, appliances and desalination plants.

Industry in emerging market and developing economies is the key driver of natural gas demand growth in all three scenarios. In the STEPS, the large increase in natural gas demand comes from the manufacturing sector and depends on new grid infrastructure to connect clusters of small- and medium-scale factories and industrial hubs (notably in India, which has ambitious plans to develop city gas distribution networks [IEA, 2021b]). Gas also replaces coal, oil and the use of biomass in a range of industrial applications: around 35 bcm of additional gas use in emerging market and developing economies is related to fuel switching in industry by 2030 in both the STEPS and the APS. In the NZE, natural gas demand remains stable to 2030 as growth in steel and cement production is offset by declines in manufacturing and other light industries. Heavy industry facilities using natural gas also start to be equipped with CCUS.

In the **power** sector, increases in electricity demand and reductions in coal-fired generation mean natural gas use increases in each scenario to 2025. Between 2020 and 2025, natural gas demand increases by 60 bcm in the STEPS, 90 bcm in the APS and 250 bcm in the NZE, although in all cases the increase in generation from renewables is much larger. In the STEPS, demand continues to rise after 2025 as a result of robust increases in emerging market and developing economies which are offset slightly by declines in advanced economies. In both the APS and NZE, the window of opportunity for coal-to-gas switching is short-lived and demand falls below 2020 levels by 2030. Natural gas plays a role in helping to balance variable renewable generation but this is generally not accompanied by a material increase in demand.

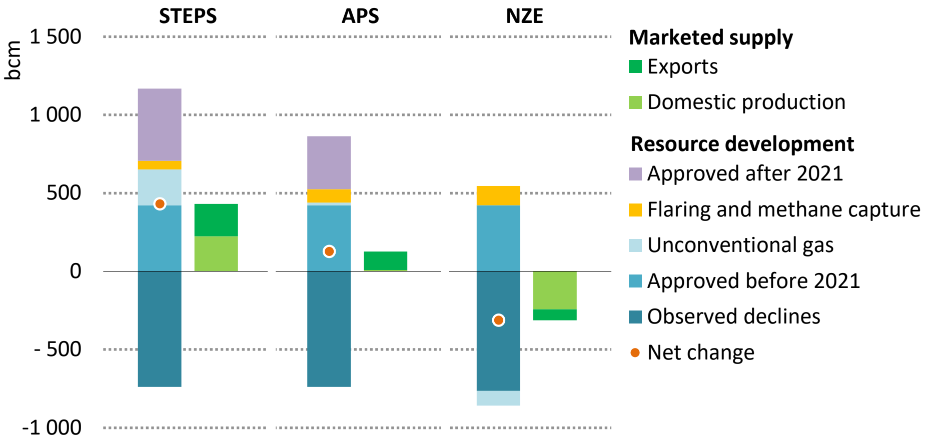
In **buildings**, changes in natural gas demand are closely correlated with the pace and scale of building retrofit rates and of the roll-out of heat pumps, especially in regions where gas plays a seasonal role in heating. In the STEPS, natural gas remains the default option for space heating, the building retrofit rate is less than 1% per year and around 3 million heat pumps are installed every month in buildings around the world in 2030 (compared with 1.5 million today). In the APS, countries with net zero pledges accelerate ambition in both areas, leading to a retrofit rate of around 1.5% per year globally and the installation of 3.5 million heat pumps every month in 2030. The implementation gap between STEPS and APS is closed through measures such as bans on the sale of new gas-fired boilers (except where they are compatible with low-carbon gases) and the introduction of strict performance standards for existing and new buildings together with incentives for retrofits. In the NZE, the global rate of retrofits increases to 2.5% per year and around 5 million heat pumps are installed every month in 2030. Natural gas demand in buildings, which is around 850 bcm today, grows by 70 bcm in the STEPS to 2030, falls by 30 bcm in the APS, and falls by 300 bcm in the NZE.

Supply

In the STEPS, there is a 430 bcm increase in natural gas demand between 2021 and 2030 while existing sources of conventional gas production decline by around 740 bcm (Figure 5.16). Projects that have already been approved add around 420 bcm of production in 2030, and the rest comes from new investment in around 460 bcm per year of new conventional gas projects and 230 bcm of new unconventional gas projects. Around half of the net increase in gas supply is for export. There is a 150 bcm ramp up in annual LNG export capacity, much of it in Qatar, United States, Russia and East Africa.

In the APS, the emissions performance of natural gas produced in countries with net zero pledges, or produced elsewhere for export to them, is subjected to close scrutiny. Countries with net zero pledges experience reductions in domestic demand alongside increases in production costs arising from the need to reduce emissions intensities, and this has knock-on impacts on upstream investment and production levels. In aggregate, production peaks in countries with net zero pledges in the mid-2020s. Countries without net zero pledges see broadly similar levels of production in the STEPS and APS in the period to 2030 as gas demand continues to increase and exports to Asia see similar rates of growth in the two scenarios over the period to 2030. The exception is pipeline exporters to Europe, where exports remain static at 2020 levels in the APS, but increase by 20% in the STEPS by 2030.

Figure 5.16 ▻ Changes in upstream resource development and marketed natural gas supply by scenario between 2021 and 2030



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In the STEPS, new gas fields are required; in the APS, this need diminishes; in the NZE, there is no need for any new upstream development

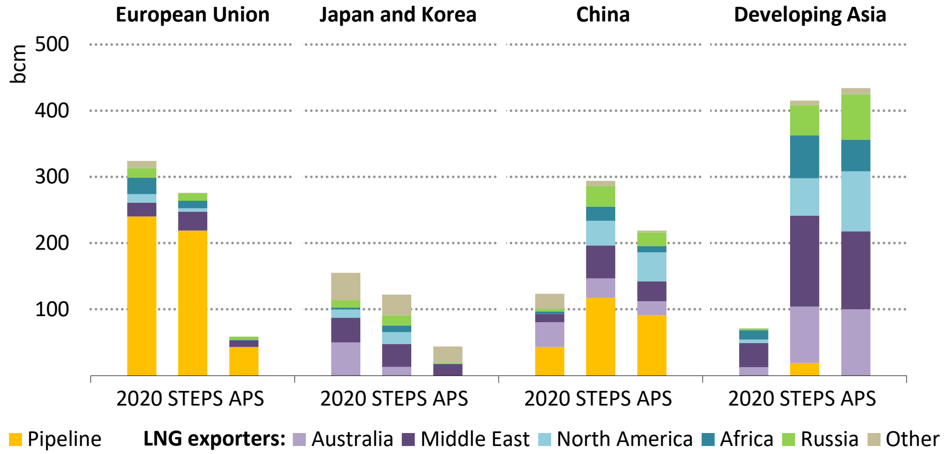
In the NZE, no new gas fields are developed beyond those that have already been approved for development. LNG trade peaks in the mid-2020s at 475 bcm and falls to 2020 levels of 390 bcm by 2030. Around 600 bcm of LNG liquefaction capacity exists today and a further 180 bcm is under construction, implying a reduced rate of utilisation of LNG export capacity globally from the mid-2020s compared with historical utilisation rates (around 85%). Given the low prices of natural gas in the NZE, any LNG projects with a break-even price of more than USD 5 per million British thermal units (MBtu) would be at risk of failing to recoup their investment costs in this scenario.

5.3.2 Natural gas trends after 2030

In the STEPS, natural gas demand continues to increase after 2030, albeit at a slower pace. There is no peak in demand, which reaches 5 100 bcm in 2050, around 30% higher than today. Natural gas demand in industry remains the main engine of growth, but its contribution to overall energy demand growth decreases as emerging market and developing economies transition to more service-oriented economies. Around 70% of the increase in supply between 2020 and 2050 comes from Eurasia and the Middle East, and internationally traded gas volumes increase by 450 bcm over this period. Global LNG trade increasingly takes market share from gas transported by long-distance pipelines, expanding from just over 50% of traded volumes today to 60% in 2050.

In the APS, natural gas demand reaches its maximum level globally soon after 2025 and then declines to 3 830 bcm in 2050. Reductions in advanced economies offset continued growth in emerging market and developing economies. This has important implications for global gas trade, which peaks in the 2030s and falls to 2020 levels by 2050. LNG continues to grow, capturing nearly 70% of traded volumes by 2050: reduced gas demand in Europe leads to an 80% drop in pipeline imports, while LNG supplies the majority of the 430 bcm increase in gas demand in emerging and developing markets in Asia (Figure 5.17). LNG exports from North America are around 130 bcm in 2050, 25% higher than in the STEPS, as reduced demand in the region frees up larger volumes for export.

Figure 5.17 ⊳ Natural gas imports in selected regions by source in 2020 and by scenario in 2050



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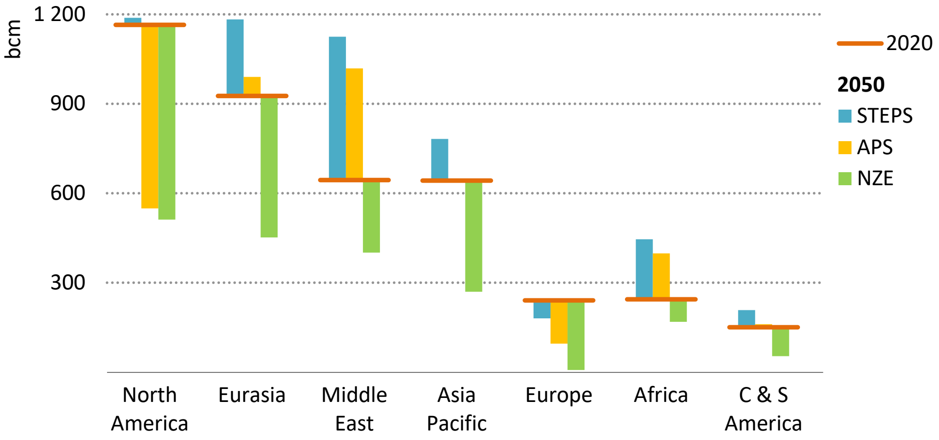
In the APS, falling domestic demand frees up additional exports from North America to developing markets in Asia. The European Union sees a sharp drop in pipeline imports

In the NZE, natural gas use in the power sector declines globally by more than 80% in the 2030s. Less than 190 bcm of natural gas is used for power generation in 2050, accounting for around 1% of electricity generation worldwide (compared with almost a quarter today), mostly from facilities equipped with CCUS. Energy demand in buildings also transitions quickly away from natural gas. In 2050, more than 50% of global gas production is used to produce low-carbon hydrogen; a further 15% is used in industry, mainly for cement production and in light industries. Without any need for investment in new upstream projects, production in emerging producers in Africa and elsewhere is constrained, and large existing producers and resource holders increasingly dominate supply. In 2050, more than 40% of global gas is produced in the Middle East and Russia (Figure 5.18). Inter-regional trade of natural gas falls to less than 300 bcm by 2050, around 40% of current levels.

Figure 5.18 ▷ **Changes in natural gas production by region and scenario between 2020 and 2050**



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North America sees a large drop in production between the STEPS and the APS, with smaller reductions in Eurasia and the Middle East. All regions produce much less gas in the NZE

Note: C & S America = Central and South America.

5.3.3 Low-carbon hydrogen and biogas

Low-carbon hydrogen

Close to 11 EJ (90 Mt) of hydrogen was produced worldwide in 2020, mainly for use in the chemicals and refining sub-sectors (IEA, 2021c).[6] Most was produced from natural gas or coal (in China): low-carbon hydrogen comprises less than 1% of current total hydrogen production.[7] Most hydrogen is produced near where it is used: there is little hydrogen pipeline and storage infrastructure today.

Low-carbon hydrogen can reduce GHG emissions by replacing existing sources of hydrogen produced from unabated fossil fuels; by meeting new demand for low emissions fuels and industrial feedstocks; and by converting electricity to a storable fuel to assist with the system integration of renewables. Hydrogen can also be converted to other low-carbon hydrogen-based fuels, including synthetic methane, ammonia and synthetic liquids.

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[6] This includes around 2.5 EJ of hydrogen used in a mixture of gases for methanol and steel production without purification of the hydrogen. It does not include hydrogen contained in residual gases from industrial processes that is used for electricity and heat.

[7] Low-carbon hydrogen is hydrogen produced in a way that does not contribute to atmospheric CO_2. Emissions associated with fossil fuel-based hydrogen production must be permanently prevented from reaching the atmosphere and the natural gas supply chain must result in very low levels of methane emissions, or the electricity input to hydrogen produced from water must be from renewable or nuclear sources.

In 2017, Japan was the first country to publish a detailed hydrogen strategy and was followed shortly thereafter by Korea. Today, 17 governments have published low-carbon hydrogen strategies and more than 20 countries are developing them. These strategies generally include targets for hydrogen supply, although attention is increasingly being paid to the policies needed to stimulate low-carbon hydrogen demand.

To 2030 in the STEPS, there is limited demand for low-carbon hydrogen (although recent policy developments mean demand is higher than in previous *World Energy Outlooks)*. Around 0.2 EJ of low-carbon hydrogen is produced globally in 2030, equivalent to 0.05% of final energy consumption. The majority of low-carbon hydrogen in 2030 is produced via electrolysis to take advantage of renewable energy resources near demand centres in China, Europe, Japan and North America. Some cross-border trade also emerges, notably from Australia and the Middle East to demand centres in Asia.

In the APS, total low-carbon hydrogen production rises to around 2 EJ (16 Mt) in 2030. Just over 40% is used in transformation sectors, including to provide flexibility in the power sector (for both inter-seasonal and intra-day storage) and to produce hydrogen-based fuels. The rest is used in gaseous form to decarbonise end-uses. The implementation gap between the STEPS and APS is closed mainly through additional demand policies in Japan, Korea and the European Union. There is also a need to scale up production, which is done in part without the need for new transmission and distribution infrastructure by replacing the hydrogen used today in industry with low-carbon hydrogen and by blending small volumes of low-carbon hydrogen into natural gas grids. In 2030, more than 0.5 EJ low-carbon hydrogen is used in industry and 0.3 EJ is consumed in transport, predominantly for heavy trucks. Low-carbon hydrogen also emerges as an emissions reduction option for some buildings, mainly those in cold climates that are difficult to retrofit or connect to a district heating network, especially if they are close to a source of hydrogen supply. Supplying the low-carbon hydrogen to meet demand in the APS requires many more projects to develop electrolysers and to use CCUS with fossil fuels than are in the current pipeline (Box 5.2).

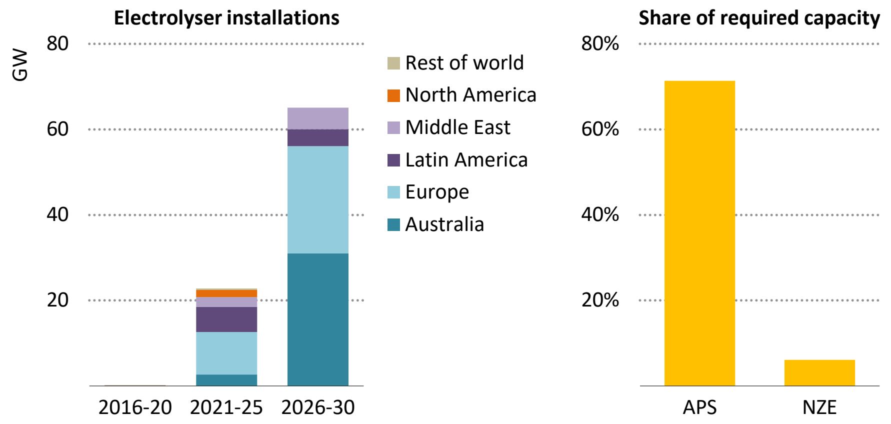
Box 5.2 ▻ Are hydrogen production plans falling short?

The recent upsurge of interest in low-carbon hydrogen production has led to a large pipeline of new production projects. If all planned and announced electrolyser projects were to be completed, we estimate that this would lead to around 90 gigawatts (GW) of capacity installed globally by 2030, producing 1 EJ low-carbon hydrogen (Figure 5.19). This would represent a large increase from the current production level, but this is less than three quarters of the level of low-carbon hydrogen production from electrolysers in 2030 in the APS and less than 10% of projected production in the NZE.

Plans for a number of new facilities producing hydrogen using natural gas with CCUS have also been announced. These include: projects connected to the Porthos CCUS project in the Netherlands, which has been granted government funding; projects in Canada and the Middle East that are targeting exports to Asia; and five industrial clusters in the

United Kingdom that have funding for hydrogen-related engineering studies. Despite these announcements, currently planned projects for low-carbon hydrogen production from fossil fuels also fall far short of deployment levels in the APS and the NZE.

Figure 5.19 ▷ Planned and announced electrolyser installations to 2030 and their proportion of required additions, 2021-2030



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The project pipeline for new electrolyser capacity is expanding rapidly, but far more projects are required to keep pace with deployment rates in the APS and NZE

Source: IEA (2021c).

Integrating low-carbon hydrogen in the energy system will require concerted efforts by governments during the 2020s to create market certainty and close the cost gap with incumbent technologies, for example by establishing targets and long-term policy goals, supporting demand creation in industry and other sectors, mitigating investment risks, promoting research and development projects, and harmonising standards to remove barriers. Recent examples include a contracts-for-difference (CfD) system in the Netherlands that provides a guaranteed price for hydrogen production, a proposed auction mechanism in Germany and consultation on a support system based on the CfD model in the United Kingdom. Governments also need to ensure deployment of the new infrastructure required to support longer term increases in low-carbon hydrogen supply and demand, including hydrogen pipelines, port facilities and storage, as well as CO_2 storage.

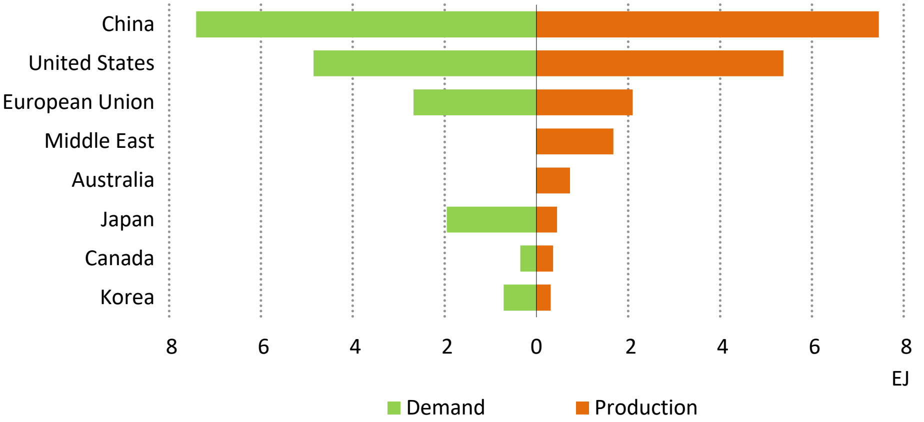
The overall increases in hydrogen demand to 2030 in the APS and NZE may be small compared with increases in electricity and many other clean energy technologies, but they depend on early action by governments and industry.

In the NZE, total low-carbon hydrogen production rises to 17 EJ in 2030. Around one-third is used in the power sector, 25% in industry, and just over 15% is converted into hydrogen-based fuels and the remainder is used in buildings and transport. This uptake of low-carbon hydrogen requires a large increase in the installation of hydrogen end-use equipment and leads to there being more than 15 million hydrogen fuel cell vehicles on the road in 2030, many of which are heavy trucks. Around half of low-carbon hydrogen production in 2030 is from electrolysis and half is from coal and natural gas with CCUS (although this ratio varies considerably between regions).

After 2030, in the STEPS, low-carbon hydrogen production continues to expand and demand in 2050 is equivalent to around 15% of today's total hydrogen use in industrial feedstocks and oil refining. Around 80% of the low-carbon hydrogen produced in 2050 uses electrolysis, reflecting the significant policy support for electrolytic hydrogen in various regions.

In the APS, total low-carbon hydrogen production increases to 20 EJ in 2050 and it plays a key role in displacing oil in transport and coal and natural gas in power generation and industry. Japan, Korea and some countries in Europe develop domestic hydrogen production but rely on imports to meet some of their demand. Many of the largest exporters do not have net zero pledges and there is a need for importing countries to engage with trading partners to encourage and guarantee investments in supply and ensure that hydrogen imports are low-carbon (Figure 5.20) (see Chapter 6).

Figure 5.20 ▷ Low-carbon hydrogen demand and production in selected regions in the Announced Pledges Scenario, 2050



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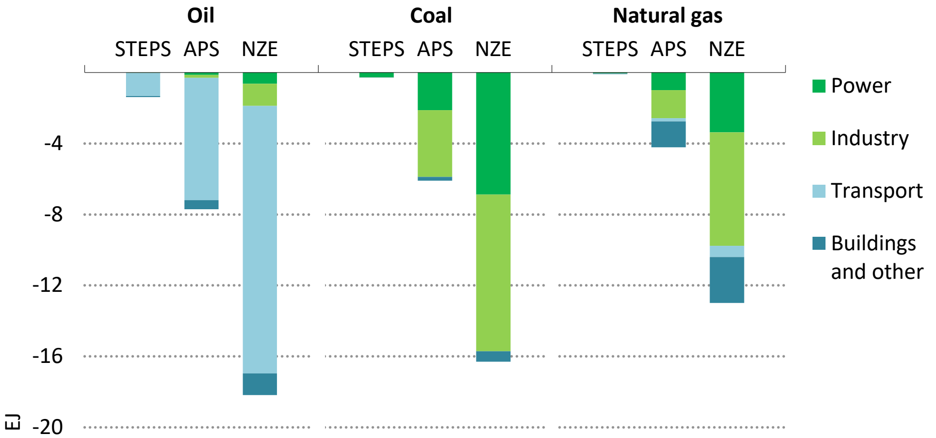
Many countries can satisfy a large share of their hydrogen demand with domestic production, yet multiple hydrogen trade routes emerge

Note: Includes low-carbon hydrogen consumed at the point of end-use as gaseous hydrogen and in hydrogen-based fuels.

In the NZE, total low-carbon hydrogen production increases to 60 EJ in 2050, around one-quarter of which is converted into hydrogen-based fuels. Most of the increase in gaseous hydrogen use after 2030 is in transport, which accounts for one-quarter of total hydrogen use in 2050 (Figure 5.21). Two-thirds of total low-carbon hydrogen produced in 2050 comes from electrolysis and the remainder from natural gas with CCUS. The electricity required for low-carbon hydrogen production in 2050 is more than current electricity demand in China and the United States combined, and the natural gas required accounts for 25% of natural gas supply. The NZE is the only scenario to see any notable rise in synthetic methane, which is produced from low-carbon hydrogen and CO_2 captured from bioenergy or the air. Synthetic methane supply in 2050 in the NZE is 4 EJ, equivalent to 3% of natural gas supply in 2020, and it is used to reduce emissions from applications where it is not cost effective to shift to the use of biomethane, hydrogen or electricity by 2050.

Figure 5.21 ⊳ Fuel substitution of oil, coal and natural gas by low-carbon gaseous hydrogen and synthetic methane, 2050



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Direct use of hydrogen displaces oil in trucks, as well as coal and gas in power and industry

Biogas

Every part of the world has significant scope to produce biogases – biogas and biomethane – but these have not enjoyed as much recent policy support as hydrogen.[8] Biogas can provide access to clean cooking, but the relatively high upfront cost of biodigesters and the challenges of continuous maintenance of dispersed and small-scale units has slowed its deployment. Biomethane faces challenges of costs and availability and a number of non-economic barriers need to be overcome, including sourcing adequate volumes of feedstocks of consistent quality. Nonetheless, the global potential is significant.

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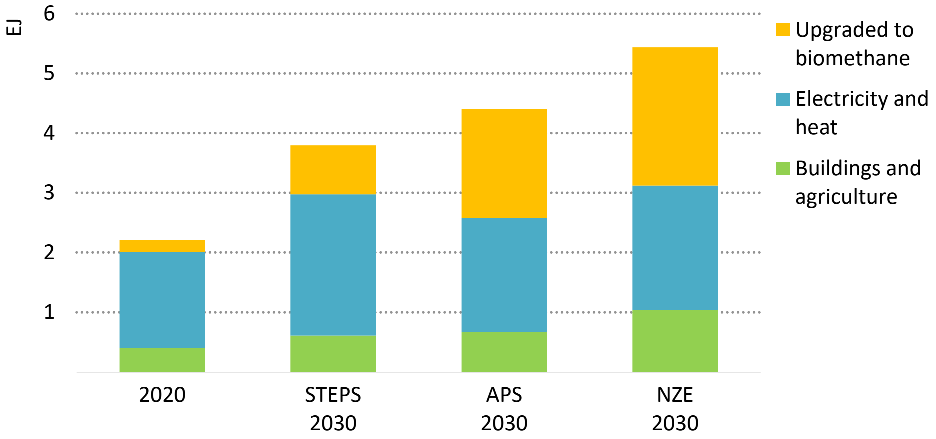
[8] Biogases includes both biogas and biomethane. Biogas is a mixture of methane, CO_2 and small quantities of other gases; biomethane is a near-pure source of methane.

Our bottom-up assessment of sustainable feedstocks indicates that around 25 EJ of biomethane could be developed globally and a further 7 EJ of biomethane could be produced from biomass gasification. With today's high prices for natural gas, around quarter of the global sustainable potential is cost competitive.

Around 70% of biogas developed today is used for power and heat, 20% is for cooking purposes and the other 10% is upgraded to biomethane. More than half of biogas production today takes place in Asia, which also has the largest growth potential given the availability of significant volumes of organic feedstocks such as crop residues and rising levels of municipal solid waste. Well managed biogas projects not only help to reduce emissions but also provide co-benefits such as rural development and local job creation.

Some potential biogas feedstocks would produce methane emissions if left untreated, so converting them to biogas can prevent such emissions.[9] If methane leaks occur during biogas production, however, they would add to overall GHG emissions and presently there is some uncertainty about the extent to which this happens (Bakkaloglu, et al., 2021; Scheutz and Fredenslund, 2019). Many factors affect leakage levels, including the type of facility, whether biogas production is a primary or secondary activity, and whether operators use open or closed storage tanks. The industry needs to anticipate – and should support – more robust methane measurement, reporting and verification, and should move swiftly to put in place plans to detect and repair potential leaks.

Figure 5.22 ⊳ Biogas production by use and scenario in 2020 and 2030



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Biogas production sees strong growth, yet accounts for a small share of gas demand in 2030. In the NZE, biomethane meets 2% of gas demand in 2030

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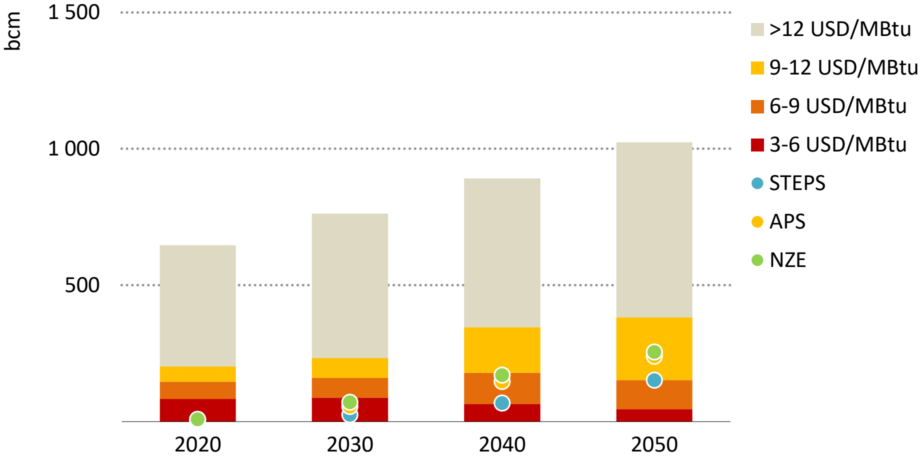
[9] Feedstocks such as animal manure and the organic fraction of municipal solid waste can produce methane emissions. Crop residues which decompose in the presence of oxygen generally do not produce methane emissions.

To 2030, policy support for biogas development in the STEPS, especially in China, Europe, India and United States, sees production nearly double by 2030 (Figure 5.22). Around 20% of biogas production in 2030 is upgraded to biomethane, which is mostly used in industry and transport. In the APS, the consumption of biogas rises to 4 EJ in 2030 as countries with net zero targets expand subsidies and implement more robust blending mandates. Closing the implementation gap between the STEPS and the APS depends on improving the cost competitiveness of biomethane, developing low-carbon gas certification schemes and blending mandates, and ensuring preferential access to gas infrastructure. For biogas, a more concerted push to overcome financing barriers, through low cost loans or grant funding, could help to scale up adoption by low income households (IEA, 2020b). In the NZE, the need to ensure universal access to clean cooking by 2030 gives a boost to biogas in emerging market and developing economies.

After 2030, in the STEPS, biomethane consumption continues to grow (reaching 5 EJ in 2050) and volumes blended into gas grids account for 3% of global gas demand by 2050. In the APS, around 8 EJ of biomethane is consumed globally in 2050 and blending into gas grids accounts for more than 5% of global gas demand. In Europe, the use of biomethane expands to heavy industry where emissions reductions are likely to be particularly challenging. In the NZE, biomethane captures a bigger share of remaining gas demand, with a number of regions seeing blending rates of 20-40%. Yet, just one-quarter of the total sustainable potential is tapped; a significant portion remains too costly to develop, and biogas and biomethane have to compete for support with other forms of bioenergy (Figure 5.23).

Figure 5.23 ▷ Cost ranges for global development potential and volumes of sustainable biomethane by scenario



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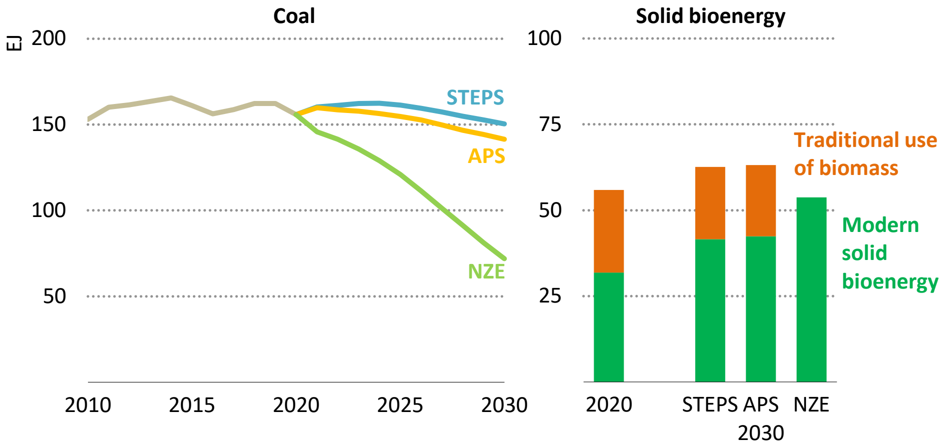
Biomethane use grows strongly in each scenario, reaching 230 bcm by 2050 in the NZE. This is only 5% of global gas demand today and one-quarter of the total potential

5.4 Solid fuels

Figure 5.24 ▷ Coal and solid bioenergy demand by scenario



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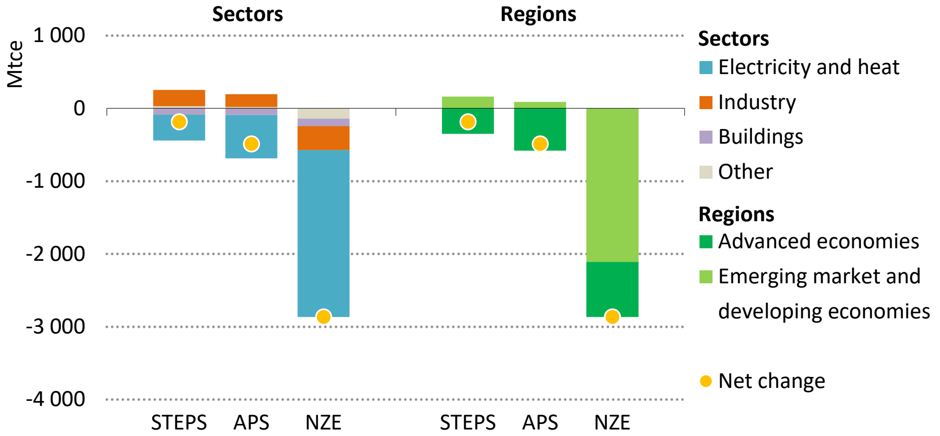
Coal demand declines by 55% to 2030 in the NZE, far below levels in the other scenarios. Modern bioenergy increases in each scenario; traditional uses are phased out in the NZE

Since the 1990s, around 60% of coal consumed has been used to generate electricity and most of the rest was coking coal used in steel production. Coal's role in the power sector is increasingly under pressure from climate policies and the rapid growth in renewables. The key question for the global coal outlook is whether increased demand from developing economies in Asia will offset the pace of decline in advanced economies. In the STEPS, global coal demand peaks in the mid-2020s and falls to 2020 levels in 2030 (Figure 5.24). In the APS, total demand falls by around 10% between 2020 and 2030 as coal is phased out of the power sector in countries with net zero pledges. In the NZE, coal use is hit hard in all markets and falls by 55% globally through to 2030.

Solid bioenergy is the largest single fuel type consumed today after fossil fuels. Around 40% is used in traditional methods for cooking. This use of solid bioenergy drops marginally in the STEPS and APS, and is entirely eliminated in the NZE through the push to achieve universal access to clean cooking by 2030. Modern forms of solid bioenergy increase in all scenarios: some of it is used for electricity generation, some as feedstock to produce liquid and gaseous biofuels, and some is consumed directly in end-use sectors. Growth is contingent on supportive policies as well as sufficient availability of biomass from sustainable sources; there is uncertainty on both accounts.

5.4.1 Coal trends to 2030

Figure 5.25 ⊳ Change in coal demand by scenario between 2020 and 2030



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The 55% drop in coal demand in the NZE stems mainly from large reductions in coal use in power generation around the world; coal use in industry varies across the scenarios

Note: Mtce = million tonnes of coal equivalent.

In the STEPS, coal use rises slightly in the early-2020s, mainly as a result of increased demand in China's industry and power sectors (Figure 5.25). Between 2025 and 2030, total coal demand in China falls and there are large reductions in coal use in North America (a 45% reduction between 2020 and 2030), Europe (40%) and Japan (25%), mainly as a result of lower demand in the power sector. Coal use in industry also falls in these regions, but at a much slower rate. However, coal use expands in many emerging market and developing economies, mainly in Asia, and this offsets some of the reductions.

In the APS, advanced economies see a more rapid phasing out of coal across the power and industry sectors than in the STEPS, with demand declining by around 40% in aggregate to 2030. However, more than 80% of coal demand today comes from countries that do not have net zero pledges or aim only to reduce emissions after 2030, and their demand increases through to 2030. As a result, global coal demand in 2030 is only 6% lower than in the STEPS. Closing the implementation gap between the STEPS and the APS requires stronger policies to promote the deployment of renewables as well as more stringent efficiency and emissions standards to reduce the use of inefficient power plants.

In the NZE, global coal demand falls by around 55% to 2030, with a 65% reduction in the power sector and a 20% decline in industry. Just under 10% of coal use in the power sector is equipped with CCUS in 2030, as is 3% of coal use in industry. Retrofitting coal-fired power plants with CCUS or co-firing low emissions fuels such as bioenergy or ammonia allows emissions to come down without widespread retirement of existing plants.

China is both the consumer and producer of more than half of the world's coal today; it holds the key to future global coal trends. More than 90% of coal demand in China is supplied with domestic production, but imports play an important role in setting prices through arbitrage, especially in coastal regions, and in filling some gaps. There have been major efforts to restructure the coal supply industry in China in recent years (Box 5.3). In the STEPS, domestic coal production moves broadly in line with changes in demand; imports fall slightly to 180 million tonnes of coal equivalent (Mtce) in 2030.

Oil and natural gas imports are set to grow rapidly in China. Plans are underway to convert coal to gas and oil products to reduce import dependence. Coal can be converted to chemicals, natural gas and oil products, but such facilities are capital intensive, require large quantities of water and lead to high levels of CO_2 emissions. These technologies have gained some attention in coal-rich countries outside of China, notably in India, but planned production levels elsewhere are dwarfed by those in China. In the STEPS, around 3.5 EJ (120 Mtce) of coal worldwide is converted to chemicals, liquids and gases in 2030, of which China accounts for 70%. In the APS, the need to reduce emissions sharply in China after 2030 means that any investments in coal conversion plants prior to 2030 are at risk of becoming stranded assets. Equipping facilities with CCUS could limit this risk. Coal conversion plants produce a concentrated stream of CO_2, which would reduce the overall costs of CO_2 capture. But this would still require an additional level of capital expenditure, and facilities may not be suitable for retrofitting with CCUS unless specifically designed with it in mind.

India has seen increasing thermal coal imports in recent years. This reflects domestic production and quality constraints, and significant distances between its coal deposits and demand centres. Imports currently account for around 30% of total coal demand, though there is a strong policy push to reduce imports as much as possible. The coal industry, led by state-owned Coal India Limited, is charged with raising output. But ambitious volumetric targets have run up against major uncertainties about the demand trajectory as well as challenges associated with the low quality of large portions of domestic coal production. In the STEPS, coal demand in India grows by around 30% to 2030, mainly as a result of a 70% increase in demand in industry. Coal use in the power sector increases by around 20% to the mid-2020s but starts to decline slowly as wind and solar photovoltaics (PV) meet the vast majority of electricity demand growth. Domestic coal production expands broadly in line with the increase in demand to 2030 and so it continues to import around 200 Mtce of coal in 2030 (similar to current levels), mainly in the form of coking coal for use in blast furnaces and high quality thermal coal for use in some coastal power plants.

Coal exporters have to contend with a variety of different possible futures. Producers from Colombia and the United States face strong competition from Russian producers in the Atlantic market, while Australian exports often compete with Indonesian exports in the Pacific market. In the STEPS, Australia remains the world's largest exporter of coal but exports fall by 5% to 340 Mtce in 2030 as demand falls in Japan and Korea, which have historically been important markets for Australian coal. Coking coal exports increase slightly and Australia displaces some Indonesian exports of steam coal, which fall by more than 10%

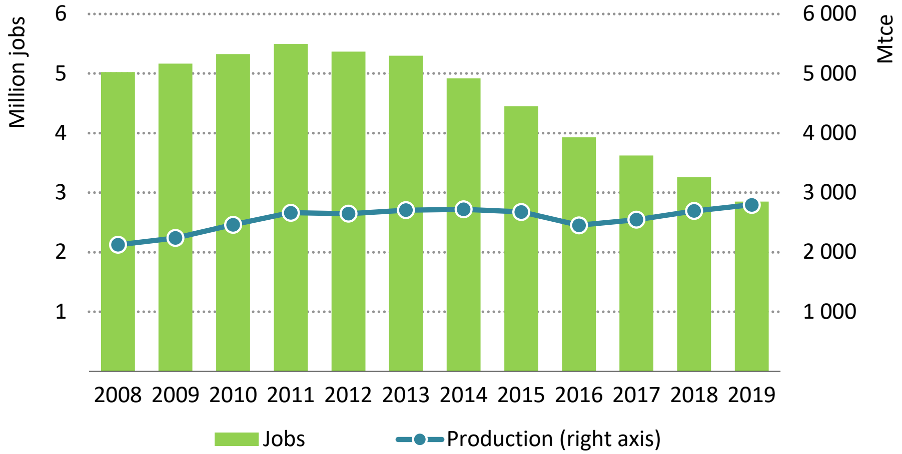
to 2030. Russian exports remain flat through to 2030. In the APS, exports from Russia fall by around 15% to 2030 while Australian exports fall by 25%. In the NZE, global coal trade drops by more than 50% to 2030 and production in all exporting countries falls sharply.

Box 5.3 ⊳ Impacts of coal reforms on production and workers in China

One of the priorities of China's 13th Five-year Plan was to eliminate excess coal production capacity to achieve a better match between demand and supply. As part of this process, more than half of Chinese coal mines – the least productive and unsafe ones – have been closed, which has led to an 80% decline in coal mining deaths and a 10% reduction in average mining costs.

The reforms eliminated 2.5 million coal mining jobs (a near 50% reduction) between 2013 and 2019 without significantly affecting production (Figure 5.26). Production is now more geographically concentrated with 70% of output in 2019 from just three regions (Inner Mongolia, Shanxi and Shaanxi). A number of measures were introduced to support redundant workers in the hardest hit areas, including resettlement, early retirement and the creation of alternative jobs, still, job losses have had a profound impact on local communities. The financial system was also affected by the coal supply reforms as public authorities had to assume the debts and environmental liabilities of closed mines and failed companies.

Figure 5.26 ⊳ Coal mining jobs and production in China, 2008-2019



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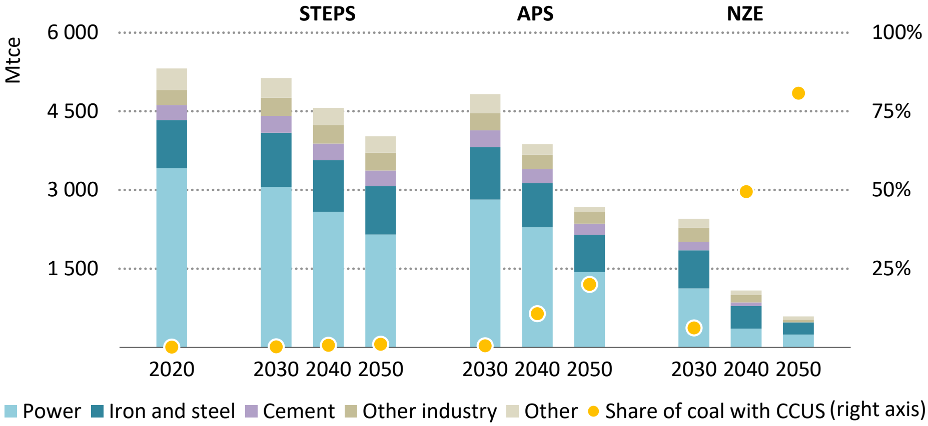
Coal production in China was relatively stable over the decade though with a large decrease in coal jobs reflecting closure of less productive mines

Note: IEA analysis based on NBS (2018).

Coal reforms are not yet complete. Efforts continue to focus coal production in the most productive areas, integrate advanced mining technologies to boost productivity and safety, and foster merger and acquisitions to create companies with more capacity to invest and improve technology. There is also a continuing focus on reducing the environmental impacts of mining, including through reclamation of old mines, improved processing of mine water, and reducing coal waste and methane emissions from operations.

5.4.2 Coal trends after 2030

Figure 5.27 ▷ Global coal demand by sector to 2050



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Coal use in the power sector falls to the largest extent in the STEPS and APS. Coal use is much lower in the NZE across all sectors and 80% of coal use in 2050 is paired with CCUS

In the STEPS, there is a steady reduction in coal demand between 2030 and 2050 to around 4 000 Mtce in 2050 (25% less than in 2020) (Figure 5.27). This stems mostly from a 30% decline in the power sector over this period as wind and solar provide an increasing share of electricity generation, while coal use in industry falls by around 10% between 2030 and 2050. In China, there is a 30-35% reduction in coal use in both its electricity and industry sectors between 2030 and 2050. In India, coal demand peaks in the mid-2030s, though still above 2020 levels in 2050. Coal use in India for electricity generation declines by around 35% between 2030 and 2050, but most of the reduction is offset by increases in the industry sector. China continues to focus on domestic supply and it imports around 100 Mtce in 2050. The import dependency of India increases and imports rise to 240 Mtce in 2050. Russia and Australia both see a small increase in coal exports after 2030, most of which is coking coal.

In the APS, coal demand declines much faster to 2 650 Mtce in 2050 (half of 2020 levels). To achieve net zero pledges, countries in Europe and North America rapidly phase out coal use in industry and electricity and by 2040 almost all coal power plants still in use have been retrofitted. Coal use in China falls by close to 70% between 2030 and 2050 and its share of global coal demand drops to 30% in 2050 (from 55% in 2020). This decline comes about because China electrifies many industrial processes (e.g. by switching iron and steel production to electric arc furnaces) and significantly reduces coal use in the power sector. China has 800 GW of coal-fired power plants remaining in 2050 (down from more than 1 000 GW today), 20% of which are equipped with CCUS. The annual average utilisation of unabated coal-fired power plant capacity in China drops to less than 10% in 2050, down from more than 50% today.

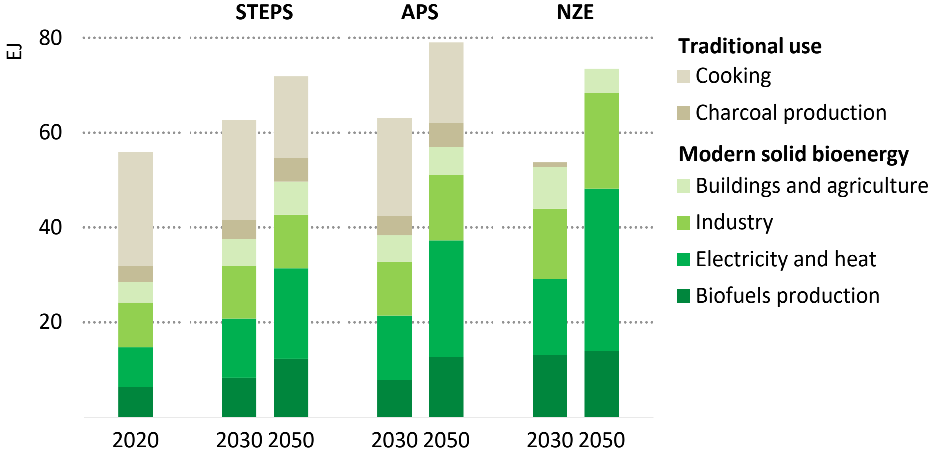
In NZE, global coal use drops by 90% from 2020 to 2050, and around 80% of remaining coal use is in facilities equipped with CCUS by 2050. All new coal industrial facilities built after 2030 are near zero emissions and most facilities built before then are retrofitted to use CCUS or to enable co-firing with bioenergy or hydrogen-based fuels. The majority of remaining coal use in 2050 is in the chemical, iron and steel industries.

5.4.3 Solid bioenergy

Around 55 EJ of solid bioenergy is consumed worldwide today. Almost half is in the form of solid biomass used in traditional methods for cooking and charcoal production, which is a major cause of household air pollution and premature deaths. Modern solid bioenergy, which accounts for the remainder, is used to produce liquid and gaseous biofuels or electricity and heat or is consumed directly in end-use sectors. There is a high degree of uncertainty over the precise levels of the world's sustainable bioenergy supply potential; it has been assessed as being at least 100 EJ (Creutzig et al., 2015) and could be as much as 150-170 EJ (Frank, 2021; Wu, 2019). Sustainable bioenergy could come from energy crops, organic by-products and residues from agriculture, forestry, municipal solid waste and wastewater.

To 2030, the largest difference between the STEPS and APS on the one hand and the NZE on the other is related to the phase-out of the traditional use of solid biomass. In the STEPS and APS, 1.9 billion people still rely on traditional use of biomass for cooking in 2030 and its use declines by only 15% to 2030. In the NZE, universal access to clean cooking is achieved by 2030 and traditional use of biomass is fully phased out (Figure 5.28). There are smaller differences in the rate of increase in modern solid bioenergy over the period to 2030. In the STEPS and the APS, the supply of modern solid bioenergy increases by 10 EJ to 2030. Power is the fastest growing sector in these scenarios, accounting for half of the increase in demand to 2030. In the NZE, modern solid bioenergy is around 12 EJ higher than in the STEPS and APS in 2030, with higher demand as a feedstock for biofuels production, in industry and buildings, and for electricity and heat.

Figure 5.28 ▷ Solid bioenergy supply by scenario



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Modern bioenergy plays a key role in meeting net zero pledges. Traditional uses of biomass continue in the STEPS and APS, but not in the NZE

After 2030, the use of modern solid bioenergy continues to rise steadily in the STEPS while the traditional use of solid biomass falls slightly. In the APS, traditional use of biomass continues at much the same level as in the STEPS, but countries with net zero pledges make greater use of modern solid bioenergy, especially for electricity and heat and in industry. As a result, solid bioenergy demand reaches 80 EJ in 2050, the highest level in any scenario. In the NZE, the supply of modern solid bioenergy expands to 75 EJ in 2050, of which around 45% comes from forestry by-products and residues, 25% from energy crops, and the remainder from agricultural residues and municipal solid waste.

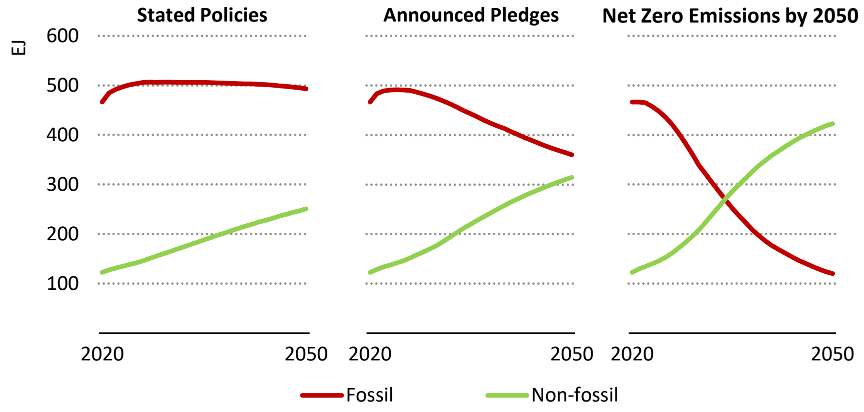
Secure transitions

...a clean break?

SUMMARY

- By design, the scenarios in this *Outlook* describe smooth, orderly processes of change. In practice, however, energy transitions can be volatile and disjointed affairs, contested by a diverse cast of stakeholders with competing interests, and there is an ever-present risk of mismatches between energy supply and demand.
- Energy security risks can materialise in various parts of the energy system, over different time frames, and they become more or less pronounced in different scenarios. In the Announced Pledges Scenario (APS), countries undertake clean energy transitions at different speeds, raising the risk of tensions in global trade and constraints on technology transfer. In the Net Zero Emissions by 2050 Scenario (NZE), the sharp drop in coal, gas and oil investment could destabilise regions and local communities dependent on income from these fuels if it is not carefully managed.

Figure 6.1 ▷ Energy supply to 2050 by scenario



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In clean energy transitions, managing the decline in fossil fuel investments in parallel with a scale up in low-carbon technologies is essential for energy security

- In all scenarios, rising shares of wind and solar photovoltaics bring fundamental changes in how power systems operate, requiring policy makers to mobilise investment in all sources of flexibility in order to maintain electricity security. Digital technologies and smart networks play a central role in facilitating more reliable, interconnected and distributed power systems, integrating some 240 million rooftop solar PV systems and 1.6 billion electric cars by 2050 in the NZE, although they also open the door to increased cybersecurity risks. Investing in energy efficiency remains

a cornerstone in all scenarios because it acts as a brake on peak demand and mitigates the need for additional infrastructure.

- As transitions accelerate, reliable operation of the energy system rests on an increasingly complex set of interactions between electricity, fuels and storage. In the NZE, 40% of energy consumed worldwide by 2050 has undergone at least two conversion steps on the way to consumers. By contrast, hardly any of the energy reaching consumers today has been converted more than once. Markets and regulation need to recognise the new interlinkages that arise among sectors as a result of these interactions, in particular those between electricity and various types of gas. Maintaining a gas delivery system brings energy security benefits, but clear interim and long-term sector-specific targets are essential to guide decisions on fuel delivery infrastructure as countries move towards a net zero emissions future.
- Increasing physical risks from a changing climate have to be factored in alongside mitigation priorities. Energy infrastructure around the world already faces risks from cyclones, coastal floods and inadequate water supplies. These risks are set to increase over time, highlighting the urgent need for policy action to enhance the resilience of energy systems in the face of climate change.
- Trade patterns, producer policies and geopolitical considerations continue to be of crucial importance to energy security even as the world shifts to an electrified, renewables-rich energy system. Higher or more volatile prices for critical minerals could slow global progress towards a clean energy future or make it more costly. Recent price rallies for critical minerals illustrate the point: all other things being equal, they will increase the costs of solar modules, wind turbines, electric vehicle batteries and power lines by 5-15%. If maintained, the price rises add USD 700 billion to the investment needed for these technologies in the current decade in the NZE.
- New vulnerabilities could also arise from rapidly expanding trade in hydrogen and critical minerals. The combined share of hydrogen-rich fuels and critical minerals in international energy-related trade doubles from 13% today to 25% in the APS and to over 80% in the NZE by 2050. Hydrogen trade increases to around USD 100 billion by 2050 in the APS, higher than the value of current international coal trade, and to USD 300 billion in the NZE.
- Uncertainty about the trajectory for future oil and gas demand increases the potential for mismatches between demand and investment, while trade flows are dominated by a relatively small number of countries, and most major oil and gas producers remain inadequately prepared for transitions. Oil and gas supplies in the APS and NZE become increasingly concentrated in a small number of low cost producer countries, with OPEC members and Russia accounting for 61% of global oil production in 2050 in the NZE, up from 47% today. At the same time, fossil fuel import dependency rises in Asia in each of the three scenarios, and flows between the Middle East and Asia account for an increasingly large share of global oil and gas trade.

6.1 Introduction

By design, the scenarios in this *World Energy Outlook* describe smooth, orderly processes of change. Energy markets, technologies and policies adapt to one another and evolve in a mutually consistent direction. Prices follow a smooth trajectory, international energy trade is assumed to be free of geopolitical friction, and the scaling up of clean energy technologies occurs in parallel with a gradual decline in investment in unabated fossil fuels. In practice, energy transitions can be volatile and disjointed affairs, characterised by competing interests, market imbalances and stop-go policies. The uneven distribution of gains and losses from transitions could deepen existing fault lines in the global political economy, or create new ones. Change could have sharp edges, and bring energy security risks with it.

As the commodity price shocks in 2021 showed, mismatches between supply and demand are the root cause of energy security risks. Such mismatches may be the consequence of short-term factors like unseasonal weather or interruptions to supply; they may also have deeper underlying causes like a lack of appropriate investment signals, inadequate market design or bottlenecks arising from a lack of infrastructure. The basic goal of energy security remains ensuring uninterrupted availability of energy sources at an affordable price, and the best strategies for achieving this remain diversity of energy sources, robust and consistent policy and well-functioning markets. Moving towards net zero emissions adds potential new energy security hazards, and traditional risks do not disappear, though they may evolve.

This chapter explores the security risks that arise across our scenarios. It starts with electricity security, which comes to the fore in transitions as reliance grows on electricity generated from solar and wind, bringing with it an ever-growing need for various forms of flexibility to maintain reliable system operation, facilitated by digital technologies. It then considers how transitions affect other parts of the energy system, including existing infrastructure – in particular for natural gas – as well as the new links that arise through more complex chains of energy conversions. We also explore growing concern with the risks that arise for energy infrastructure from a changing climate.

Further on, we consider changing patterns of global energy trade, investment and geopolitics. Critical minerals such as lithium, cobalt, copper or rare earth elements are essential to make tomorrow's clean energy system work and vulnerabilities in these areas could make global progress towards a clean energy future slower or more costly. Meanwhile, risks related to oil and gas supply do not disappear as the world moves towards net zero emissions. If the supply side moves away from oil or gas before the world's consumers do, then the world could face periods of market tightness and volatility. Alternatively, if companies misread the speed of change and over-invest, then these assets risk under-performing or becoming stranded. There are also potential hazards for markets as supply starts to concentrate in the lowest cost producers whose economies are most vulnerable to the process of change.

6.2 Energy security in increasingly integrated systems

Today's energy sector in essence is a series of interlinked but largely independent delivery channels for fuels, heat and electricity to consumers. Between the extraction of primary energy and the final consumers stands a set of distinct sectors that transform fuels, largely to produce electricity and heat, and deliver the resultant products to users. A typical household today might use liquid fuels for transportation, gas or solid fuels for heating and cooking, and electricity for most other residential needs.

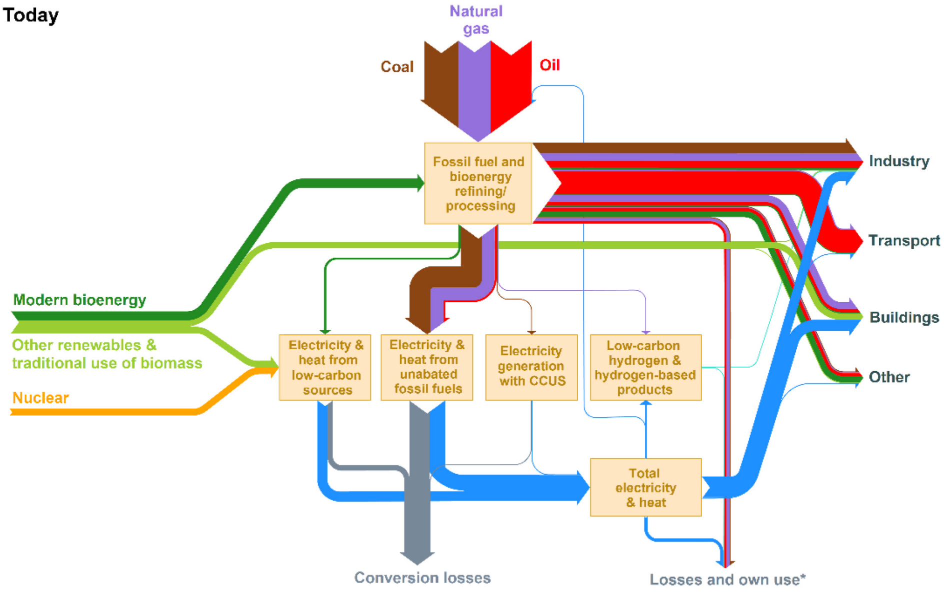
The energy systems that need to emerge during clean energy transitions are very different from those that exist today (Figure 6.2). In the energy system of the future, consumption narrows toward electricity, which is increasingly used by households and industries to meet demand for heat and transportation. The rest of the energy system becomes considerably more complex and integrated, but this process is mostly hidden from consumers, who continue to have their energy service needs met through familiar infrastructure.

Liquids and gases continue to play an important role, especially as new transformations of energy increase in importance, for example those that turn electricity into fuels or store it. There is an increasingly large premium on flexibility as a core component of system reliability, enabled by an array of digital technologies, as well as new interdependencies among the end-use sectors. An essentially uni-directional energy system, where energy flows from extraction and generation through networks to consumers, is replaced by a much more intricate web of interactions. Integration may also occur in parallel with the progressive decentralisation of energy, with the number of participants expanding and the unit size of energy technologies shrinking. Secure energy transitions require an understanding of the multi-directional flows of energy across this complex system, ensuring that change in one area is complemented where necessary by change elsewhere.

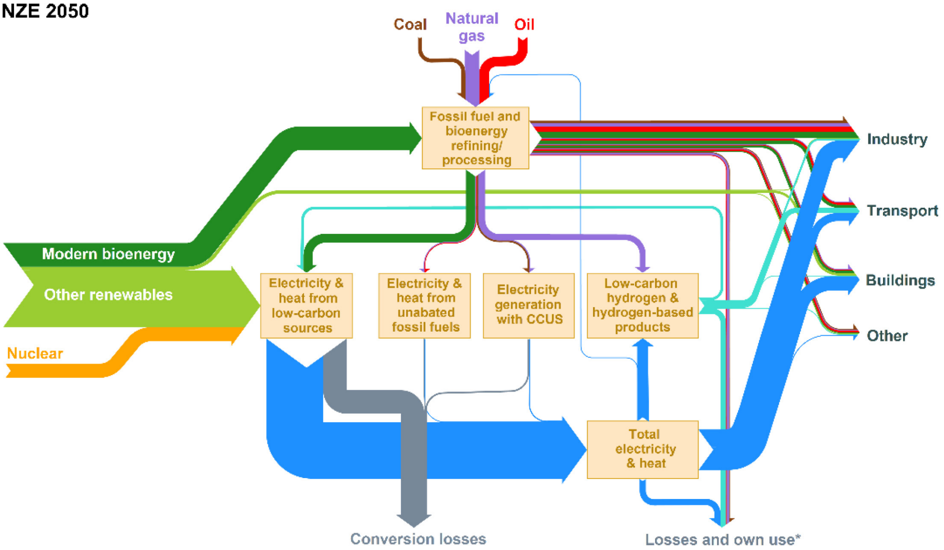
Efficient use of energy remains a cornerstone of any approach to energy security, and becomes even more important in clean energy transitions. End-user energy efficiency acts as a brake on peak demand, e.g. for cooling, and therefore mitigates the need for additional infrastructure upstream. A clean energy transition also calls for waste heat, bioenergy or other potential losses or by-products from economic activity to be put to productive use: action on this front can further dampen demand, but is likely to create integration challenges as supply chains become more closely interlinked. Meanwhile, more robust tools are required to manage flows of electricity into and out of multiple sectors as electricity accounts for an increasing share of consumption.

Figure 6.2 ▻ Global energy system today and in 2050 in the Net Zero Emissions by 2050 Scenario

Today



NZE 2050



Transformative changes in the energy system occur on the path to net zero emissions

* Includes transformation losses and fuel consumed in refining/processing, generation lost or consumed in the process of electricity production, and transmission and distribution losses.

Note: Traditional use of biomass in the buildings sector today is completely phased out by 2050 in the NZE and replaced by modern fuels.

6.2.1 Electricity security

Clean energy transitions reshape the electricity sector and the nature of electricity security. The central challenge in the years ahead will be to continuously match electricity demand and supply at all times as the share of variable sources like wind and solar photovoltaics (PV) grows. But there are plenty of other challenges. The impacts of climate change and cybersecurity threats both pose increasing risks to electricity security, and they will become more important still as electricity meets more of the world's transport, heating and industrial needs. Ensuring continued electricity security means institutionalising responsibilities and incentives; identifying, managing and reducing key areas of risk; monitoring progress; and making preparations for handling disruptions (IEA, 2020a).

Variable renewable electricity

Strong growth in wind and solar PV across all scenarios and regions drives a shift from systems that are based predominantly on dispatchable generation to ones with abundant variable renewable electricity (VRE) and this require changes in the operation of electricity systems. To understand those changes, the IEA has developed a framework which characterises the different phases of renewable integration (IEA, 2018). The framework captures the evolving challenges[1] as countries transition to higher shares of VRE, and helps to prioritise actions that ensure continuity of supply. The framework has been applied to China, India, European Union and United States for the Stated Policies Scenario (STEPS) and the APS.

At present, China, India and United States are categorised as Phase 2, meaning that they are drawing on existing flexibility in their systems, with minimal changes to system operation. The European Union collectively has progressed to Phase 3, which requires additional investment in existing flexibility measures, including battery storage and the application of more advanced changes to system operations.

By 2030, India, China and United States progress to Phase 3 in the STEPS, and the European Union enters Phase 4 (Figure 6.3). In the APS, each region progresses to Phase 4 by 2030. VRE accounts for most or all generation for increasing periods of time in Phase 4, requiring sophisticated system management and frequent interventions by system operators to balance electricity demand and supply and to support power quality requirements. Ultimately, system operators will need additional tools to ensure grid reliability and stability in light of the increased deployment of VRE and could draw on the experience of countries such as Denmark and Ireland which have already reached Phase 4.

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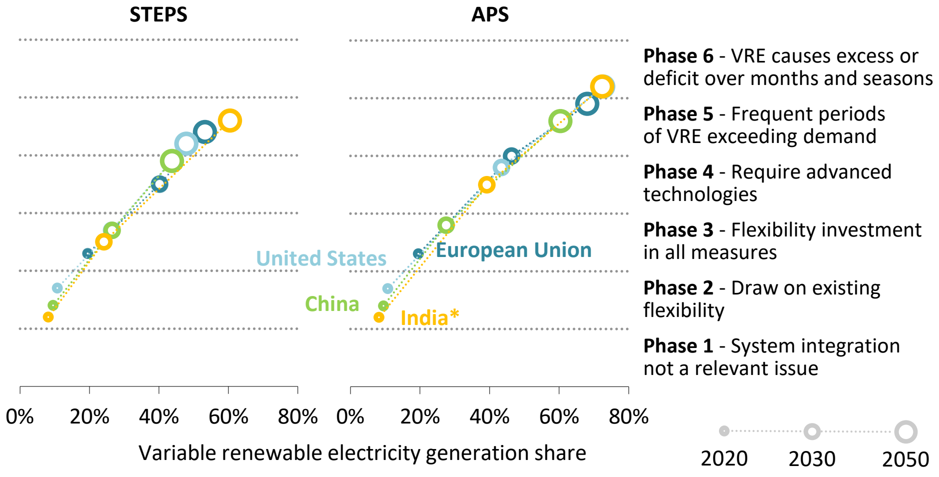
[1] Challenges depend on the unique characteristics of each country and region, including the size of its power system, the share and mix of variable renewables (solar PV and wind), the mix of other technologies and resources, operational practices and standards, and market and regulatory design.

Figure 6.3 ⊳ Phases of renewables integration by scenario



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Accelerated transitions bring new challenges related to the integration of variable renewables in power systems in all scenarios, and early action is needed to address them

Note: *values for India in the APS graph are based on the Sustainable Development Scenario.

By 2050, China, India, European Union and United States all reach Phases 5 or 6 in their energy transitions in the APS, and also in the STEPS (except for China, which comes close). Phases 5 and 6 have not yet been reached by any country. These phases are characterised by longer periods (from days to seasons) of mismatch between VRE generation and demand. During those periods, if VRE generation is inadequate to meet demand it has to be supplemented by sufficient dispatchable sources of generation, withdrawals from long-term storage systems, or measures to manage demand.

Maintaining security of electricity supply is a multidimensional task. Among other things, system operators need to ensure sufficient generation capacity to meet peak demand, provision of hour-to-hour and sub-hourly flexibility to accommodate changes in VRE generation or demand, and the ability to maintain power system stability[2] within very short time frames. As clean energy transitions progress, system planners will need to ensure that there is a seamless shift from traditional sources of flexibility such as coal and gas plants towards low emissions sources of dispatchable generation, even if they are utilised infrequently. Long-duration storage, including in the form of heat, could also play a part by moving excess VRE generation across weeks or months to times of shortage – a function currently performed by short- and long-term gas storage in many countries.

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[2] The ability to maintain a state of operational equilibrium and to withstand disturbances.

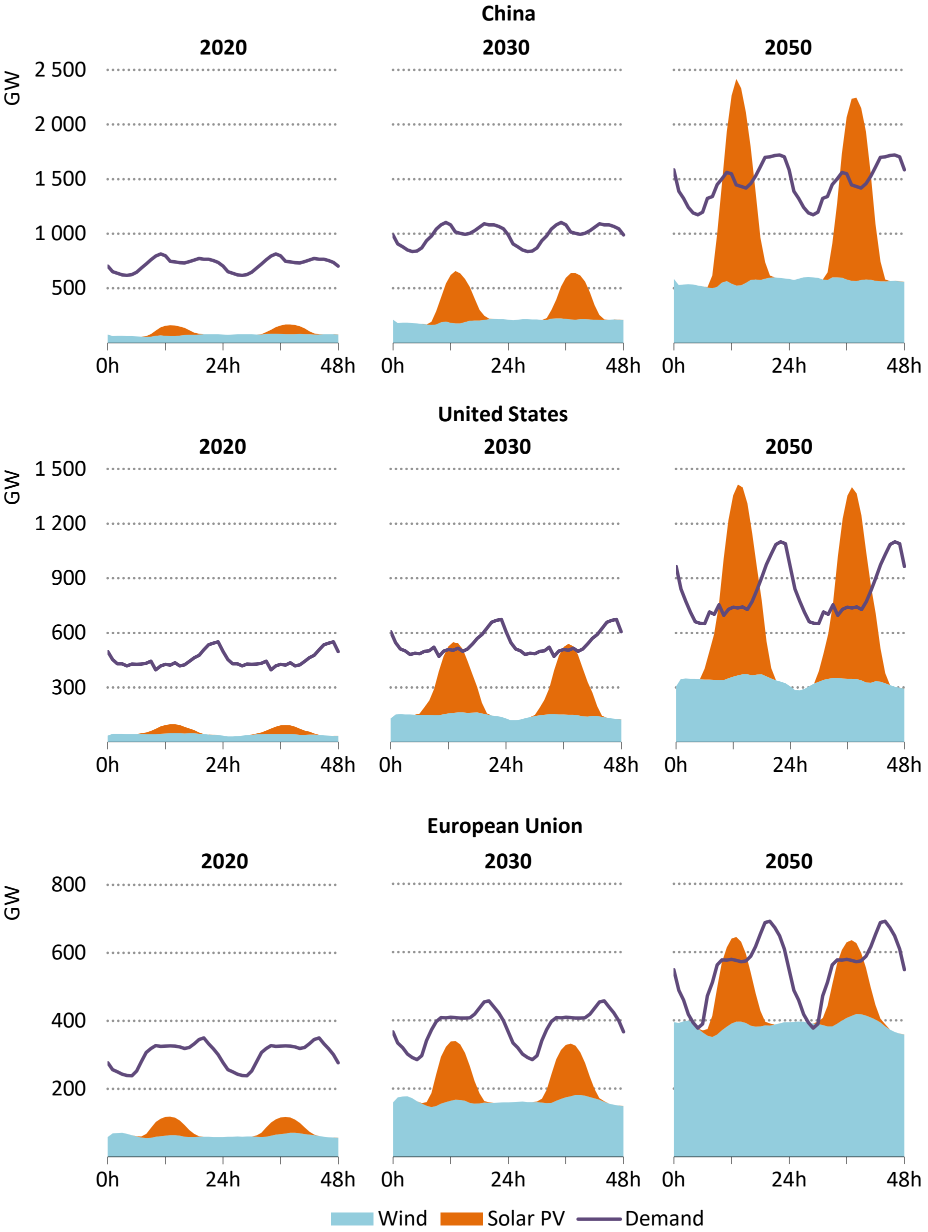
The weather dependent nature of wind and solar PV generation also requires short-term contingency plans to deal with sudden or unanticipated changes to generation patterns. Larger shares of VRE may increase the need for contracted reserve volumes and balancing markets that are closer to real-time. The volume of required reserves depends in part on demand and generation forecasting capabilities, and improvements in those capabilities could offset some of the increases that are required. The sources of reserve and balancing provisions could also evolve, for example with solar PV and wind providing downward reserve by decreasing their output, battery storage acting to smooth generation patterns, and efficiency and demand response measures to flatten peaks.

Electricity systems need to adhere to a set of physical boundaries and standards in order to maintain system stability and operate safely and reliably. Those boundaries include frequency and voltage constraints (IEA, 2021a). Traditionally, thermal generators have been able to play a central part in ensuring that systems can withstand and recover from changes in frequency because of their inherent inertia as rotating generators. With the share of non-rotating generation increasing, alternative solutions are likely to be required to ensure that frequency is maintained within safe ranges. Possible solutions include synchronous condensers (which can increase inertia levels), battery storage and demand response measures (which can respond quickly to changes in frequency). Nuclear power can also support system stability in those regions where it remains part of the generation mix. Where they exist, high voltage direct current interconnectors can provide additional support to respond to changes in inertia levels.

The task of meeting electricity service needs at all times will require very responsive sources of generation and demand that can be operated in an integrated way, as indicated when simulating the behaviour of selected power systems on an hourly basis during sample days in the first quarter of the year (Figure 6.4). For example, batteries could absorb high solar PV generation in the middle of the day and discharge it when demand picks up during the evening. Market frameworks and regulations that incentivise investment in flexibility and encourage consumers to shift demand at times of high or low VRE generation are essential to manage volatility and reduce the risks of supply-demand imbalances (see Chapter 4). System planners will also need to ensure contingency for instances when VRE output during the day is low combined with batteries in a low state of charge. Hydrogen and ammonia, carbon capture, utilisation and storage (CCUS)-fitted dispatchable generation and load-following nuclear power technologies are well placed to fill this gap.

Transmission and distribution networks have a vital part to play in enabling electricity systems to make full use of flexibility resources. Interconnections between regions are important in this context. They enable more efficient use to be made of flexibility resources by making them more widely available. They also provide for smoother VRE generation by providing countries/regions access to wind and solar PV resources across larger geographical areas with more diverse weather and wind patterns. Advanced economies typically enjoy high electricity interconnection levels, but some emerging market and developing economies have national systems that are very poorly interconnected with neighbouring ones and consequently have much higher flexibility needs relative to average demand.

Figure 6.4 ⊳ **Wind and solar PV generation and electricity demand for sample days in Q1 by region in the Announced Pledges Scenario**



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Clean energy transitions will reshape the profiles of electricity systems as rising shares of wind and solar PV bring fundamental changes in how systems operate

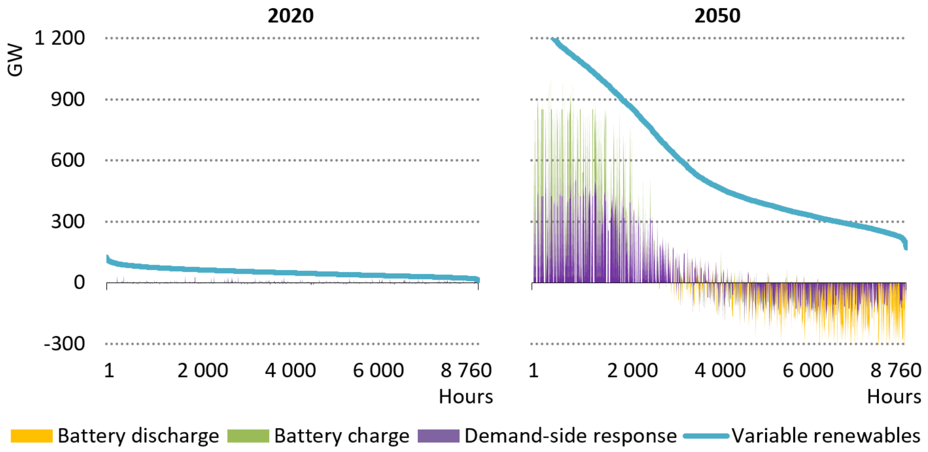
Notes: GW = gigawatts. Q1 = the first quarter of the year.

Digitalisation and two-way flows

Advances in digital technologies, declining costs and ubiquitous connectivity are accelerating the digital transformation of electricity systems. Spending on digital grid technologies reached USD 40 billion in 2019, making up around 15% of total network investment. Most of the investment in digital grids goes to smart meters and grid automation equipment (IEA, 2020b).

Digitalisation – combining data, analytics and connectivity – has tremendous potential to make energy systems more efficient, flexible and resilient in each of our scenarios. In the NZE, more than 70 000 terawatt-hours (TWh) are generated globally in 2050, which is almost three-times the current level, and the share of electricity in total final consumption reaches 50%. Digitalised and user-centric technologies, distribution networks and business models all facilitate a more interconnected and distributed electricity system, integrating some 240 million rooftop solar PV systems and 1.6 billion electric cars, and these digitalised electricity systems feature multi-directional flows of data and electricity. In the United States, for example, meeting net zero targets require a huge scale up in battery storage and demand-side response, which by 2050 are used to absorb a significant portion of the peak hourly output from VRE, while also playing a crucial balancing role when output is low (Figure 6.5).

Figure 6.5 ⊳ Duration curves of variable renewables, storage and demand-side response in the United States in the Announced Pledges Scenario



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Managing the rise in variable renewables requires the deployment of demand response and storage capabilities, enabling larger two-way flows between supply and demand

In this more interconnected power system, digital technologies such as machine learning could vastly improve the accuracy and temporal and spatial resolution of electricity supply and demand forecasts, increasing the resilience and flexibility of electricity systems as they integrate higher shares of variable renewables. Smart meters, machine learning and connectivity together could unlock the full potential of demand-side flexibility ranging from connected appliances and electric vehicles (EVs) to large industrial users. The number of connected products is doubling every five to ten years, and is projected to reach 100 billion in the next decade (4E EDNA, 2021).

There are additional ways in which digital technologies could help. Distributed ledger technologies such as blockchain have the potential to provide secure payment systems to facilitate electricity trading and EV charging, and to help integrate distributed energy resources, including rooftop solar PV. Sensors, machine learning and drones could help to detect outages, restore service and conduct preventative maintenance of electricity transmission and distribution networks to improve efficiency, extend asset lifetimes and reduce downtime. China Southern Power Grid, for example, has already used these technologies to reduce the number of interruptions by 7.5% annually between 2015 and 2020, while boosting maintenance staff productivity by 8% per year (ADB, 2021).

Unless well managed, however, the roll-out of digital clean energy technologies could involve unforeseen costs, reliability issues or behavioural change burdens. For example, digitally enabled demand response services could override consumer preferences for heating or cooling set points: this recently happened to some consumers with smart thermostats during a heatwave in Texas (Morrison, 2021). The most imminent concern is the increased risk to cybersecurity (Box 6.1). A successful cyberattack could lead to the loss of control over devices and processes in electricity systems, causing physical damage and widespread service disruption to consumers and businesses.

Box 6.1 ▷ Managing digital security risks and enhancing cyber resilience

Digitalisation offers many benefits for consumers and electricity systems, but increased connectivity and automation throughout the system raise cybersecurity risks (IEA, 2017). For example, connected devices and energy assets such as EVs and smart meters could be compromised by attackers to launch a co-ordinated cyberattack causing large demand fluctuations and imbalances across a distribution grid, ultimately triggering an outage (Soltan, Mittal and Poor, 2018; Acharya, Dvorkin and Karri, 2020). Emerging digital technologies such as machine learning could help improve threat detection and thwart attacks, but equally could boost the capability of attackers. Attackers are also increasingly using cryptocurrencies to collect ransomware payments.

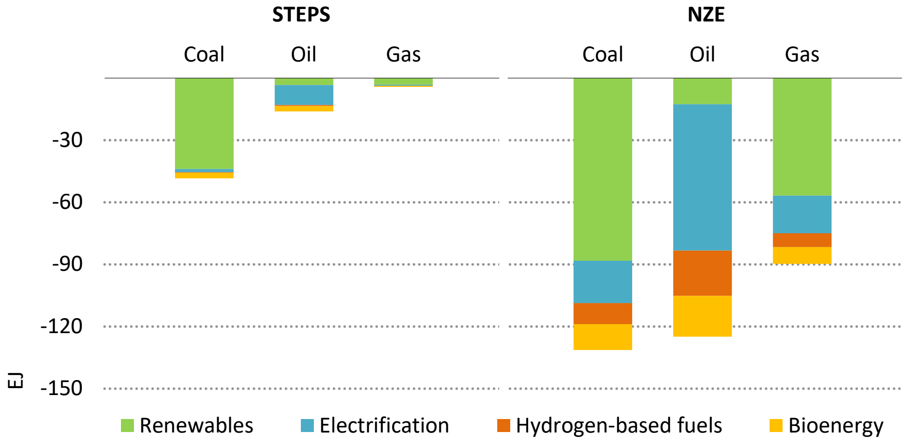
While the full prevention of cyberattacks is not possible, electricity systems have to become more cyber resilient. This means putting in place ever more robust network system and security management protocols, together with cybersecurity technologies and tools, in order to detect, withstand, adapt to and rapidly recover from incidents and attacks, while preserving the continuity of critical infrastructure operations. Policy makers, regulators, utilities and equipment providers have key roles to play in ensuring the cyber resilience of the entire electricity value chain. The recent IEA report, *Enhancing Cyber Resilience of Electricity Systems*, offers guidance to policy makers, electric utilities and other stakeholders on how policies and actions could enhance the cyber resilience of electricity systems (IEA, 2021b).

Digitalisation also raises concerns for consumer data privacy and security. Smart grids and demand response technologies rely on vast quantities of consumer-specific, real-time electricity usage data, raising important questions around data privacy and ownership. Policy makers need to balance privacy concerns with the operational needs of utilities and the wide-ranging potential of the digital transformation of electricity.

6.2.2 New demands on fuel infrastructure

In the NZE, half of final energy consumption by 2050 is provided by electricity, of which two-thirds is generated from variable renewable sources such as solar PV and wind, placing enormous demands on power systems. The other half of final energy consumption consists of liquids, gases and solid fuels of various sorts, almost all of which are low or zero carbon. By 2050, renewables and electricity displace 270 exajoules (EJ) of fossil fuels in the NZE, or around 60% of current demand, while bioenergy, hydrogen and hydrogen-based fuels displace a further 80 EJ (Figure 6.6).

Figure 6.6 ▷ Reductions in coal, oil and natural gas use from switching to electricity and low-carbon energy by scenario, 2020-2050



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Renewables, electrification and low-carbon fuels not only replace fossil fuels for various end-uses but could also make use of repurposed fossil fuel delivery systems

These transformations have profound implications for the delivery systems used around the world for solid, liquid and gaseous fuels. Some parts of the infrastructure may be adapted or repurposed over time for low emissions fuels. Refineries could be retooled to process bioenergy feedstocks, for example, and coal-fired power plants to co-fire ammonia or bioenergy. Hydrogen or biomethane could be blended into natural gas pipelines and renewables used in existing heat delivery networks.

Other parts of today's delivery infrastructure are still operating in 2050 in each of the three scenarios to provide energy services in sectors not directly amenable to electrification. There is growing interest in employing gas storage for hydrogen, for example, although the suitability of different types of storage sites varies: some depleted gas reservoirs and aquifers contain contaminants that could react with hydrogen. Salt caverns have particular potential, but if all the existing 15 EJ of gas storage capacity was to be used entirely for hydrogen, it would hold 10-25% of the total low-carbon hydrogen produced in the NZE in 2050.

There is a need for some new infrastructure, especially in some emerging market and developing economies. In particular this is needed to enable hydrogen to be used for transport purposes and to supply new industrial facilities with hydrogen. New infrastructure is also needed to transport CO_2. The NZE sees almost 8 gigatonnes (Gt) CO_2 captured each year by 2050 from remaining fossil fuel use and from negative emissions technologies. Although none of it would be likely to be moved over long distances, substantial pipeline infrastructure would be needed nonetheless. Where new gas infrastructure is developed, it will be important to ensure that it is compatible with climate and other sustainable development goals, especially in emerging market and developing economies facing significant energy demand growth in the years ahead.

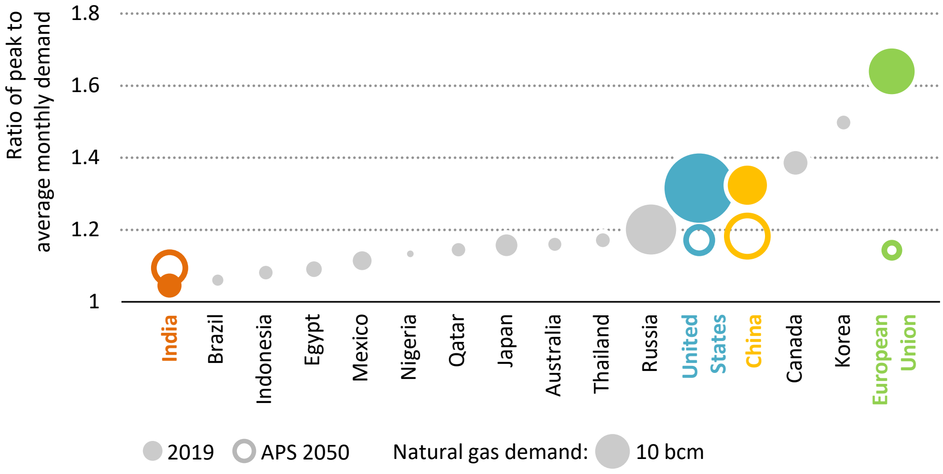
Deciding which parts of the current fossil-based infrastructure have a future in clean energy transitions is no easy task. In the case of natural gas, clear sector-specific targets, both interim and long term, could help to calibrate market player expectations about the investments required in midstream infrastructure, and to ensure that all such investments are matched where possible to low emissions supply options such as biomethane and hydrogen as well as to storage plans. Markets, regulations and certification will need to be adapted. It will be especially important to ensure that regulations are updated to recognise and value flexibility, and that long-term network planning is consistent with developments in other energy markets and delivery systems, particularly electricity.

Natural gas infrastructure and energy security

In many countries, natural gas infrastructure is a crucial asset for security of supply. In many parts of the northern hemisphere, where gas provides a large share of seasonal heating, infrastructure is designed to accommodate large peaks in demand: operators plan their networks around the capacity to supply the entire customer base during extremely cold winters (with a 1 in 20 year probability), even when a certain quantity of infrastructure is not available. Infrastructure is also crucial for the supply of gas to thermal power plants in order to provide flexible, dispatchable capacity to meet daily, weekly and seasonal peaks in electricity demand.

A suite of flexibility and other options to safeguard energy security are available across the natural gas supply chain. These options include spare production and import/export capacity. They also include gas storage, which worldwide currently amounts to over 400 billion cubic metres (bcm), equivalent to around 10% of annual global natural gas demand. There is also substantial gas deliverability in the form of linepack (the volume of gas stored inside gas pipelines): where grids are well developed, as in northwest Europe and the United States, this is an essential tool to meet short-term peaks in demand (SGI, 2020). Liquefied natural gas (LNG) import terminals play an especially important role in several countries in Asia: Japan, for example, has 285 bcm per year of LNG import capacity, equivalent to more than twice its annual demand, although its LNG storage capacity is far smaller.

Figure 6.7 ▻ Ratio of peak to average monthly natural gas demand in selected regions



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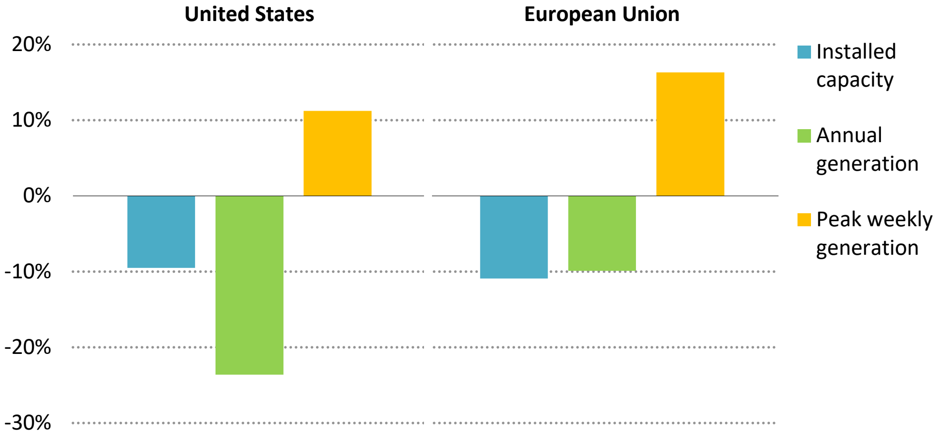
Natural gas demand has a strong seasonal element in many countries today. This weakens in countries with net zero pledges and does not become significantly stronger elsewhere.

In clean energy transitions, changes in the use of gas affects infrastructure in different ways. In advanced economies with net zero targets, the use of natural gas for space heating drops 30% by 2030 in the APS and is virtually eliminated by 2050. In the European Union, winter gas demand is around 90% lower in 2050 than today, and the seasonal variation falls from almost double the annual average to less than 20% more than the annual average (Figure 6.7). By 2050, only 12% of space heating demand in the EU is met by gaseous fuels, compared to nearly 45% today. This gradually weakens the case for maintaining long-duration gas storage.

Natural gas use in the power sector follows a different trajectory, and maintaining infrastructure, including storage to manage short-term peaks, remains crucial to ensure electricity security. This is true in all three scenarios over the next decade, but especially in cases where variable wind and solar PV power are added to the generation mix at a rapid pace, and where electricity takes a growing share of space heating demand. The experience of Texas in February 2021 illustrates the challenge: an extreme cold snap and a surge in electricity demand drove up demand for gas in both the residential and power sectors, and demand could not be met due to the combined failure of delivery pipelines and power plants (IEA, 2021c). Such vulnerabilities may become more pronounced: in the APS, installed capacity and annual generation from natural gas in both the United States and European Union are lower by 10-25% in 2030, whereas the peak level of weekly gas-fired power generation actually increases by 10-15% relative to 2020, reflecting a much more substantial role for natural gas in balancing variable renewables (Figure 6.8).

Figure 6.8 ▷ Changes in key gas-based electricity indicators in selected regions in the Announced Pledges Scenario, 2020-2030



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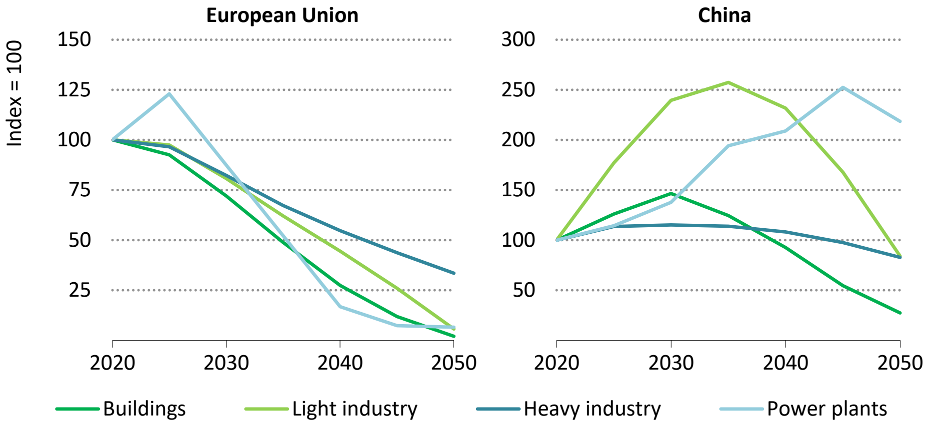
The call on natural gas to ensure electricity security becomes more important in the APS to 2030, even as overall demand and installed capacity decline

In emerging market and developing economies, gas-fired power generation in the NZE peaks in the late 2020s at a level over 40% higher than in 2020, but falls sharply thereafter, and provides a mere 1% of total power generation by 2050. Gas-fired capacity on the other hand increases strongly throughout the *Outlook* period, nearly doubling on 2020 levels by 2050. The result is that gas power plants, which also run on hydrogen and biogas, operate at 10% utilisation, compared to an average of 40% today.

After 2030, the flexibility services required of gas infrastructure are eroded by end-use efficiency gains and by the increasing use in the power sector of battery storage and demand-side response. However, there are still significant benefits in maintaining a parallel gas delivery system as a hedge against slow growth in building retrofit rates or power system flexibility (where many of the options remain in the early stages of technological maturity). Moreover, there is a longer term case for injecting biomethane into gas networks or repurposing them to transport hydrogen. In the NZE, biomethane and hydrogen make up nearly 30% of total grid-based gases by 2050. This would bring gains in terms of clean energy, but it would also create new security challenges that would need to be overcome: the different technical characteristics of hydrogen or the dispersed supply of biomethane would have to be managed within gas transportation infrastructure, and the use of different gases could lead to reduced flexibility if gas networks were to become less interconnected.

Assessing the viability of gas infrastructure in the transition to a net zero emissions economy also involves other complex trade-offs. Households, businesses and industries connected to the same gas grid may switch to other fuels at variable speeds (Figure 6.9), raising questions about how to sequence the decommissioning of assets while minimising adverse impacts on supply security or overall system flexibility (in addition to equity and affordability concerns). The record high spot gas prices in Asia and Europe in 2021 were a further indication of the potential for a mismatch between short-term signals to maintain or even expand gas infrastructure and the longer term case for reducing unabated gas consumption.

Figure 6.9 ▷ Changes in natural gas demand in selected sectors in the European Union and China in the Announced Pledges Scenario, 2020-2050



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Infrastructure operators face the dilemma of accommodating uncertainty about natural gas demand in sectors with different infrastructure needs

Unless the transition is well managed, remaining consumers of natural gas would be at risk of supply shortages or volatility during the process of phasing out supply lines or delivery infrastructure. They would also be likely to incur higher costs: in the European Union, for example, the combined value of existing gas transmission and distribution networks is estimated at around USD 120 billion, and around USD 8 billion is spent each year maintaining it. On average, network charges comprise around 20% of household gas bills (EC, 2020), but this could rise if fewer consumers were to be charged higher fees to maintain infrastructure which was utilised less frequently. Innovative financial tools or regulatory interventions such as capacity markets may be required to maintain the option value of gas infrastructure, avoiding asset stranding even as total delivered volumes decline.

In the case of China, natural gas demand in the APS increases in all sectors in the decade ahead, and spending on gas networks rises by 50% compared to 2020, reaching over USD 8 billion by 2030. Gas use in buildings and light industry sees strong growth: these are sectors made up of dispersed, less energy-intensive customers, and therefore require high upfront investment in distribution networks across a wide geographic area. Demand in these sectors peaks in the 2030s, and falls below current levels by 2050. This implies either a relatively short capital recovery period for the investment in networks (meaning higher fixed charges for households and businesses) or higher tariffs on remaining large-scale gas consumers, such as heavy industry and power plants, for whom the drop in demand begins in the 2040s. Incorporating an eventual shift to non-fossil gases such as hydrogen or biomethane could help future-proof such infrastructure investments.

In emerging market and developing economies, a further challenge in a world moving towards net zero is to secure financing for new gas infrastructure where the longer term use case may be uncertain. Around 70% of debt financing for large-scale gas infrastructure projects in emerging market and developing economies (excluding China) comes from entities domiciled in countries with net zero emissions targets (IEA, 2021d). Such lenders may struggle to value the security of supply benefits, or to predict how they will be valued in future years by governments and regulators. Such benefits should ideally be assessed on the basis of whether any given gas infrastructure helps to displace more polluting fuels, aids the integration of renewables, supports the uptake of low emissions gases or provides access to modern energy services.

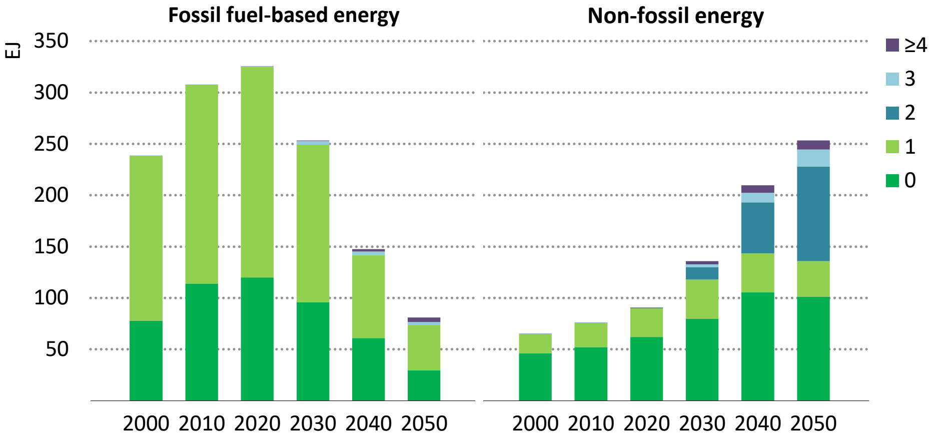
6.2.3 Additional energy conversions

As clean energy transitions progress, the resources entering the energy system require more conversions before they reach end-users. This trend leads to more integration of energy networks, and it has implications for energy security.

Conversions are needed when energy is in forms that are not what end-users want or need, as for example when coal needs to be converted into electricity, or when electricity is supplied at times or in places that are not matched with demand and must be converted until it can be used. These conversions involve changes to the chemical composition of fuel molecules or changes in the form of the energy, e.g. from electrical to chemical, kinetic, potential or thermal. A wide variety of technologies exist that can be used to convert energy until it is needed, e.g. pumped storage hydro, electrochemical batteries and fly wheels.

Around one-quarter of primary energy today is used in the same form as it is supplied. This includes nearly 40% (around 120 EJ) of all natural gas and coal produced in 2020, most of which was burned to produce heat for the world's factories and buildings or used directly as raw materials for chemicals. Most of the rest of the natural gas and coal that was produced (around 180 EJ) was converted to electricity and heat. Most other primary energy requires one conversion step in order to provide useful energy services: over the course of 2020, for example, 160 EJ of liquid fuels underwent refining processes to be produced from crude oil; 4 EJ were converted from bioenergy inputs; and less than 1 EJ was converted from coal and natural gas.

Figure 6.10 ▷ Total final consumption by the number of conversion steps from primary energy supply in the Net Zero Emissions by 2050 Scenario



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Multiple conversions are needed to store electricity and heat and to produce low emissions fuels

Notes: Figure shows energy consumption by end-users. Conversions are counted based on the IEA method of constructing energy balances. Fossil energy combined with CCUS is allocated to fossil fuel-based energy. Carbon-containing hydrogen-based fuels are not derived from fossil carbon in the NZE.

By 2050, around 40% of energy consumed globally in the NZE undergoes at least two conversion steps, whereas today almost none does (Figure 6.10). The peak year for direct use of fossil fuels without conversion in the NZE is 2020 and, while there is a rise in the direct use of electricity from renewable sources, this is outpaced in terms of growth rates by new energy products, notably low-carbon hydrogen and hydrogen-based fuels such as ammonia and synthetic liquids. Energy products in 2050 that have undergone one conversion step include biofuels, district heat, nuclear power and low-carbon hydrogen from solar PV and wind, and natural gas with CCUS. Energy products in 2050 that have undergone two conversion steps include biomethane and low-carbon ammonia from fossil fuels with CCUS, while those involving three conversion steps include electricity from biomass, nuclear or fossil fuels with CCUS that have passed through one round trip in a battery or other storage device. In the NZE, some pathways emerge that involve even more conversions, such as the production of hydrogen or ammonia from electricity that has been converted and reconverted during storage.

The additional energy conversions featured in the NZE are an integral feature of a net zero energy system. They are a core means of providing the flexibility that systems need in order to match the supply of variable renewables and demand for electricity at least cost. The need – and the capacity – for flexibility in the NZE is considerable. Utility-scale battery storage reaches 3 000 GW, and there are millions of behind-the-meter potential enablers of flexibility, in the form of smart meters, EVs and charging infrastructure. However, each conversion step is associated with energy losses. Some of these are modest, such as the 5-20% of energy lost during two conversions in a lithium-ion battery. Some are more substantial, such as the roughly 50% loss experienced during the conversion of electricity to hydrogen-based synthetic liquids. In addition to conversion losses, electricity distribution losses alone more than double to reach 17 EJ by 2050 in the NZE as a result of electrification and demand growth. One major role for energy efficiency in the NZE is to offset conversion losses and thereby avoid a possible weakening of energy security (and increase in prices) resulting from the use of more primary energy per unit of delivered energy service.

Each additional conversion step requires equipment to be installed to facilitate it. In many cases, new market designs are also required to link various energy value chains. The web of interdependencies in the energy system, which is already extensive, becomes much denser. This raises important questions about how to judge whether such a system will be able to absorb disturbances or withstand shocks. Given that a network is only as strong as its weakest link, it is necessary for regulators to consider how much redundancy and storage capacity each part of the system requires. In some cases, additional conversions might provide "release valves" in times of congestion – for example if two-way flows are possible – but in others they might present risks of failure that could cascade back up their supply chains. As electricity comes to provide power for a bigger share of consumption, the potential impacts on consumers of a disruption to electricity supply also grow bigger and spread to new sectors. Such disruptions could arise externally from low probability weather events or cyberattacks, or internally from equipment failure.

Ensuring the security of supply chains with multiple conversions requires integrated system planning, and an appropriate balance of responsibility between public and private actors. The task for governments is to provide a policy architecture that enables investment choices that reflect the system value of assets during peak demand periods, without prescribing the technological pathway. There is a long history of energy governance and regulation directed to this end, but the rising complexity of energy systems calls for an ever-expanding suite of tools. Government efforts to ensure minimum safeguards may need to intensify, and may need to include action to set operating standards and support a level playing field for market participants, while staying at the forefront of developments in digital technology.

6.2.4 Building climate resilient infrastructure

The increasing physical risks from climate change are exemplified by a growing catalogue of recent extreme weather events such as heatwaves, periods of exceptional cold snaps, wildfires, droughts, cyclones and floods. Some of these events have disrupted the operation of critical infrastructure, including power plants, networks and offshore energy facilities. In the United States, for example, in August 2021 Hurricane Ida damaged long-distance power transmission lines and shut down many oil refining and petrochemical facilities in Louisiana and disrupted 95% of oil and gas production facilities in the Gulf of Mexico that went offline temporarily. Exceptionally cold weather in Texas took a heavy toll on the its natural gas and power supply in February 2021, while severe heat waves in California have strained the power system and caused load shedding. Such extreme weather events have also been responsible for significant power outages in Argentina and Australia over the past few years (IEA, 2021e). These events demonstrate that existing infrastructure can be far from resilient, and also expose consumers to energy price spikes.

One particular aspect of these severe weather events is related to the rising intensity of cyclones[3], which can cause serious damage to energy supply infrastructure, particularly in coastal areas. According to our geospatial analysis, around a quarter of the world's electricity networks are estimated to be at high risk of destructive cyclone winds.[4] The share is notably higher in North America and Australia, where over 40% of distribution networks are exposed to a high risk of damaging cyclone winds. LNG plants and refineries, a large part of which are located in coastal areas, are also heavily exposed to risks from violent storm surges, with some 50% and over 35% of today's facilities situated in very high risk areas respectively (Figure 6.11). The growth of offshore wind means that it is also increasingly facing hostile meteorological conditions requiring new turbine designs together with improved operational practices to deal with cyclone-force winds.

Climate change is increasing the frequency and intensity of short-term extreme weather events, and it is also causing more systemic shifts in general climatic conditions. For example, the global mean sea level is currently rising at almost double the pace observed during the 20th century. Rising sea levels, coupled with high tides and storm surges, have the potential to cause flooding affecting energy supply infrastructure in low lying coastal areas. They may also limit the availability of appropriate locations for new energy infrastructure. We have assessed the exposure of various energy supply assets to risks from coastal flooding, combining coastal flood risk datasets with the geographical co-ordinates of each asset. Around 13% of the world's coastal thermal power plants (200 GW of dispatchable generation

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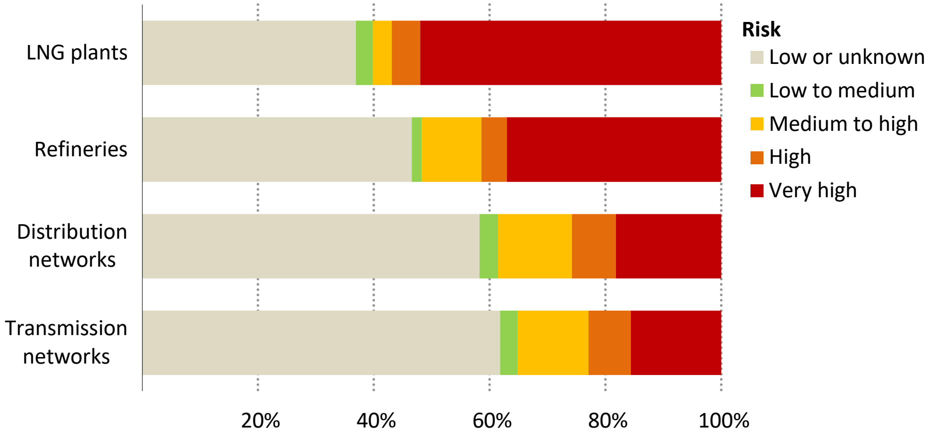
[3] A tropical cyclone is a generic term used to describe a rotating, organised system of clouds and thunderstorms that originates over tropical or subtropical waters. Once a tropical cyclone reaches maximum sustained winds of 119 km/hr or higher, it is then classified as a hurricane, typhoon, or tropical cyclone, depending upon where the storm originates in the world (NOAA, 2021).

[4] The risk exposure analyses in Section 6.2.4 were built on the geospatial analyses in *Electricity Security 2021: Climate Resilience* (IEA, 2021e).

fleets), 25% of onshore LNG plants and 10% of coastal refining facilities already are at risk of experiencing severe coastal floods.[5] These levels of risk will increase as sea levels rise.

Figure 6.11 ▷ Share of energy infrastructure capacity at risk of destructive cyclones, 2020



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A large portion of electricity networks and fuel supply infrastructure is exposed to high risk from destructive cyclones

Notes: Risk levels are classified based on the probability of wind speed exceeding 80 kilometres per hour (1 in 50, 100, 250, 500 and 1 000 years). Those within 60 degrees latitude north and south are included in the assessment. Source: IEA analysis based on UNDRR (2015) and Arderne et al. (2020).

Changing climate patterns can also put stress on infrastructure that depends on hydrological conditions or adequate water supplies. A shift in precipitation patterns could have significant impacts on hydropower generation and lead to a major drop in capacity utilisation. Water shortages could also reduce output from thermal power plants using freshwater cooling, especially in regions where freshwater flows are dependent on seasonal rainfall. Around one-third of existing thermal and nuclear power plants using freshwater cooling are located in high water stress areas[6], and this share is set to increase over time as the changing climate turns today's low risk sites into high risk ones. Based on the projected water availability under the IPCC RCP 4.5 scenario (an intermediate emissions scenario), over 40% of freshwater-cooled thermal and nuclear fleets are projected to be in high risk areas by 2040.

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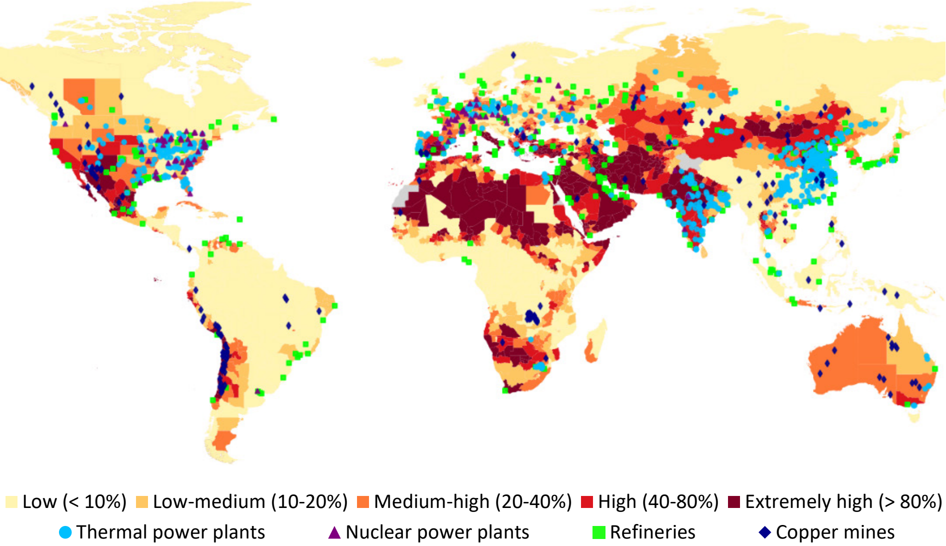
[5] Based on the return period of 100 years and the sea level rise of 0.72 metres. The anticipated sea level rises in the representative concentration pathway (RCP) scenarios by the Intergovernmental Panel on Climate Change range from 0.59 metres in the RCP 2.6 (a low emissions scenario) to 0.72 metres in the RCP 4.5 (an intermediate emissions scenario) and to 1.1 metres in the RCP 8.5 (a high emissions scenario) by the end of the century (IPCC, 2019).

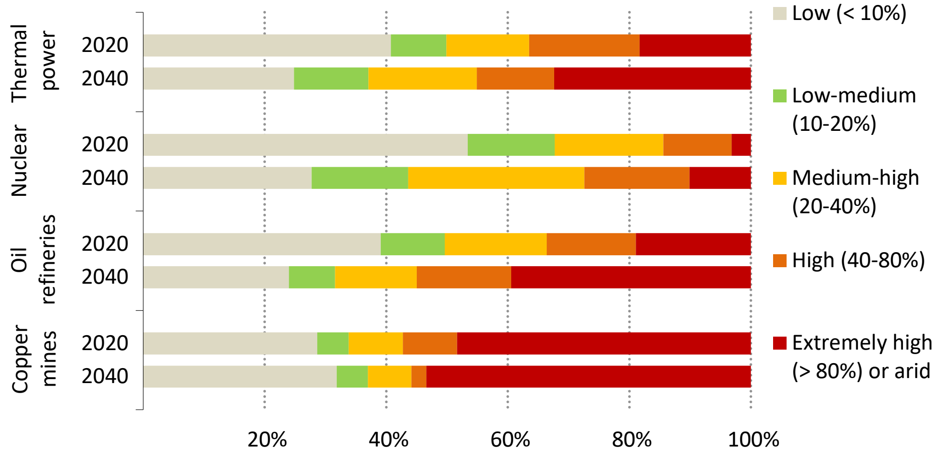
[6] For power plants where type of cooling systems information is not available, we estimated the cooling type based on the distance from the coast. Overall, around 40% of existing thermal (oil, gas and coal) and nuclear plants are estimated to use freshwater cooling.

Figure 6.12 ⊳ Water stress exposure of freshwater-cooled thermal and nuclear power plants, refineries and copper mines

Location of selected energy-related infrastructure and water stress levels, 2020



Share of capacity by water stress level



The share of energy supply infrastructure in high water stress areas is set to increase as changing precipitation affects water availability in many regions

Notes: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies. In the bottom chart, power plants include those estimated to use freshwater cooling and the share of copper mines is based on production.

Source: IEA analysis based on WRI Aqueduct 3.0 (2019) and S&P Global (2021).

The risks from water stress are not confined to electricity infrastructure. Other types of energy infrastructure are also dependent on water availability: these range from upstream oil and gas facilities that employ water flooding to increase production through to biofuel facilities that use irrigation and to refining operations that depend on water for operations. Around one-third of global refining capacity is currently located in high water stress areas, and this share is set to increase to 55% by 2040. Decreasing availability of water already affects refinery throughput in countries such as India, Iran, Iraq and Venezuela. Stable supplies of copper, a critical material used widely in clean energy technologies, are also dependent on the availability of high quality water resources. In 2019, severe drought affected mining operations in Chile, the world's largest copper producing region. Droughts have also had similar effects in Australia, Zambia and elsewhere. Over half of today's global copper production is concentrated in areas of high water stress, and there is no indication that this will change significantly in the future (Figure 6.12).

The increase in the frequency and intensity of natural disasters and extreme weather events highlights the urgent need for action by policy makers to enhance the resilience of energy systems to climate change. IEA analysis shows that around 25% of IEA member and association countries do not address climate resilience in their energy and climate plans and that most countries have scope to improve the level of their policy preparedness. The IEA Climate Resilience Policy Indicator is an initial effort to assess the level of climate hazard that a country is facing against its policy preparedness (IEA, 2021f). It is intended to help prepare the ground for climate risks to be incorporated into planning and regulation for future infrastructure development.

As a first step, policy makers should mandate assessments of existing infrastructure to determine vulnerabilities and adaptation priorities, focusing on areas that are critical to overall system operation and particularly susceptible to climate impacts. This would help with the identification of cost-effective resilience measures. Effective implementation of these measures could be supported by introducing appropriate incentives to attract investment. At the same time recovery plans need to be developed in preparation for possible disruptions. As ever, an integrated, systems-level approach will be essential to develop a resilient energy system that takes account of impacts of short-term weather events as well as long-term changes in climate patterns.

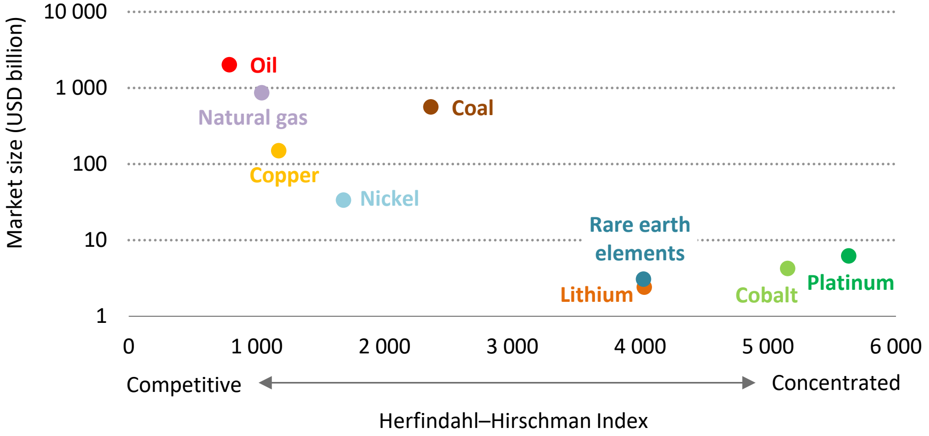
6.3 International aspects of energy security

In a world where fossil fuels represent the majority of energy supply, concerns about energy geopolitics understandably focus on major oil and gas resource holders, and on the international trade patterns that have formed around them. However, clean energy transitions bring about a major shift in the primary energy mix away from carbon-intensive fuels towards low-carbon energy sources. Although the share of fossil fuels in the mix has remained at around 80% over several decades, it declines to around 50% by 2050 in the APS and just over 20% in the NZE. This raises major questions about the nature and relevance of geopolitical concerns about energy.

Lower demand for oil and gas ultimately reduces some traditional energy security hazards, but they do not all disappear. Mismatches between the pace of demand and supply reductions could bring periods of price volatility even when demand is declining, while a relatively small number of exporters with low cost and low emissions resources tends to dominate oil and gas supplies in climate-driven scenarios, which means that physical disruptions, trade disputes or other geopolitical events in major producing countries could have a significant impact on global supply and prices. Moreover, the chances of social and political turmoil in some supplier countries could increase as lower global demand for oil and gas puts huge financial strains on those that rely heavily on hydrocarbon revenues.

Clean energy technologies such as solar PV and wind are sometimes seen as being immune from geopolitics. The hazards are undoubtedly lower, but the supply chains for these technologies are nonetheless subject to various risks arising from trade in equipment and raw materials. Critical minerals are of particular concern because many clean energy technologies are mineral intensive and the supply of minerals is concentrated in a smaller number of countries than is the case for oil and natural gas. A combination of smaller market size and higher levels of geographical concentration provides reasons for vigilance, especially as demand for critical minerals rises (Figure 6.13).

Figure 6.13 ▷ Market size and level of geographical concentration for selected commodities, 2019



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Markets for critical minerals are much smaller and more concentrated than those for traditional hydrocarbon resources

Notes: The Herfindahl–Hirschman Index (HHI) is a measure of market concentration. It is calculated by squaring the market share of each producing country and summing the resulting numbers. An HHI of less than 1 500 is considered to be a competitive market, and an HHI of 2 500 or higher to be a highly concentrated market. The HHI for critical minerals is calculated based on mining operations. The values for refining operations are generally higher than those for mining.

Although most renewables are produced very close to where they are consumed, the rise of hydrogen could bring a new form of low-carbon energy into the global trading system. Every country has the potential to produce hydrogen, but differences in resource endowments and quality create incentives for trade (hydrogen could be exported in various forms, including ammonia or other hydrogen-rich fuels). The emergence of inter-regional hydrogen trade would add another international aspect to energy security in a decarbonising world.

Trade patterns, producer country policies and geopolitical considerations remain crucial even in an electrified, renewables-rich energy system, with different sets of players coming into play. In this section, we look at two areas – critical minerals and oil and gas – that face different prospects in energy transitions. We then move on to explore shifting patterns of international energy trade and their implications for energy security.

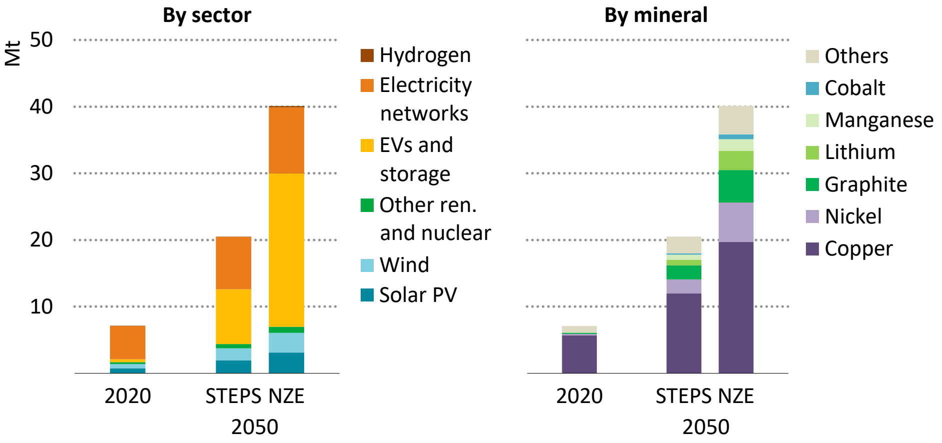
6.3.1 Critical minerals

The rapid deployment of low-carbon technologies as part of clean energy transitions implies a significant increase in demand for critical minerals. Solar PV plants, wind farms and EVs generally require more mineral resources to build than their fossil fuel-based counterparts. For example, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% since 2010 as the share of renewables has risen (IEA, 2021g).

In the STEPS, overall requirements for critical minerals for clean energy technologies nearly triple between today and 2050. In the NZE, achieving net zero emissions globally by 2050 means record levels of clean energy deployment, and requires up to six-times more mineral inputs in 2050 than today. Mineral demand for EVs and battery storage increases by well over 50-times by 2050, while the expansion of electricity networks leads to a doubling of demand for copper for power lines in the period to 2050. Lithium sees the fastest growth among the key minerals, with demand up over 100-times its current level through to 2050, while cobalt, nickel and graphite also see rapid demand growth. Copper demand registers the largest absolute growth, rising by around 14 million tonnes (Mt) by 2050, expanding the size of the global copper market by 60% in the period to 2050 (Figure 6.14). As a result, in the NZE, clean energy technologies emerge as the fastest growing segment of demand for most minerals, evolving from a niche consumer to a leading source of demand.

The prospect of a rapid increase in demand for critical minerals – well above anything seen previously in most cases – raises questions about the availability and reliability of supply. Current supply and investment plans are geared towards a world of gradual and insufficient action on climate change, raising the risks of supply lagging behind projected demand in climate-driven scenarios. The challenges are compounded by long lead times for the development of new projects, declining resource quality, growing scrutiny of environmental and social performance and a lack of geographical diversity in extraction and processing operations. For example, the world's top-three producing nations control well over three-quarters of global output for lithium, cobalt and rare earth elements. The level of concentration is even higher for processing operations, with China having a strong presence across the board.

Figure 6.14 ▷ Mineral requirements for clean energy technologies by scenario



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In the NZE, mineral requirements for clean energy technologies increase by up to six-times by 2050, with particularly high growth for EV-related materials

Notes: Mt = million tonnes; ren. = renewables. Includes most of the minerals used in various clean energy technologies, but does not include steel and aluminium. (See IEA, 2021g for a full list of minerals assessed.)

The impacts of a shortage of mineral supplies would be different from those of an oil supply shortage. There would be no immediate effect on consumers driving EVs or using solar-generated electricity. Higher and volatile prices or supply disruptions nevertheless would be damaging because they could make global progress towards a clean energy future slower and/or more costly. Tightening supplies could prompt various industry and consumer responses such as demand reduction, material substitution, increased recycling or increased investment in supply. For example, a massive growth in battery deployment in the NZE could put substantial strain on mineral supplies and prices, triggering efforts such as switching to alternative battery chemistries that require less material inputs (Box 6.2). However, these responses have often come with non-negligible time lags or considerable price volatility. Sustained periods of higher critical mineral prices could push up costs of clean energy technologies and delay energy transitions, although they could help to bring new supply to the market or spur the development of alternatives.

Box 6.2 ▹ EV battery chemistries: Exploring constrained nickel and cobalt supply cases in the Net Zero Emissions by 2050 Scenario

Periods of high cobalt prices in the late-2010s led many EV manufacturers to look for ways to reduce cobalt use and develop batteries with higher energy density. As a result, EV batteries shifted away from cobalt-rich chemistries in recent years towards chemistries that use more nickel. We assume that this trend will continue, with NCA+ and NMC811[7] accounting for 65% of the light-duty EV market in 2050 compared with 35% in 2020.[8] In the NZE, a stronger focus on innovation and international co-operation leads to an accelerated market penetration of lithium-metal anode all-solid-state batteries. These have several advantages over the current generation of lithium-ion batteries, including higher energy density and improved operational safety.

Nonetheless, the mineral implications of a major increase in clean energy deployment in the NZE are huge. EV battery deployment in the NZE is over three-times higher than in the STEPS over the next three decades, and this could put a major strain on mineral supplies and prices, in particular for battery-grade nickel and cobalt. Demand for these two minerals in clean energy technologies is set to rise by nearly 40-times between 2020 and 2050 in the NZE. This could result in price volatility and market tightening and thus delay the achievement of the EV deployment targets set by many countries. Therefore it is conceivable that the NZE could see more EV batteries with lower critical mineral needs (such as lithium iron phosphate [LFP] and manganese-rich chemistries such as lithium nickel manganese oxide [LNMO] batteries), even if these might be sub-optimal from a performance perspective. Following the price rallies of nickel manganese cobalt oxide (NMC) precursors in the first-half of 2021, several companies have already dissented from the consensus view that nickel-rich NMC cathode chemistries will dominate future EV chemistries.

We have explored the potential impacts of an accelerated shift away from high nickel and cobalt chemistries in the *constrained mineral supply case* (Figure 6.15). In the constrained case, the share of NCA+ and NMC811 battery chemistries falls to 40% compared with 65% in the base case, and this is offset by an equivalent increase in the share of LFP and manganese-rich chemistries. As a result, there is lower demand for cobalt (-35%) and nickel (-23%) in 2050 than in the base case. This underscores the important role of technology choices and innovation in shaping future mineral requirements and alleviating potential supply strains. It also underscores the potential

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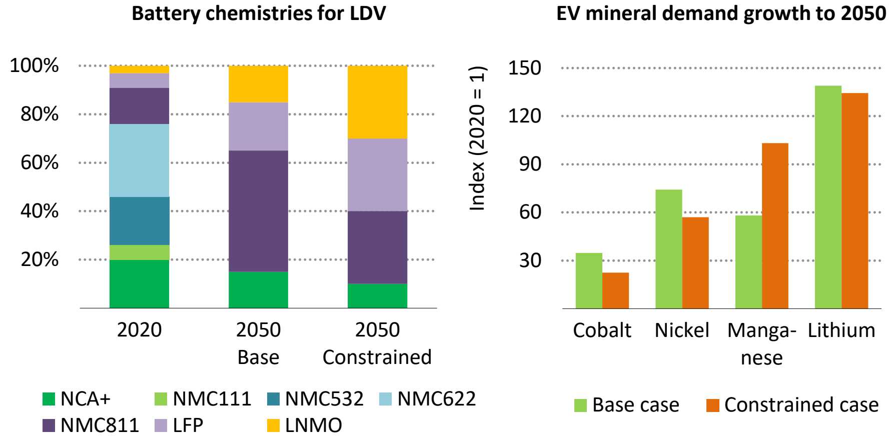
[7] NCA+ = A nickel-rich (and lower cobalt) variant of nickel cobalt aluminium oxide (NCA) chemistry. NMC811 = nickel manganese cobalt oxide chemistry with 80% nickel, 10% manganese and 10% cobalt.

[8] The base case assumptions for battery chemistry shares have been updated to reflect recent company announcements and market developments since the publication of the *Role of Critical Minerals in Clean Energy Transitions: World Energy Outlook Special Report* (IEA, 2021g). In particular, the base case now assumes a higher share of lithium iron phosphate for passenger cars (27% in 2030) due to its increasing use in China and entry-level models from automakers worldwide.

trade-offs involved. For example, manganese demand in the constrained case is 80% higher while lithium demand decreases only slightly.

Figure 6.15 ⊳ Battery chemistries and EV-related mineral demand growth in the Net Zero Emissions by 2050 Scenario in the base and constrained mineral supply cases



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A switch away from high nickel chemistries towards LFP and LNMO chemistries in the constrained case shows complex trade-offs between mineral demand and prices

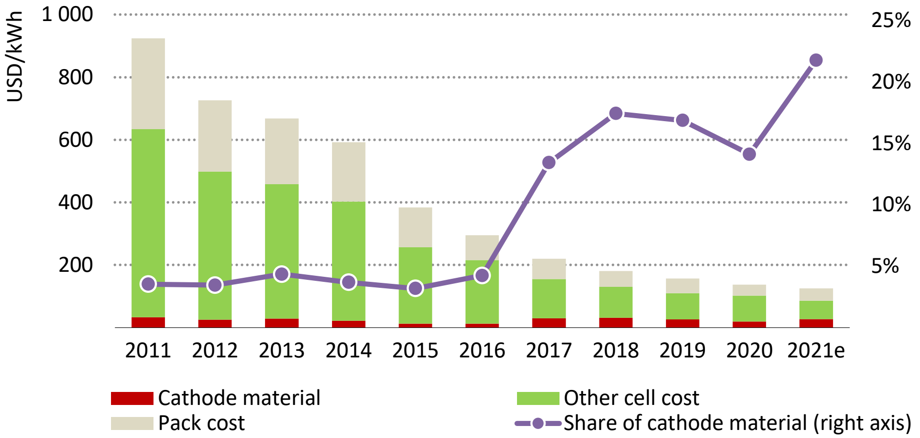
Notes: LDV = light-duty vehicles including passenger light-duty vehicles, light commercial vehicles and two/three-wheelers. LFP = lithium iron phosphate; LNMO = lithium nickel manganese oxide.

Impacts of mineral price increases on clean energy investment

Over the past decade, technology learning and economies of scale have pushed down the costs of key energy technologies significantly. For example, the cost of lithium-ion batteries has fallen by 90% since 2010. However, this also means that raw material costs now loom larger in total cost of clean energy technologies. The share of cathode materials in battery costs has continued to increase over the past decade, and has recently reached over 20% (Figure 6.16). When anode materials and other raw materials are added in, the share of raw materials rises further to some 50-70% (IEA, 2021g). Higher or more volatile mineral prices therefore could have a significant effect on the costs of transforming our energy systems.

The impact of raw material prices on total costs varies by technology, but the commodity price rallies in the first-half of 2021 illustrate the possible strains if these trends are sustained over the longer term. A combination of surging commodity prices, shipping costs and supply chain bottlenecks has put pressure on industry margins and equipment prices. Prices for new wind turbine contracts have reportedly increased in 2021, reversing the trends seen over the past few years (Wood Mackenzie, 2021). Steeply rising silicon and silver prices have similarly driven up the price of solar PV modules.

Figure 6.16 ▷ **Average pack price of lithium-ion batteries and share of cathode material cost**



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Increasing significance of raw materials in total battery costs means that mineral prices could have a substantial impact on industry cost targets

Notes: kWh = kilowatt-hours. The 2021 values (labelled 2021e) are estimated based on material prices in June 2021. Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation.

Source: IEA analysis based on BNEF (2020).

For **solar PV**, materials represent a major part of module costs. Key materials include silicon (10-15% of module costs) and silver (5-7%). Solar-grade polysilicon prices have more than doubled since last year while the price of silver has surged by around 30% (BNEF, 2021a). These increases have led to a cost increase of USD 0.04/watt, or around 16% of module costs. For a typical 100 megawatt (MW) utility-scale PV project, a 16% increase in the cost of a module represents a 4% hike in total project cost on a dollar-per-watt basis, if not compensated for by reductions in other cost elements.

For **wind**, turbine materials have typically accounted for around 15% of the total wind turbine price over the past decade (excluding foundations) (Elia et al., 2020). The shares of material costs vary by turbine type, but are typically dominated by steel, with copper, rare earth elements and zinc accounting for most of the balance. Since June 2020, steel prices have nearly doubled in China and tripled in North America, while copper prices have risen by 50% over the last year. These price rises have led to an 8-10% increase in the cost of turbine manufacturing which could increase total capital costs by around 5%. Prices of the rare earth elements used in turbines based on permanent magnet synchronous generators have also doubled over the past year, contributing to the rise in turbine costs.

For **electricity grids**, copper and aluminium costs are estimated to represent around 14% and 6% of total grid investment respectively, based on average prices over the past ten years. At the highest prices observed, these figures increase to almost 20% and 8% respectively, raising overall grid investment costs by around 9%. Average copper prices in 2021 so far have averaged over USD 9 300/tonne – close to the highest prices observed in the past decade – compared with an average price in the 2010s of around USD 7 000/tonne.

For **EV batteries**, average prices for cathode materials showed a broad-based increase in the first-half of 2021 of 20-40% for lithium and nickel, and two-thirds for cobalt. These translate into a 6% increase in the costs of EV batteries, provided that other cost elements remain the same (Figure 6.17). The impacts vary by battery chemistry. For NMC622 chemistries[9], a doubling of the prices of any of the three key minerals – nickel, cobalt or lithium hydroxide – results in pack costs increasing by 5-7%. If nickel and cobalt prices were to double at the same time, this would offset all the anticipated unit cost reductions associated with a doubling of battery production capacity (IEA, 2021g). In contrast, rising prices for iron, phosphorus and lithium carbonate have a limited impact on the cost of LFP battery packs, which dominate storage applications, because these three key materials account for just 2.5% of final capital expenditure at the project level (BNEF, 2021b).

It is uncertain if, and for how long, the surge in prices in the first-half of 2021 will continue. The rise in key material prices at the scale seen recently would generate upward pressure on total capital costs by 5-15%. This could add USD 430 billion to cumulative investment needs for solar PV, wind, batteries and electricity networks over this decade in the STEPS, and nearly USD 700 billion in the NZE. High material prices would require large reductions in other cost elements to keep the overall costs on a continued downward trajectory.

These risks to mineral supplies are real, but they can be mitigated through comprehensive policies and actions by government and industry. The *Role of Critical Minerals in Clean Energy Transitions* presented key areas of action to ensure reliable and sustainable mineral supplies (IEA, 2021g). Scaling up investment in new mining and processing facilities is vital. To attract capital to new projects, policy makers must provide clear signals about their climate ambitions and how their targets will be turned into action, while taking steps to strengthen geological surveys and streamline permitting procedures. Technology innovation on both the demand and production sides can bring substantial security benefits by promoting more efficient use of materials, enabling material substitution and unlocking sizeable new supplies. Stepping up efforts for recycling would enable valuable mineral resources to be recovered from spent equipment. These measures should form part of a broad strategy that also encompasses supply chain resilience, transparency and sustainability standards. The response from policy makers and companies will determine whether critical minerals remain a vital enabler for clean energy transitions or become a bottleneck in the process.

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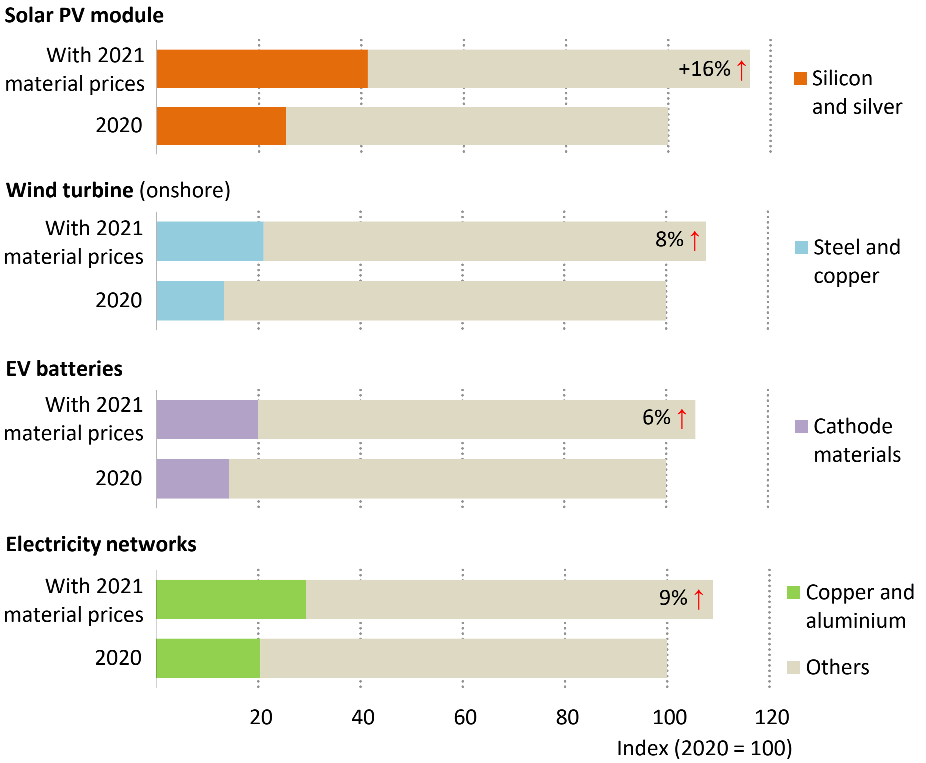
[9] NMC622 = nickel manganese cobalt oxide chemistry with 60% nickel, 20% manganese and 20% cobalt.

Figure 6.17 ⊳ Impacts of 2021 material price increases on the costs of selected clean energy technologies



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Rising costs of key materials could make clean energy technologies 5-15% more expensive, if not compensated by other cost reductions

Notes: This analysis applied the estimated 2021 prices for key materials in each technology to equipment costs in 2020, keeping other cost elements constant. Cathode materials for EV batteries include lithium, nickel, cobalt and manganese.

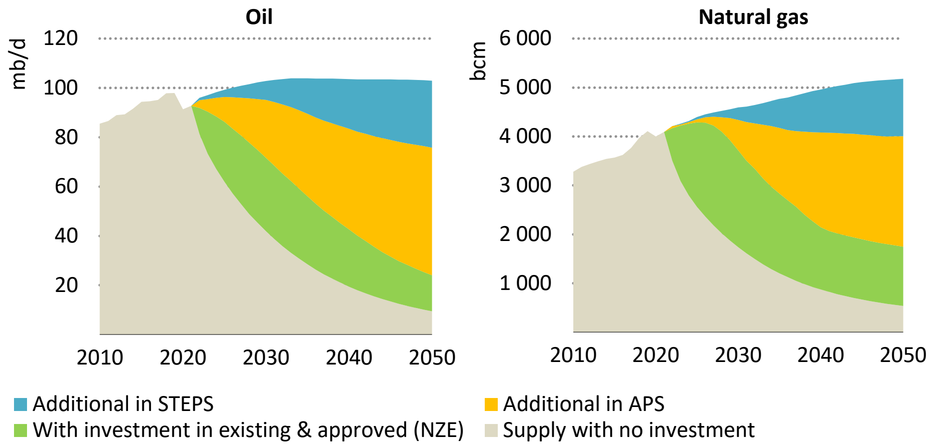
Source: IEA analysis based on BNEF (2020) and S&P Global (2021).

6.3.2 Oil and gas investment

The trajectory of oil and gas demand varies significantly across the three scenarios, and this naturally has implications for the investment required to ensure adequate supplies. In the STEPS, annual upstream oil and gas spending averages around USD 650 billion between 2021 and 2030, and USD 700 billion through to 2050, which is higher than the average investment in the 2010s. Over 60% of total investment is spent on developing new fields (Figure 6.18).

In the APS, investment requirements to develop new fields are reduced markedly. Average annual upstream oil and gas spending between 2021 and 2050 amounts to USD 495 billion, with spending on new fields down by a third compared with the STEPS. In the NZE, demand for oil and gas plummets to levels that do not require new field developments beyond those already approved, although investment in existing fields continues. At USD 235 billion, average annual upstream oil and gas spending between 2021 and 2050 is two-thirds lower than in the STEPS and, with the exception of fields already approved, is entirely spent on existing fields (Table 6.1). In this scenario, there is much greater focus on boosting productivity from existing fields and reducing emissions from operations (see Chapter 5).

Figure 6.18 ▻ Global oil and natural gas demand and declines in supply by scenario



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In climate-driven scenarios, a large part of upstream oil and gas investment is spent on maintaining production at existing fields

Note: mb/d = million barrels per day; bcm = billion cubic metres.

Table 6.1 ▻ Average annual upstream oil and gas investment by scenario

USD billion (2020)		STEPS		APS		NZE	
	2020	2021-2030	2031-2050	2021-2030	2031-2050	2021-2030	2031-2050
Existing fields		244	255	240	204	288	171
New fields		403	436	331	251	77	0
Total	**330**	**647**	**691**	**572**	**455**	**365**	**171**

Note: New fields also include those that have already been approved.

The fact that no new oil and natural gas fields are required in the NZE does not mean that limiting investment in new fields will lead to the energy transition outcomes in the NZE. If demand remains at higher levels, reduced investment would result in a shortfall in supply in the years ahead, and this would lead to higher and more volatile prices. Therefore, a strong policy push to reduce oil and gas demand in line with the trajectory envisaged in the NZE is key to achieve deep reductions in emissions and to avoid the risk of market tightening.

Nonetheless, actions on the supply side remain crucial to orderly and rapid energy transitions. Over investment creates the risk of underutilised, unprofitable or stranded assets, putting greater financial pressure on producing countries and companies alike. For example, most of the 200 bcm worth of LNG projects currently under construction do not recover their invested capital in the NZE, with the total stranded capital estimated at USD 75 billion. Over investment also creates the risk of excess capacity that puts downward pressure on prices, requiring stronger policy efforts to offset the possibility of a rebound in demand. On the other hand shortfalls in investment, which cannot be ruled out even in lower demand scenarios such as the APS and NZE, would likewise be disruptive: higher oil or gas prices could become a political distraction and a signal to make new (and risky) upstream investments, even as they improve the competitiveness of lower carbon options. Supply-side actions to minimise emissions, especially methane leaks, remain essential in any scenario. In some cases, individual company actions to divest assets may bring the attendant risk that the new owners may be less transparent or concerned about environmental performance.

Oil and gas supplies in the APS and NZE are increasingly concentrated in a small number of low cost producers. The share of OPEC members and Russia in oil production rises from 47% in 2020 to 58% in 2050 in the APS, and to 61% in the NZE, comparable to the highest level in the history of oil markets in the 1970s. In practice, there would be a long queue of producers making claims to a shrinking oil market, complicating attempts at market management and increasing the possibility of a bumpy and volatile ride. Falling income from oil and gas compound the uncertainties facing many of the producer economies poised to take a larger share in future supply, underscoring the need for vigilance on the security of supply even in a world with contracting demand (Spotlight).

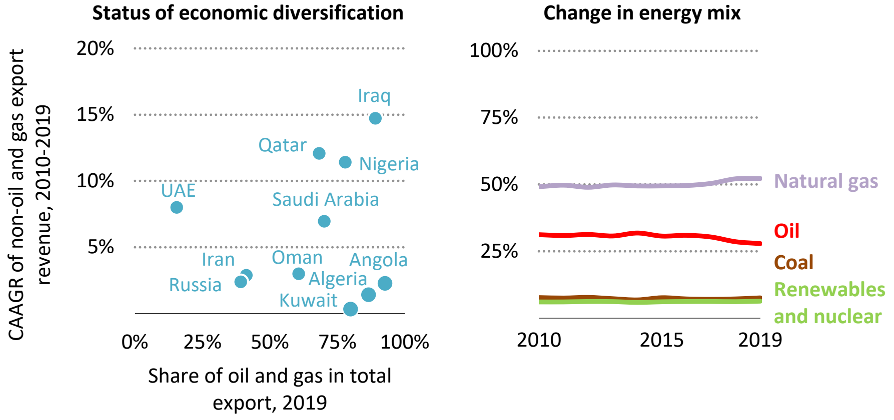
SPOTLIGHT

Diversification: Where do different producer economies stand?

The pandemic provided a preview of the social and economic strains that producer economies could face from reduced oil and gas revenue. Although higher prices in 2021 and the possibility of further tightening of markets in the 2020s provide some respite, there is little comfort for producers in our longer term projections. The decline in oil and gas demand and the consequent fall in prices in the APS and NZE lead to a major drop in hydrocarbon income in these economies. By the 2030s, annual per capita income from oil and natural gas in producer economies falls by a third in the APS and nearly 80% in the NZE from the levels in the 2010s.

Pressures on producers to reform and diversify their economies are not new, but energy transitions give additional urgency to the task. For the moment, however, there are few signs that major hydrocarbon-rich countries are moving fast. The value of non-oil and gas exports has been on an upward trend since 2010, and its share in total exports rose from 35% in 2010 to 57% in 2020. However, this increased share was largely attributable to the falling value of oil and gas exports rather than major strides in economic reforms (Figure 6.19).

Figure 6.19 ▷ Progress with economic and energy diversification in selected producer economies



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While some countries have made strides towards economic diversification, progress has been very modest on energy diversification

Notes: CAAGR = compound average annual growth rate. Analysis based on 11 producer economies: Algeria, Angola, Iran, Iraq, Kuwait, Nigeria, Oman, Qatar, Russia, Saudi Arabia and the United Arab Emirates.

Source: IEA analysis based on export data from IMF (2021).

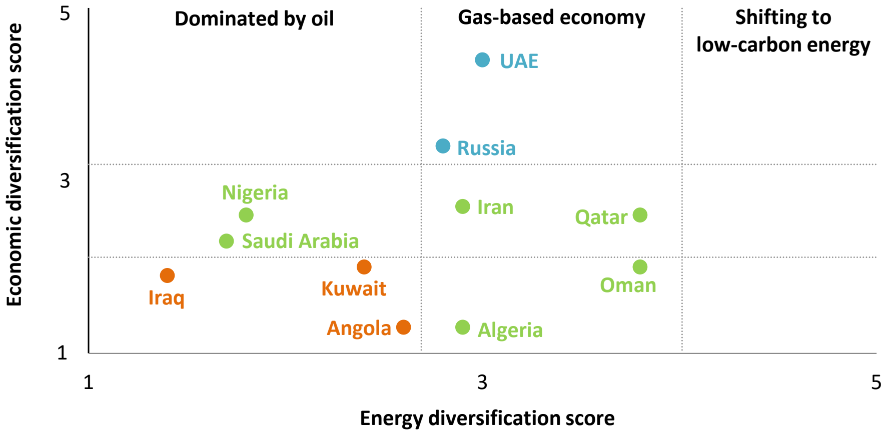
Progress has also been extremely modest in terms of energy diversification. For the moment, most producer economies do not have ambitious climate pledges, nonetheless they have cost-effective opportunities to invest in low-carbon sources – notably in solar power. However, the share of low-carbon energy in producer economies remains one of the lowest in the world. The only noticeable shift in the energy mix in recent years has been a slight move in favour of natural gas versus oil in some countries.

We have grouped the main producer economies into three categories based on their progress with economic and energy diversification (Figure 6.20). In the first group, Russia and the United Arab Emirates (UAE) are doing relatively well on both dimensions. In the UAE, the value of non-oil and gas exports has doubled over the past decade, halving the share of oil and gas export in total exports to 16% in 2019. In October 2021, the UAE became the first Middle East producer to commit to net zero emissions by 2050. There are signs, including a presidential order in May 2021, suggesting that Russia may now be looking more seriously at measures to reduce its emissions intensity as well, including growing attention to low-carbon hydrogen.

There are also countries, including Iraq, that are faring less well on indicators of both economic and energy diversification. These countries face an urgent need to develop holistic and realistic national economic diversification strategies alongside mechanisms to guard against revenue volatility. Iraq is taking steps in this direction, with the elaboration of a White Paper for Economic Reform to put the economy and the federal budget on a sustainable path, with a priority given to amplifying the role of the private sector.

Economic diversification is likewise a priority for the countries in our middle group, building on existing foundations. Qatar, for example, is investing in services, tourism and information and communication technologies while also strengthening its petrochemicals sector. Most of the countries in this group have an abundance of cheap solar resources which could help them to diversify their energy consumption structure, reduce emissions and potentially secure additional income from hydrogen exports. Saudi Arabia recently signed deals for seven solar power plants with a combined capacity of 3.7 GW as part of a national strategy to generate 50% of electricity production from renewables by 2030. It has also declared its ambition to become a major exporter of hydrogen and ammonia, produced via natural gas with CCUS or solar power.

Figure 6.20 ▷ Categorisation of producer economies by economic and energy diversification performance



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Each producer economy has a different track record of diversification, but none shows a visible shift towards low-carbon energy systems

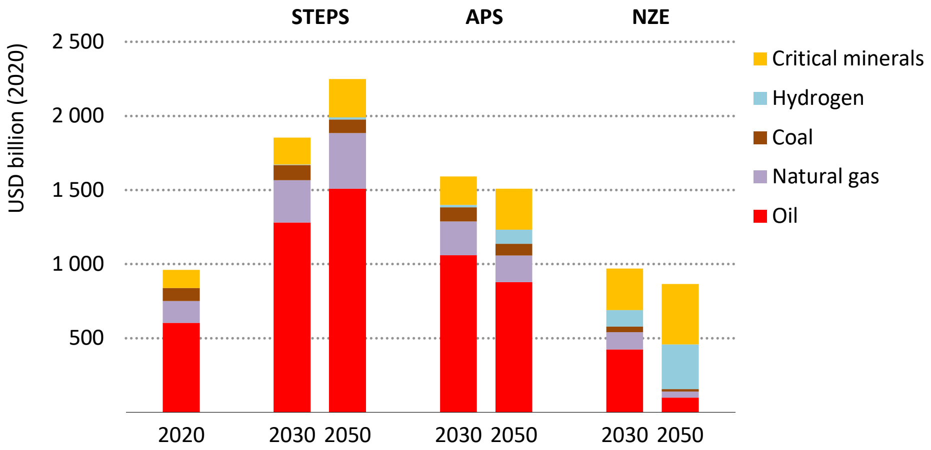
Notes: Economic diversification score was calculated as the weighted average of the share of non-oil and gas exports in total exports in 2019 (70%) and the growth of non-oil and gas export revenue since 2010 (30%). Energy diversification score was calculated as the weighted average of the share of oil, coal and traditional use of biomass in 2019 and the changes since 2010 (50% and 20% each) and the share of renewables and nuclear in 2019 (30%).

Source: IEA analysis based on export data from IMF (2021).

6.3.3 New patterns of energy trade

International trade plays a crucial role in today's global energy economy. It provides a major source of income for exporters and a means for countries without resources to secure supplies. It has, on occasion, been a source of geopolitical tension. For the moment, this trade is dominated by fossil fuels, oil in particular. However, changing energy consumption patterns in the APS and NZE herald some major shifts and bring new characters onto the stage – notably critical minerals and low-carbon hydrogen. The combined share of hydrogen and critical minerals in global energy-related trade doubles from 13% today to 25% by 2050 in the APS. In the NZE, the share rises further to over 80% by 2050 as the value of fossil fuels trade declines significantly, completely overturning the present dynamics of international energy-related trade (Figure 6.21).

Figure 6.21 ▷ Value of international energy-related trade by scenario



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Clean energy transitions are set to bring about a major change in longstanding global energy resource trade patterns

Notes: Values for hydrogen trade include volumes for liquid hydrogen, ammonia and synthetic fuels. Values for critical minerals trade include volumes for processed copper, nickel, lithium and cobalt, with assumptions that the ratio of trade value to total demand remains constant.

Source: IEA analysis based on historical critical minerals trade data from UN (2021).

Critical minerals are already widely traded worldwide, but their presence in global resources trade is set to increase further with the rise of clean energy. On a refined product basis, the value of key critical minerals such as copper, nickel, lithium and cobalt is estimated to double by 2050 in the APS from around USD 120 billion today. In the NZE, their value more than triples to USD 400 billion over the same period.

Although most low-carbon sources of energy are typically produced close to where they are consumed, the trade in hydrogen (or hydrogen-rich fuels) could prove to be an exception. Transport costs are relatively high, but there is still scope for regions with abundant low cost hydrogen production potential to export cost effectively to those with more limited production options. The value of the various forms of hydrogen trade grows from low levels today to around USD 100 billion by 2050 in the APS, higher than the value of current international coal trade, and to around USD 300 billion in the NZE. This poses important questions about infrastructure, market norms and energy security (Box 6.3). It also poses questions about which currency will be used for pricing and trading hydrogen and some critical minerals.

Box 6.3 ⊳ Trading up: Creating an international market for hydrogen

Higher levels of low-carbon energy use in our scenarios create incentives for new forms of energy trade, and trade in hydrogen – including hydrogen-based fuels such as ammonia – looks set to increase. However, experience with establishing efficient international markets, especially for seaborne goods, suggests that the requisite infrastructure, standardisation and regulatory measures may take time to be developed and harmonised.

Practically all of the hydrogen and hydrogen-based fuels traded today are produced from fossil fuels without CCUS. International trade in hydrogen is limited, with only a small number of cross-border pipelines. Around half a million tonnes of hydrogen with a value of around USD 200 million was exported in 2019. The biggest exporters were Netherlands, Canada, Belgium, Sweden, France and Germany. Most exports were made by pipeline, with Canada being the only major road-based exporter. By contrast, the global anhydrous ammonia market, mostly for use in fertilisers, is thirty-times more valuable, with traded volumes equivalent to over 2 Mt hydrogen. Most ammonia is traded by rail or sea. Saudi Arabia, Russia, Indonesia, Canada and Malaysia were the biggest exporters in 2019. As with natural gas, pipeline transport offers the lowest cost trade route where it is feasible, and can readily be used for hydrogen converted to synthetic methane. However, pipelines could face competition from high voltage transport of electricity for direct use or as an electrolyser input in some cases.

The regions that stand to benefit most from future low-carbon hydrogen imports are today's importers of fossil energy. The most salient examples are Japan and Korea, which have ambitions to use low-carbon energy at a rate that is likely to quickly outpace their ability to meet demand locally. In the APS, Japan's demand for hydrogen and ammonia passes the level that can be competitively produced domestically before 2030, and imports rise to 1.3 EJ by 2050, equivalent to 11 Mt hydrogen per year.

Careful co-ordination and dialogue will be essential to bring forward new supply chains in a timely way. Many potential exporters do not yet have climate policy commitments on a par with countries whose policy pledges imply a future role for low-carbon hydrogen imports. Japan has engaged in dialogue with a number of countries, including Brunei, Saudi Arabia and the UAE, while Australia and Chile have developed plans to invest in export infrastructure. Korea and European countries also stand to gain from engaging countries, including those in the Middle East, North Africa and Latin America, to ensure that all countries have a shared stake in rapid clean energy transitions. Support measures such as long-term contracts will initially be essential if exporting countries are to invest in large-scale hydrogen production, storage and port infrastructure, or where possible to repurpose existing pipelines, and if importing countries are to be able to rely on imports for secure supplies.

In the APS, exports of hydrogen and hydrogen-based fuels from the Middle East reach the equivalent of around 13 Mt hydrogen per year, or 1 million barrels per day (mb/d). This helps in part to offset the decline in fossil fuel export revenues, but also means that new supply investments are required at a time when budgets are under pressure. The reliability of these new supply routes will also depend on how exporters manage the broader diversification of their economies.

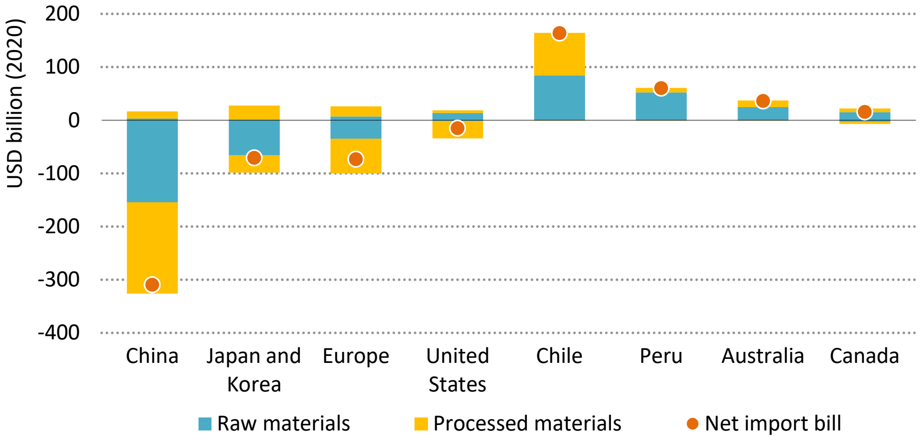
While some international trade takes place overland in our scenarios, the biggest import/export opportunities lie in connecting countries with different climates and geologies by shipping. There are competing options for shipping hydrogen with different efficiencies and maturities. The first demonstration vessel for liquefied hydrogen at 253 °C (90 °C colder than LNG) has recently been constructed with Japanese government co-funding. For applications that can use the ammonia directly, such as power plants, there is an emerging consensus that conversion to ammonia is the most promising means of transporting hydrogen over long distances, especially where pipelines are not viable. In all cases, infrastructure and certification norms for low-carbon cargoes need to be established this decade.

Many commentators point to the LNG market as a useful precedent and the parallels are striking: the technology was pioneered in the 1960s by companies working under the mandate of potential importer countries and in collaboration with potential exporters (with France, for example, working with Algeria on the development of facilities overseas), while the Japanese government was instrumental in facilitating the long-term bilateral contracts that allowed the industry to scale up from the 1990s and reduce transport costs. However, given that liquefaction and safe handling is less technically challenging for natural gas than it is for hydrogen, it is sobering to note that it took several decades to reach the point where very long-distance (so-called inter-basin) trade was possible, and 60 years until global liquefaction capacity could process LNG equivalent to Japan's total primary energy supply (which is around 10% of global gas demand).

Countries pursuing climate policies that would make imports of hydrogen and hydrogen-based fuel attractive have strong incentives to co-operate to ensure that hydrogen supplies do not become a bottleneck for energy security. Near-term objectives should include discussions between bilateral trading partners on whether new sources of financing are needed for export infrastructure and how to align policies that increase demand for hydrogen with the timetable for exports, for example by prioritising the market for fuels for which there is existing shipping capacity. Current demand for ships that can handle ammonia, for example, is often seasonal (in line with fertiliser use), and it may be possible to maximise their use by adding cargoes for energy applications. However, it is important that such bilateral discussions and contracts do not preclude the introduction by commodity traders of more international liquidity and trading over time as the market develops.

Critical mineral supply chains are set to involve multiple stakeholders since resource endowments, equipment manufacturing locations and consumption patterns are varied and complex. At present, Chile, Peru, Australia and Canada are among the top exporters of critical minerals and China, Japan, Korea and the European Union are major importers (Figure 6.22). As China has a decisive share in refining operations, around half of raw material trade flows to China. Somewhat counterintuitively, China also imports processed materials, highlighting the scale of the country's role in clean energy technology manufacturing. How these trade flows evolve is an open question, and the answer will depend in large measure on countries' industrial policies or strategic initiatives to ensure security of supply. A number of countries are looking to develop domestic mineral resources, or have ambitions to nurture supply chains for clean energy equipment manufacturing and materials production.

Figure 6.22 ▷ Average annual import bills and export revenues for selected critical minerals by country/region, 2015-2019



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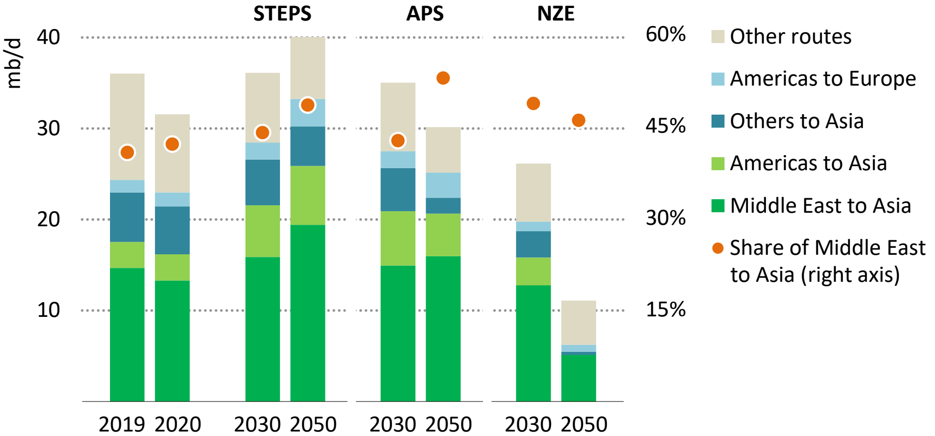
Critical minerals bring new trade patterns and geopolitical considerations into play

Notes: Calculated based on copper, nickel, lithium and cobalt trade. Positive values denote export bills and negative values denote import bills.

Source: UN (2021).

Around 760 gigawatt-hours (GWh) of global lithium-ion battery cell manufacturing capacity exists today, and some 3 600 GWh of new projects have been announced in recent years (BMI, 2021). While China has a large share of the project pipeline, a growing number of projects are also being planned in other parts of Asia, Europe and North America. These projects have the potential to help diversify supply sources and make supply chains more resilient. But there is also a risk that attempts to build domestic capability may in some cases prove to be expensive. Such attempts are most likely to be worthwhile where a country has a competitive edge of some sort or faces particular risks from disruption, but in general there is a balance to be struck between supply chain diversification and economic competitiveness. Part of the answer may lie in international collaboration, given the strong interest that many countries share in building secure and resilient global supply chains.

Figure 6.23 ▻ Seaborne crude oil trade by route and scenario



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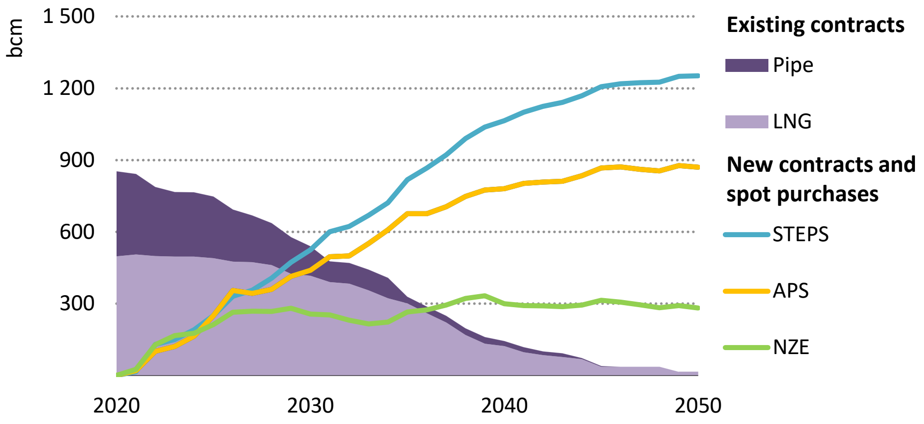
A concentration of global crude oil trade on the routes between the Middle East and Asia is set to intensify, especially in the APS

New dimensions of energy trade and geopolitics arise in clean energy transitions, but the traditional significance of trade in hydrocarbons does not vanish. As in production, oil and gas trade sees a similar concentration of flows, notably between the Middle East and Asia (Figure 6.23). In the STEPS, the share of seaborne crude oil trade from the Middle East to Asia, the current mainstay for global crude oil trade, rises from around 40% today to 48% by 2050. In the APS, relatively robust demand for hydrocarbon imports in developing economies in Asia coincides with an increased share of production among low cost producers in the Middle East: this combination pushes up the share of the Middle East-Asia route in total seaborne trade to 53% by 2050. This means that Asian importers continue to be exposed to risks arising from physical or geopolitical events in the Middle East or accidents near trade chokepoints. In the NZE, trade volumes shrink substantially with plummeting demand, but the share of trade flows between the two regions remains high, implying a continued, deep mutual dependence. Import dependency is also set to remain high for Asian importers across other fuels in all scenarios. In developing economies in Asia, as well as rising from 72% today to 80-90% by 2050 for oil under different scenarios, the level of import dependency rises from 24% to 50-55% for natural gas, and from 7% to 12-16% for coal.

Trade in oil products varies across the three scenarios, but a common denominator is increasing pressure on the global refining industry. Today's major importers, notably developing economies in Asia, continue to import significant volumes in the APS, so the volume of oil products traded internationally keeps rising despite the reduction in overall demand. Nevertheless, the decline in oil demand means that the window for new investment decisions in refining capacity, beyond those that are already approved, becomes increasingly small in this scenario. In the NZE, a broad-based plunge in demand means that export-oriented refiners face much greater challenges in finding outlets as domestic refineries seek to ensure that they meet as much of the remaining demand as they can.

A similar concentration of trade flows towards Asia is also seen for natural gas. In the STEPS, inter-regional natural gas trade rises by 40% between 2020 and 2050, reaching over 1 200 bcm, with emerging Asian markets leading growth. In the APS, there is still a rise of 20% to 2030, but this is followed by a slow decline after 2030 as growth moderates in places such as China and India, while Europe and Japan sharply reduce their imports as natural gas demand falls. In the NZE, import requirements peak before 2030 and fall below 400 bcm by 2050.

Figure 6.24 ▷ Natural gas import requirements by scenario



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There is significant uncertainty about gas contracting needs for net importing regions

Note: Existing contracts includes sales and purchase agreements for projects currently under construction, which total around 150 bcm.

Given the wide differences in possible scenario outcomes, there is significant uncertainty about gas contracting needs for net importing regions (Figure 6.24). If no additional agreements are signed, the contract gap in the NZE would rise to 250 bcm per year by 2030, which could largely be met by renewing existing contracts, while in the STEPS this gap rises to over 500 bcm per year. These divergent trajectories illustrate the difficulties buyers have in agreeing to long-term offtake contracts, especially those that can underpin investment decisions for new projects. While contracts with minimum offtake commitments provide some measure of security of supply, there is also a risk of procuring volumes that may not be needed in future. A combination of flexible contracting and a vibrant spot market could give project sponsors confidence about finding an outlet for production. However, sufficient liquidity in the market would be required to ensure that investment decisions are made according to price signals that accurately reflect long-term supply-demand fundamentals in each region.

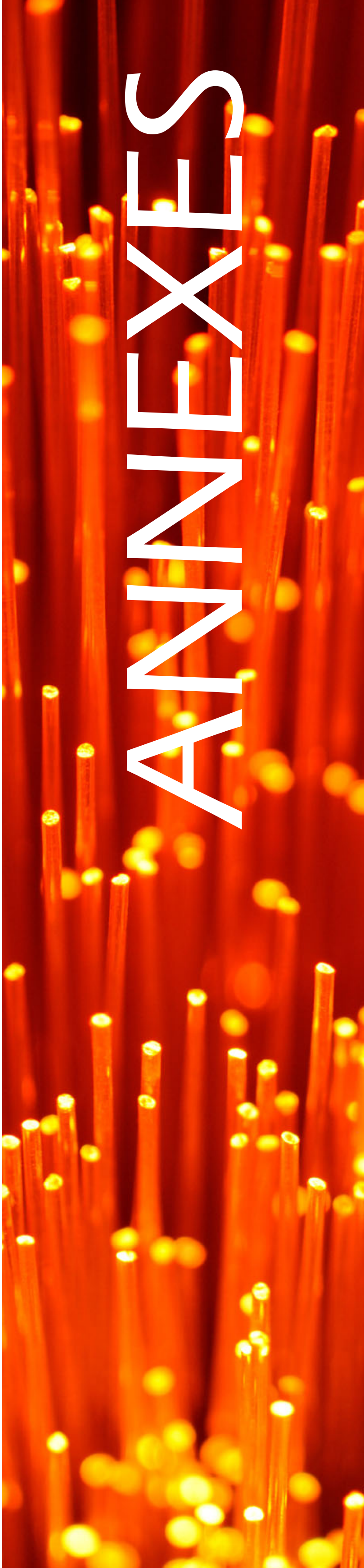
Europe's waning demand for natural gas in clean energy transitions has important implications for global gas trade. At present the region's large storage and import capacity helps to absorb surpluses and manage deficits of globally traded gas. In the absence of this release valve, pressure would grow on producers to provide more flexible gas supplies. There would also be pressure on importers, primarily in Asia, to develop storage or agree flexible contracts with consumers further downstream.

Conclusion

An evolving energy system calls for an evolving approach to energy security, maintaining close vigilance on the traditional risks while broadening horizons to encompass new potential hazards, based on a clear understanding about the way that security is being reshaped by clean energy transitions. Our analysis highlights the issues in play. A core concern is the possibility of investment imbalances and mismatches as the world moves forward with the transformation of the energy sector. Signals from policy makers to those making investment decisions are often not clear, or can change rapidly; the implementation of declared objectives can face delays, societal pressures can add momentum to transitions, or rule out technology options or new infrastructure in ways that slow them down; companies can misread the signals or simply shy away from investment in the face of increased uncertainty. The road to a zero-emissions system could well be a bumpy one.

As the world demands less oil, it may also see supply and trade being concentrated in a smaller number of producers who are themselves facing difficult transitions as traditional revenues decline. An electrified and renewables-rich energy system requires much more flexibility in power systems, which cannot be taken for granted, while creating new linkages with other aspects of energy supply – notably the delivery and storage of different kinds of gases. Digital technologies can help to manage the complexities of a more integrated energy system, but they also create concerns about cybersecurity. Critical minerals become a major new element in secure transitions, with demand increasing multiple times from today's levels, and many potential bottlenecks could emerge as deployment of solar, wind, batteries, electrolysers and EVs ramp up. Last, but not least, access to reliable and affordable energy, and attention to the social and economic consequences of change, are preconditions for maintaining public support for the transformation of the energy sector. The IEA, drawing on its longstanding and deep expertise in all aspects of energy security, is committed to support transitions that are secure, people-centred, affordable and rapid.

ANNEXES



Box A.1 ▹ *World Energy Outlook* **links**

WEO homepage

General information	www.iea.org/weo
***WEO-2021* information**	iea.li/weo21

WEO-2021 datasets

Data in Annex A is available to download free in electronic format at:
iea.li/weo2021-freedata

An extended dataset, including the data behind figures, tables and the WEO-2021 slide deck is available to purchase at:
iea.li/weo2021-extendeddata

Modelling

Documentation and methodology / Investment costs
www.iea.org/weo/weomodel

Recent analysis

The Role of Critical Minerals in Clean Energy Transitions	iea.li/minerals
Net Zero by 2050	iea.li/netzero
Financing Clean Energy Transitions in Emerging and Developing Economies	iea.li/fcet
Sustainable Recovery Tracker	iea.li/recoverytracker
Curtailing Methane Emissions from Fossil Fuel Operations	iea.li/methaneemissions

Databases

Policy Databases	iea.li/policies-database
Sustainable Development Goal 7	www.iea.org/SDG
Energy subsidies: Tracking the impact of fossil-fuel subsidies	www.iea.org/topics/energy-subsidies

Tables for scenario projections

General note to the tables

This annex includes global historical and projected data by scenario for the following four datasets:

- A.1: Energy supply.
- A.2: Total final consumption.
- A.3: Electricity sector: gross electricity generation and electrical capacity.
- A.4: CO_2 emissions: carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes.

Each dataset is given for the following scenarios: (a) Stated Policies [Tables A.1a. to A.4a]; (b) Announced Pledges [Tables A.1b. to A.4b]; (c) Sustainable Development [Tables A.1c. to A.4c]; and, (d) Net Zero Emissions by 2050 [Tables A.1d. to A.4d].

This annex also includes regional historical and projected data for the Stated Policies, Announced Pledges and Sustainable Development scenarios for the following datasets:

- Tables A.5 – A.6: Total energy supply, renewables energy supply in exajoules (EJ).
- Tables A.7 – A.10: Oil production, oil demand, world liquids demand, and, refining capacity and runs in million barrels per day (mb/d).
- Tables A.11 – A.12: Natural gas production, natural gas demand in billion cubic metres (bcm).
- Tables A.13 – A.14: Coal production, coal demand in million tonnes of coal equivalent (Mtce).
- Tables A.15 – A.21: Electricity generation by total and by source (renewables, solar photovoltaic [PV], wind, nuclear, natural gas, coal) in terawatt-hours (TWh).
- Tables A.22 – A.25: Total final consumption and consumption by sector (industry, transport and buildings) in exajoules (EJ).
- Table A.26 – A.28: Total CO_2 emissions, electricity and heat sectors CO_2 emissions, final consumption in million tonnes of CO_2 emissions (Mt CO_2).

Tables A.5 to A.28 cover: World, North America, United States, Central and South America, Brazil, Europe, European Union, Africa, Middle East, Eurasia, Russia, Asia Pacific, China, India, Japan and Southeast Asia. The definitions for regions, fuels and sectors are in Annex C.

Common abbreviations used in the tables include: CAAGR = compound average annual growth rate; CCUS = carbon capture, utilisation and storage. Consumption of fossil fuels in facilities without CCUS are classified as "unabated".

Both in the text of this report and in these annex tables, rounding may lead to minor differences between totals and the sum of their individual components. Growth rates are calculated on a compound average annual basis and are marked "n.a." when the base year is zero or the value exceeds 200%. Nil values are marked "-".

Please see Box A.1 for details on where to download the *World Energy Outlook (WEO)* tables in Excel format. In addition, Box A.1 lists the links relating to the main *WEO* website, documentation and methodology of the World Energy Model (WEM), investment costs, policy databases and recent *WEO* special reports.

Data sources

The World Energy Model (WEM) is a very data-intensive model covering the global energy system. Detailed references on databases and publications used in the modelling and analysis may be found in Annex E.

The formal base year for the scenario projections is 2019, as this is the most recent year for which a complete picture of energy demand and production is available. However, we have used more recent data when available, and we include our 2020 estimates for energy production and demand in this annex. Estimates for the year 2020 are based on updates of the IEA Global Energy Review reports which are derived from a number of sources, including the latest monthly data submissions to the IEA Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA Market Report series that cover coal, oil, natural gas, renewables and electricity.

Historical data for gross electrical capacity are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2021 version) and the International Atomic Energy Agency PRIS database.

Definitional note: Energy supply and transformation tables

Total energy supply (TES) is equivalent to electricity and heat generation plus the *other energy sector*, excluding electricity, heat and hydrogen, plus total final consumption (TFC), excluding electricity, heat and hydrogen. TES does not include ambient heat from heat pumps or electricity trade. Solar in TES includes solar PV generation, concentrating solar power and final consumption of solar thermal. *Other renewables* in TES include geothermal, and marine (tide and wave) energy for electricity and heat generation. Hydrogen production and biofuels production in the other energy sector account for the energy input required to produce low-carbon hydrogen (excluding on site production and consumption within industrial facilities) and for the conversion losses to produce biofuels (mainly primary solid biomass) used in the energy sector. While not itemised separately, non-renewable waste and other sources are included in TES.

Definitional note: Energy demand tables

Sectors comprising **total final consumption** (TFC) include industry (energy use and feedstock), transport, buildings (residential, services and non-specified other) and other (agriculture and other non-energy use). Energy demand from international marine and aviation bunkers are included in global transport totals.

Definitional note: Fossil fuel production and demand tables

Oil production and demand is expressed in million barrels per day (mb/d). Tight oil includes tight crude oil and condensate production except for the United States, which includes tight crude oil only (US tight condensate volumes are included in natural gas liquids). Processing gains cover volume increases that occur during crude oil refining. Biofuels and their inclusion in liquids demand is expressed in energy-equivalent volumes of gasoline and diesel. Natural gas production and demand is expressed in billion cubic metres (bcm). Coal production and demand is expressed in million tonnes of coal equivalent (Mtce). Differences between historical production and demand volumes for oil, gas and coal are due to changes in stocks. Bunkers include both international marine and aviation fuels. Refining capacity at risk is defined as the difference between refinery capacity and refinery runs, with the latter including a 14% allowance for downtime. Projected shutdowns beyond those publicly announced are also counted as capacity at risk.

Definitional note: Electricity tables

Electricity generation expressed in terawatt-hours (TWh) and installed electrical capacity data expressed in gigawatts (GW) are both provided on a gross basis (i.e. includes own use by the generator). Projected gross electrical capacity is the sum of existing capacity and additions, less retirements. While not itemised separately, other sources are included in total electricity generation. Installed capacity for hydrogen and ammonia refers to full conversion only, not including co-firing with natural gas or coal.

Definitional note: CO_2 emissions tables

Total CO_2 includes carbon dioxide emissions from the combustion of fossil fuels and non-renewable wastes, from industrial and fuel transformation processes (process emissions) as well as CO_2 removals. Three types of CO_2 removals are presented:

- Captured and stored emissions from the combustion of bioenergy and renewable wastes.
- Captured and stored process emissions from biofuels production.
- Captured and stored CO_2 from the atmosphere, which is reported as direct air capture (DAC).

The first two entries are often reported as bioenergy with carbon capture and storage (BECCS). Note that some of the CO_2 captured from biofuels production and direct air capture is used to produce synthetic fuels, which is not included as CO_2 removal.

Total CO_2 captured includes the carbon dioxide captured from CCUS facilities (such as electricity generation or industry) and atmospheric CO_2 captured through direct air capture, but excludes that captured and used for urea production.

Table A.1a: World energy supply

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	544.7	613.0	589.1	671.0	714.8	743.9	100	100	100	1.3	0.8
Renewables	47.7	65.8	68.5	109.0	153.0	192.5	12	16	26	4.8	3.5
Solar	0.8	4.0	4.7	15.9	30.0	43.5	1	2	6	13	7.7
Wind	1.2	5.1	5.7	14.4	23.5	31.3	1	2	4	9.6	5.8
Hydro	12.4	15.2	15.6	18.3	21.1	24.3	3	3	3	1.6	1.5
Modern solid bioenergy	27.3	31.1	31.8	41.6	49.3	54.7	5	6	7	2.7	1.8
Modern liquid bioenergy	2.4	4.1	3.8	7.1	9.7	11.9	1	1	2	6.5	3.9
Modern gaseous bioenergy	1.0	2.1	2.2	3.8	6.1	9.4	0	1	1	5.6	4.9
Other renewables	2.6	4.2	4.5	7.9	13.3	17.6	1	1	2	5.8	4.7
Traditional use of biomass	26.2	24.2	24.1	21.0	19.1	17.2	4	3	2	-1.3	-1.1
Nuclear	30.1	30.5	29.4	34.0	38.4	40.5	5	5	5	1.5	1.1
Unabated natural gas	115.1	141.4	138.7	155.9	168.0	174.0	24	23	23	1.2	0.8
Natural gas with CCUS	0.1	0.4	0.4	1.0	1.3	1.5	0	0	0	8.3	4.2
Oil	172.1	187.9	171.4	198.5	199.6	198.3	29	30	27	1.5	0.5
of which non-energy use	23.6	28.5	28.5	34.6	37.5	38.2	5	5	5	1.9	1.0
Unabated coal	153.0	162.2	155.8	150.2	132.9	116.8	26	22	16	-0.4	-1.0
Coal with CCUS	-	0.0	0.0	0.2	0.8	1.0	0	0	0	35	18
Electricity and heat sectors	199.8	233.5	230.5	253.5	280.0	301.9	100	100	100	1.0	0.9
Renewables	21.2	35.7	38.1	66.9	100.4	131.3	17	26	43	5.8	4.2
Solar PV	0.1	2.5	3.0	12.6	24.1	34.8	1	5	12	15	8.5
Wind	1.2	5.1	5.7	14.4	23.5	31.3	2	6	10	9.6	5.8
Hydro	12.4	15.2	15.6	18.3	21.1	24.3	7	7	8	1.6	1.5
Bioenergy	5.1	9.5	10.1	15.0	19.2	23.2	4	6	8	4.1	2.8
Other renewables	2.4	3.4	3.6	6.7	12.6	17.7	2	3	6	6.4	5.5
Hydrogen	-	-	-	0.0	0.1	0.1	-	0	0	n.a.	n.a.
Ammonia	-	-	-	0.0	0.2	0.3	-	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	34.0	38.4	40.5	13	13	13	1.5	1.1
Unabated natural gas	46.7	55.7	55.1	57.3	60.8	63.3	24	23	21	0.4	0.5
Natural gas with CCUS	-	-	-	0.1	0.1	0.1	-	0	0	n.a.	n.a.
Oil	10.9	8.2	7.9	5.4	4.3	3.4	3	2	1	-3.7	-2.8
Unabated coal	91.0	103.3	100.0	89.6	75.1	62.0	43	35	21	-1.1	-1.6
Coal with CCUS	-	0.0	0.0	0.1	0.7	1.0	0	0	0	36	19
Other energy sector	54.2	59.1	58.1	66.9	72.4	76.7	100	100	100	1.4	0.9
Hydrogen production	-	-	-	0.4	1.3	2.2	-	1	3	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	11.6	16.8	20.0	8	17	26	9.9	5.1

Table A.2a: World final consumption

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total final consumption	382.5	432.9	412.8	488.6	525.6	550.3	100	100	100	1.7	1.0
Electricity	64.5	82.4	81.8	103.0	124.3	144.0	20	21	26	2.3	1.9
Liquid fuels	152.5	173.3	157.3	190.6	196.3	199.0	38	39	36	1.9	0.8
Biofuels	2.4	4.1	3.8	7.1	9.7	11.9	1	1	2	6.5	3.9
Ammonia	-	-	-	0.0	0.0	0.1	-	0	0	n.a.	n.a.
Synthetic oil	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Oil	150.1	169.3	153.5	183.5	186.5	187.1	37	38	34	1.8	0.7
Gaseous fuels	57.6	70.2	68.7	82.5	92.7	98.5	17	17	18	1.8	1.2
Biomethane	0.0	0.1	0.2	0.7	1.8	4.2	0	0	1	15	11
Hydrogen	0.0	0.0	0.0	0.2	0.5	1.0	0	0	0	37	18
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57.2	69.7	68.2	81.1	89.5	92.3	17	17	17	1.8	1.0
Solid fuels	95.6	91.8	89.2	93.1	90.5	85.3	22	19	16	0.4	-0.1
Solid bioenergy	38.8	37.8	37.9	37.8	37.4	35.5	9	8	6	-0.0	-0.2
Coal	56.4	53.4	50.6	54.7	52.5	49.3	12	11	9	0.8	-0.1
Heat	11.5	12.8	13.1	14.9	15.2	14.8	3	3	3	1.3	0.4
Other	0.9	2.3	2.6	4.6	6.7	8.6	1	1	2	5.6	4.0
Industry	146.9	158.6	156.1	188.2	201.9	206.8	100	100	100	1.9	0.9
Electricity	26.8	34.4	34.4	42.5	47.7	51.3	22	23	25	2.1	1.3
Liquid fuels	31.3	31.3	31.3	37.8	41.1	41.7	20	20	20	1.9	1.0
Oil	31.3	31.3	31.3	37.8	41.1	41.7	20	20	20	1.9	1.0
Gaseous fuels	26.1	29.5	29.1	36.9	42.4	46.0	19	20	22	2.4	1.5
Biomethane	0.0	0.0	0.1	0.3	0.8	1.9	0	0	1	17	13
Hydrogen	-	-	-	0.0	0.0	0.0	-	0	0	n.a.	n.a.
Unabated natural gas	26.1	29.4	29.0	36.4	41.4	43.8	19	19	21	2.3	1.4
Natural gas with CCUS	-	0.0	0.0	0.2	0.2	0.2	0	0	0	15	5.5
Solid fuels	57.4	57.2	54.9	63.2	62.5	59.5	35	34	29	1.4	0.3
Solid bioenergy	8.1	9.3	9.5	11.1	11.6	11.3	6	6	5	1.7	0.6
Unabated coal	49.3	47.9	45.5	52.0	50.8	48.1	29	28	23	1.4	0.2
Coal with CCUS	-	0.0	0.0	0.0	0.1	0.1	0	0	0	33	11
Heat	5.3	6.1	6.3	7.6	7.9	7.7	4	4	4	1.9	0.7
Other	0.0	0.0	0.0	0.2	0.4	0.7	0	0	0	15	9.9
Iron and steel	31.2	36.0	36.1	41.7	41.6	41.1	23	22	20	1.5	0.4
Chemicals	19.0	21.5	21.4	26.5	28.2	27.8	14	14	13	2.2	0.9
Cement	9.5	11.0	11.3	12.1	11.7	10.7	7	6	5	0.7	-0.2

Table A.2a: World final consumption (continued)

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Transport	**101.7**	**120.9**	**105.1**	**136.4**	**147.3**	**157.1**	**100**	**100**	**100**	**2.6**	**1.4**
Electricity	1.1	1.5	1.5	4.0	8.6	13.0	1	3	8	10	7.5
Liquid fuels	96.9	114.3	98.6	125.1	128.9	132.2	94	92	84	2.4	1.0
Biofuels	2.4	4.0	3.7	6.8	9.3	11.4	4	5	7	6.3	3.8
Oil	94.5	110.3	94.9	118.2	119.5	120.8	90	87	77	2.2	0.8
Gaseous fuels	3.7	5.0	4.9	7.2	9.7	11.9	5	5	8	3.9	3.0
Biomethane	0.0	0.1	0.1	0.2	0.6	1.4	0	0	1	16	11
Hydrogen	0.0	0.0	0.0	0.1	0.4	0.9	0	0	1	35	18
Natural gas	3.7	5.0	4.9	6.9	8.7	9.6	5	5	6	3.5	2.3
Road	75.9	89.5	80.5	99.0	104.2	108.4	77	73	69	2.1	1.0
Passenger cars	38.6	47.7	41.7	47.0	47.9	48.2	40	34	31	1.2	0.5
Heavy-duty trucks	20.3	24.5	22.5	32.8	37.0	41.5	21	24	26	3.8	2.1
Aviation	10.5	14.4	8.5	18.0	21.7	24.7	8	13	16	7.8	3.6
Shipping	10.4	11.4	10.7	13.5	15.0	17.0	10	10	11	2.4	1.6
Buildings	**117.9**	**128.8**	**127.2**	**136.1**	**147.4**	**157.8**	**100**	**100**	**100**	**0.7**	**0.7**
Electricity	34.6	43.2	42.6	52.5	63.6	75.1	33	39	48	2.1	1.9
Liquid fuels	13.3	13.1	12.8	11.4	9.8	9.1	10	8	6	-1.2	-1.1
Biofuels	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	2.2	1.8
Oil	13.3	13.1	12.8	11.4	9.7	9.1	10	8	6	-1.2	-1.1
Gaseous fuels	26.6	30.6	29.8	32.4	34.2	34.5	23	24	22	0.9	0.5
Biomethane	0.0	0.0	0.1	0.2	0.4	0.9	0	0	1	12	9.8
Hydrogen	-	-	-	0.0	0.1	0.1	-	0	0	n.a.	n.a.
Natural gas	26.2	30.1	29.4	31.7	33.0	32.6	23	23	21	0.8	0.3
Solid fuels	36.5	33.1	32.8	28.4	26.7	24.6	26	21	16	-1.4	-1.0
Modern biomass	4.5	4.5	4.5	5.7	6.7	6.9	4	4	4	2.3	1.4
Traditional use of biomass	26.2	24.2	24.1	21.0	19.1	17.2	19	15	11	-1.3	-1.1
Coal	5.7	4.4	4.1	1.5	0.8	0.4	3	1	0	-9.3	-7.6
Heat	6.1	6.6	6.7	7.2	7.2	7.0	5	5	4	0.6	0.1
Other	0.9	2.2	2.5	4.2	5.9	7.5	2	3	5	5.3	3.7
Residential	84.3	90.4	89.4	92.7	98.5	105.1	70	68	67	0.4	0.5
Services	33.6	38.4	37.9	43.4	48.9	52.7	30	32	33	1.4	1.1
Other	**15.9**	**24.7**	**24.3**	**28.0**	**28.9**	**28.6**	**100**	**100**	**100**	**1.4**	**0.5**

Table A.3a: World electricity sector

	Stated Policies Scenario (TWh)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total generation	21 520	26 959	26 762	33 575	40 553	46 703	100	100	100	2.3	1.9
Renewables	4 250	7 114	7 593	14 056	21 218	27 883	28	42	60	6.4	4.4
Solar PV	32	681	833	3 492	6 700	9 667	3	10	21	15	8.5
Wind	342	1 421	1 596	4 102	6 628	8 805	6	12	19	9.9	5.9
Hydro	3 446	4 236	4 347	5 087	5 872	6 739	16	15	14	1.6	1.5
Bioenergy	360	672	709	1 145	1 500	1 852	3	3	4	4.9	3.3
of which BECCS	-	-	-	-	-	-	-	-	-	n.a.	n.a.
CSP	2	13	13	46	158	302	0	0	1	13	11
Geothermal	68	91	94	176	314	423	0	1	1	6.5	5.1
Marine	1	1	1	9	47	95	0	0	0	20	15
Nuclear	2 756	2 790	2 692	3 115	3 517	3 711	10	9	8	1.5	1.1
Hydrogen and ammonia	-	-	-	5	29	44	-	0	0	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	20	87	118	0	0	0	44	20
Coal with CCUS	-	1	1	11	78	104	0	0	0	36	19
Natural gas with CCUS	-	-	-	9	9	13	-	0	0	n.a.	n.a.
Unabated fossil fuels	14 480	17 019	16 440	16 345	15 668	14 915	61	49	32	-0.1	-0.3
Coal	8 671	9 911	9 467	8 733	7 418	6 189	35	26	13	-0.8	-1.4
Natural gas	4 843	6 356	6 257	7 112	7 858	8 418	23	21	18	1.3	1.0
Oil	966	752	716	500	393	308	3	1	1	-3.5	-2.8

	Stated Policies Scenario (GW)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total capacity	5 192	7 467	7 782	11 143	14 719	17 844	100	100	100	3.7	2.8
Renewables	1 346	2 710	2 989	5 998	9 061	11 692	38	54	66	7.2	4.7
Solar PV	39	605	739	2 550	4 516	6 163	9	23	35	13	7.3
Wind	181	623	737	1 603	2 357	2 995	9	14	17	8.1	4.8
Hydro	1 027	1 306	1 327	1 564	1 779	1 995	17	14	11	1.7	1.4
Bioenergy	87	154	163	234	293	347	2	2	2	3.6	2.5
of which BECCS	-	-	-	-	-	-	-	-	-	n.a.	n.a.
CSP	1	6	6	17	50	92	0	0	1	10	9.3
Geothermal	11	15	16	27	47	61	0	0	0	5.7	4.7
Marine	0	1	1	4	19	37	0	0	0	17	14
Nuclear	402	415	415	447	495	525	5	4	3	0.7	0.8
Hydrogen and ammonia	-	-	-	-	-	6	-	-	0	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	3	14	20	0	0	0	38	19
Coal with CCUS	-	0	0	2	12	17	0	0	0	30	18
Natural gas with CCUS	-	-	-	1	2	3	-	0	0	n.a.	n.a.
Unabated fossil fuels	3 443	4 331	4 361	4 537	4 613	4 555	56	41	26	0.4	0.1
Coal	1 622	2 105	2 109	2 035	1 837	1 618	27	18	9	-0.4	-0.9
Natural gas	1 384	1 793	1 822	2 211	2 542	2 752	23	20	15	2.0	1.4
Oil	437	433	430	290	234	185	6	3	1	-3.9	-2.8
Battery storage	1	12	17	159	535	1 046	0	1	6	25	15

Table A.4a: World CO_2 emissions

	Stated Policies Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	32 345	35 966	34 156	36 267	35 312	33 903	0.6	-0.0
Combustion activities (+)	30 447	33 464	31 617	33 353	32 305	30 940	0.5	-0.1
Coal	13 828	14 768	14 240	13 487	11 857	10 277	-0.5	-1.1
Oil	10 530	11 344	10 123	11 693	11 590	11 468	1.5	0.4
Natural gas	6 040	7 270	7 165	8 091	8 779	9 123	1.2	0.8
Bioenergy and waste	49	82	89	83	79	72	-0.7	-0.7
Industry removals (-)	-	0	1	1	1	1	0.0	0.0
Biofuels production	-	0	1	1	1	1	0.0	0.0
Direct air capture	-	-	-	-	-	-	n.a.	n.a.
Electricity and heat sectors	12 380	13 933	13 530	12 425	11 116	9 915	-0.8	-1.0
Coal	8 933	10 171	9 832	8 791	7 373	6 100	-1.1	-1.6
Oil	826	626	601	412	325	256	-3.7	-2.8
Natural gas	2 621	3 136	3 097	3 222	3 418	3 559	0.4	0.5
Bioenergy and waste	-	-	-	-	-	-	n.a.	n.a.
Other energy sector*	1 434	1 565	1 435	1 725	1 770	1 786	1.9	0.7
Final consumption*	18 530	20 467	19 191	22 118	22 425	22 202	1.4	0.5
Coal	4 692	4 464	4 288	4 563	4 358	4 058	0.6	-0.2
Oil	9 075	10 106	8 967	10 700	10 719	10 718	1.8	0.6
Natural gas	2 836	3 395	3 380	3 993	4 422	4 568	1.7	1.0
Bioenergy and waste	48	82	89	83	80	72	-0.7	-0.7
Industry*	8 191	8 876	8 736	10 078	10 309	10 068	1.4	0.5
Iron and steel	1 989	2 500	2 591	2 945	2 861	2 743	1.3	0.2
Chemicals	1 143	1 182	1 160	1 382	1 456	1 428	1.8	0.7
Cement	1 921	2 455	2 534	2 774	2 771	2 630	0.9	0.1
Transport	7 010	8 211	7 102	8 886	9 082	9 229	2.3	0.9
Road	5 217	6 043	5 419	6 391	6 311	6 194	1.7	0.4
Passenger cars	2 615	3 192	2 788	3 003	2 862	2 688	0.7	-0.1
Heavy-duty trucks	1 420	1 673	1 532	2 190	2 415	2 638	3.6	1.8
Aviation	751	1 027	606	1 242	1 463	1 631	7.4	3.4
Shipping	796	866	811	999	1 063	1 171	2.1	1.2
Buildings	2 891	2 941	2 917	2 706	2 596	2 494	-0.7	-0.5
Residential	1 963	2 023	1 958	1 760	1 625	1 557	-1.1	-0.8
Services	928	918	960	946	971	937	-0.1	-0.1
Total CO_2 removals	-	0	1	1	1	1	1.8	1.6
Total CO_2 captured	4	40	40	89	176	228	8.3	6.0

*Includes industrial process emissions.

Table A.1b: World energy supply

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	544.7	613.0	589.1	651.1	670.4	674.4	100	100	100	1.0	0.5
Renewables	47.7	65.8	68.5	120.6	194.4	248.4	12	19	37	5.8	4.4
Solar	0.8	4.0	4.7	19.1	42.3	64.2	1	3	10	15	9.1
Wind	1.2	5.1	5.7	18.0	37.4	51.4	1	3	8	12	7.6
Hydro	12.4	15.2	15.6	18.3	21.5	24.7	3	3	4	1.6	1.5
Modern solid bioenergy	27.3	31.1	31.8	42.4	57.4	62.0	5	7	9	2.9	2.2
Modern liquid bioenergy	2.4	4.1	3.8	9.9	12.9	14.8	1	2	2	10	4.6
Modern gaseous bioenergy	1.0	2.1	2.2	4.4	8.3	11.9	0	1	2	7.2	5.8
Other renewables	2.6	4.2	4.5	8.5	14.5	19.5	1	1	3	6.6	5.0
Traditional use of biomass	26.2	24.2	24.1	20.7	18.8	17.1	4	3	3	-1.5	-1.1
Nuclear	30.1	30.5	29.4	35.8	44.1	48.5	5	5	7	2.0	1.7
Unabated natural gas	115.1	141.4	138.7	143.6	127.4	119.1	24	22	18	0.3	-0.5
Natural gas with CCUS	0.1	0.4	0.4	2.9	8.7	14.1	0	0	2	20	12
Oil	172.1	187.9	171.4	185.1	162.4	147.6	29	28	22	0.8	-0.5
of which non-energy use	23.6	28.5	28.5	33.7	34.3	33.9	5	5	5	1.7	0.6
Unabated coal	153.0	162.2	155.8	140.9	101.5	62.7	26	22	9	-1.0	-3.0
Coal with CCUS	-	0.0	0.0	0.6	12.0	15.6	0	0	2	55	29
Electricity and heat sectors	199.8	233.5	230.5	252.6	295.7	323.6	100	100	100	0.9	1.1
Renewables	21.2	35.7	38.1	75.1	131.0	177.7	17	30	55	7.0	5.3
Solar PV	0.1	2.5	3.0	15.1	33.3	51.1	1	6	16	18	9.9
Wind	1.2	5.1	5.7	18.0	37.4	51.4	2	7	16	12	7.6
Hydro	12.4	15.2	15.6	18.3	21.5	24.7	7	7	8	1.6	1.5
Bioenergy	5.1	9.5	10.1	16.2	23.5	29.0	4	6	9	4.9	3.6
Other renewables	2.4	3.4	3.6	7.5	15.1	21.5	2	3	7	7.6	6.1
Hydrogen	-	-	-	0.6	2.3	3.1	-	0	1	n.a.	n.a.
Ammonia	-	-	-	0.0	0.2	0.5	-	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	35.8	44.1	48.5	13	14	15	2.0	1.7
Unabated natural gas	46.7	55.7	55.1	52.9	44.8	44.5	24	21	14	-0.4	-0.7
Natural gas with CCUS	-	-	-	0.6	2.4	4.2	-	0	1	n.a.	n.a.
Oil	10.9	8.2	7.9	4.9	3.9	3.1	3	2	1	-4.6	-3.0
Unabated coal	91.0	103.3	100.0	82.2	58.2	29.9	43	33	9	-1.9	-3.9
Coal with CCUS	-	0.0	0.0	0.5	8.8	12.1	0	0	4	57	30
Other energy sector	54.2	59.1	58.1	65.9	75.1	79.1	100	100	100	1.3	1.0
Hydrogen production	-	-	-	2.5	13.7	22.7	-	4	29	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	10.6	16.1	21.6	8	16	27	8.9	5.3

Table A.2b: World final consumption

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total final consumption	382.5	432.9	412.8	473.2	477.3	479.3	100	100	100	1.4	0.5
Electricity	64.5	82.4	81.8	104.4	129.1	150.2	20	22	31	2.5	2.0
Liquid fuels	152.5	173.3	157.3	181.1	165.4	155.8	38	38	33	1.4	-0.0
Biofuels	2.4	4.1	3.8	9.9	12.9	14.8	1	2	3	10	4.6
Ammonia	-	-	-	0.1	0.9	1.6	-	0	0	n.a.	n.a.
Synthetic oil	-	-	-	0.1	0.8	1.7	-	0	0	n.a.	n.a.
Oil	150.1	169.3	153.5	171.1	150.7	137.7	37	36	29	1.1	-0.4
Gaseous fuels	57.6	70.2	68.7	76.7	78.4	78.4	17	16	16	1.1	0.4
Biomethane	0.0	0.1	0.2	1.1	3.6	6.1	0	0	1	21	13
Hydrogen	0.0	0.0	0.0	0.8	4.8	8.3	0	0	2	62	27
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57.2	69.7	68.2	74.1	69.1	62.6	17	16	13	0.8	-0.3
Solid fuels	95.6	91.8	89.2	91.3	82.8	72.5	22	19	15	0.2	-0.7
Solid bioenergy	38.8	37.8	37.9	37.7	38.8	36.8	9	8	8	-0.1	-0.1
Coal	56.4	53.4	50.6	53.1	43.6	35.5	12	11	7	0.5	-1.2
Heat	11.5	12.8	13.1	14.7	13.2	11.2	3	3	2	1.1	-0.5
Other	0.9	2.3	2.6	5.1	8.4	11.2	1	1	2	6.7	4.9
Industry	146.9	158.6	156.1	184.0	187.1	182.3	100	100	100	1.7	0.5
Electricity	26.8	34.4	34.4	43.6	51.7	57.5	22	24	32	2.4	1.7
Liquid fuels	31.3	31.3	31.3	35.9	34.8	33.0	20	20	18	1.4	0.2
Oil	31.3	31.3	31.3	35.9	34.8	33.0	20	20	18	1.4	0.2
Gaseous fuels	26.1	29.5	29.1	34.9	37.4	37.2	19	19	20	1.8	0.8
Biomethane	0.0	0.0	0.1	0.5	1.6	3.2	0	0	2	24	14
Hydrogen	-	-	-	0.2	1.1	1.2	-	0	1	n.a.	n.a.
Unabated natural gas	26.1	29.4	29.0	33.8	33.1	30.3	19	18	17	1.5	0.1
Natural gas with CCUS	-	0.0	0.0	0.4	1.6	2.5	0	0	1	23	14
Solid fuels	57.4	57.2	54.9	62.0	56.1	48.6	35	34	27	1.2	-0.4
Solid bioenergy	8.1	9.3	9.5	11.4	13.8	13.8	6	6	8	1.9	1.3
Unabated coal	49.3	47.9	45.5	50.5	39.2	31.3	29	27	17	1.0	-1.2
Coal with CCUS	-	0.0	0.0	0.1	3.2	3.5	0	0	2	49	27
Heat	5.3	6.1	6.3	7.3	6.0	4.5	4	4	2	1.6	-1.1
Other	0.0	0.0	0.0	0.3	1.0	1.5	0	0	1	24	13
Iron and steel	31.2	36.0	36.1	41.1	39.7	37.8	23	22	21	1.3	0.2
Chemicals	19.0	21.5	21.4	26.0	25.8	24.3	14	14	13	2.0	0.4
Cement	9.5	11.0	11.3	12.1	11.3	10.4	7	7	6	0.7	-0.3

Table A.2b: World final consumption (continued)

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Transport	101.7	120.9	105.1	129.9	128.3	131.4	100	100	100	2.1	0.7
Electricity	1.1	1.5	1.5	5.1	12.7	18.8	1	4	14	13	8.8
Liquid fuels	96.9	114.3	98.6	118.3	106.4	100.3	94	91	76	1.8	0.1
Biofuels	2.4	4.0	3.7	9.4	11.9	13.5	4	7	10	9.8	4.4
Oil	94.5	110.3	94.9	108.7	92.7	83.4	90	84	63	1.4	-0.4
Gaseous fuels	3.7	5.0	4.9	6.5	9.2	12.4	5	5	9	2.7	3.1
Biomethane	0.0	0.1	0.1	0.2	0.7	1.1	0	0	1	17	11
Hydrogen	0.0	0.0	0.0	0.3	2.4	5.3	0	0	4	49	25
Natural gas	3.7	5.0	4.9	5.9	6.1	6.0	5	5	5	1.9	0.7
Road	75.9	89.5	80.5	95.1	90.1	89.5	77	73	68	1.7	0.4
Passenger cars	38.6	47.7	41.7	44.5	39.2	37.3	40	34	28	0.7	-0.4
Heavy-duty trucks	20.3	24.5	22.5	31.9	33.2	35.3	21	25	27	3.5	1.5
Aviation	10.5	14.4	8.5	17.2	20.2	22.8	8	13	17	7.3	3.4
Shipping	10.4	11.4	10.7	12.6	12.6	13.2	10	10	10	1.7	0.7
Buildings	117.9	128.8	127.2	131.6	134.2	139.0	100	100	100	0.3	0.3
Electricity	34.6	43.2	42.6	51.7	60.2	69.2	33	39	50	1.9	1.6
Liquid fuels	13.3	13.1	12.8	11.0	8.6	7.9	10	8	6	-1.5	-1.6
Biofuels	0.0	0.0	0.0	0.0	0.1	0.1	0	0	0	3.6	5.6
Oil	13.3	13.1	12.8	11.0	8.5	7.8	10	8	6	-1.5	-1.6
Gaseous fuels	26.6	30.6	29.8	29.4	25.6	22.8	23	22	16	-0.1	-0.9
Biomethane	0.0	0.0	0.1	0.4	1.2	1.7	0	0	1	23	12
Hydrogen	-	-	-	0.2	1.2	1.8	-	0	1	n.a.	n.a.
Natural gas	26.2	30.1	29.4	28.2	22.3	18.3	23	21	13	-0.4	-1.6
Solid fuels	36.5	33.1	32.8	27.8	25.9	23.5	26	21	17	-1.6	-1.1
Modern biomass	4.5	4.5	4.5	5.6	6.3	6.0	4	4	4	2.1	1.0
Traditional use of biomass	26.2	24.2	24.1	20.7	18.8	17.1	19	16	12	-1.5	-1.1
Coal	5.7	4.4	4.1	1.5	0.6	0.3	3	1	0	-9.9	-8.9
Heat	6.1	6.6	6.7	7.2	7.0	6.5	5	5	5	0.6	-0.1
Other	0.9	2.2	2.5	4.5	7.0	9.1	2	3	7	6.0	4.4
Residential	84.3	90.4	89.4	90.3	90.9	94.4	70	69	68	0.1	0.2
Services	33.6	38.4	37.9	41.3	43.4	44.6	30	31	32	0.9	0.6
Other	15.9	24.7	24.3	27.7	27.7	26.5	100	100	100	1.3	0.3

Table A.3b: World electricity sector

	Announced Pledges Scenario (TWh)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total generation	21 520	26 959	26 762	34 362	45 618	54 716	100	100	100	2.5	2.4
Renewables	4 250	7 114	7 593	15 917	28 390	38 959	28	46	71	7.7	5.6
Solar PV	32	681	833	4 190	9 262	14 194	3	12	26	18	9.9
Wind	342	1 421	1 596	5 115	10 508	14 384	6	15	26	12	7.6
Hydro	3 446	4 236	4 347	5 080	5 975	6 852	16	15	13	1.6	1.5
Bioenergy	360	672	709	1 249	1 891	2 375	3	4	4	5.8	4.1
of which BECCS	-	-	-	47	284	443	-	0	1	n.a.	n.a.
CSP	2	13	13	78	359	589	0	0	1	20	14
Geothermal	68	91	94	190	331	449	0	1	1	7.3	5.3
Marine	1	1	1	15	63	115	0	0	0	27	16
Nuclear	2 756	2 790	2 692	3 282	4 040	4 449	10	10	8	2.0	1.7
Hydrogen and ammonia	-	-	-	100	376	517	-	0	1	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	131	1 152	1 729	0	0	3	74	31
Coal with CCUS	-	1	1	43	804	1 113	0	0	2	56	29
Natural gas with CCUS	-	-	-	89	348	616	-	0	1	n.a.	n.a.
Unabated fossil fuels	14 480	17 019	16 440	14 899	11 627	9 029	61	43	17	-1.0	-2.0
Coal	8 671	9 911	9 467	7 926	5 779	3 047	35	23	6	-1.8	-3.7
Natural gas	4 843	6 356	6 257	6 522	5 488	5 691	23	19	10	0.4	-0.3
Oil	966	752	716	450	361	291	3	1	1	-4.5	-3.0

	Announced Pledges Scenario (GW)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total capacity	5 192	7 467	7 782	11 996	17 867	22 795	100	100	100	4.4	3.6
Renewables	1 346	2 710	2 989	6 912	12 151	16 514	38	58	72	8.7	5.9
Solar PV	39	605	739	3 063	6 232	9 095	9	26	40	15	8.7
Wind	181	623	737	1 943	3 522	4 633	9	16	20	10	6.3
Hydro	1 027	1 306	1 327	1 584	1 837	2 050	17	13	9	1.8	1.5
Bioenergy	87	154	163	257	369	444	2	2	2	4.6	3.4
of which BECCS	-	-	-	11	54	81	-	0	0	n.a.	n.a.
CSP	1	6	6	28	110	173	0	0	1	16	12
Geothermal	11	15	16	30	56	73	0	0	0	6.9	5.3
Marine	0	1	1	7	25	46	0	0	0	24	15
Nuclear	402	415	415	465	572	641	5	4	3	1.1	1.5
Hydrogen and ammonia	-	-	-	-	300	479	-	-	2	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	21	224	341	0	0	1	68	30
Coal with CCUS	-	0	0	8	131	189	0	0	1	51	28
Natural gas with CCUS	-	-	-	14	93	151	-	0	1	n.a.	n.a.
Unabated fossil fuels	3 443	4 331	4 361	4 296	3 704	3 207	56	36	14	-0.2	-1.0
Coal	1 622	2 105	2 109	1 963	1 594	1 265	27	16	6	-0.7	-1.7
Natural gas	1 384	1 793	1 822	2 071	1 909	1 786	23	17	8	1.3	-0.1
Oil	437	433	430	261	202	156	6	2	1	-4.9	-3.3
Battery storage	1	12	17	302	916	1 613	0	3	7	33	16

Table A.4b: World CO_2 emissions

	Announced Pledges Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	32 345	35 966	34 156	33 640	26 722	20 726	-0.2	-1.7
Combustion activities (+)	30 447	33 464	31 617	30 822	24 634	19 471	-0.3	-1.6
Coal	13 828	14 768	14 240	12 614	9 235	5 713	-1.2	-3.0
Oil	10 530	11 344	10 123	10 754	9 041	7 988	0.6	-0.8
Natural gas	6 040	7 270	7 165	7 415	6 521	6 087	0.3	-0.5
Bioenergy and waste	49	82	89	40	- 164	- 317	-7.8	n.a.
Industry removals (-)	-	0	1	35	193	518	46	24
Biofuels production	-	0	1	33	142	361	45	23
Direct air capture	-	-	-	2	50	157	n.a.	n.a.
Electricity and heat sectors	12 380	13 933	13 530	11 375	8 424	5 506	-1.7	-3.0
Coal	8 933	10 171	9 832	8 056	5 787	3 045	-2.0	-3.8
Oil	826	626	601	374	298	238	-4.6	-3.0
Natural gas	2 621	3 136	3 097	2 976	2 531	2 524	-0.4	-0.7
Bioenergy and waste	-	-	-	- 32	- 193	- 301	n.a.	n.a.
Other energy sector*	1 434	1 565	1 435	1 570	1 160	726	0.9	-2.2
Final consumption*	18 530	20 467	19 191	20 696	17 188	14 650	0.8	-0.9
Coal	4 692	4 464	4 288	4 436	3 362	2 635	0.3	-1.6
Oil	9 075	10 106	8 967	9 865	8 357	7 451	1.0	-0.6
Natural gas	2 836	3 395	3 380	3 598	3 219	2 807	0.6	-0.6
Bioenergy and waste	48	82	89	72	29	- 16	-2.2	n.a.
Industry*	8 191	8 876	8 736	9 661	7 958	6 483	1.0	-1.0
Iron and steel	1 989	2 500	2 591	2 871	2 325	1 964	1.0	-0.9
Chemicals	1 143	1 182	1 160	1 301	1 009	755	1.1	-1.4
Cement	1 921	2 455	2 534	2 707	2 175	1 642	0.7	-1.4
Transport	7 010	8 211	7 102	8 149	7 012	6 339	1.4	-0.4
Road	5 217	6 043	5 419	5 889	4 855	4 338	0.8	-0.7
Passenger cars	2 615	3 192	2 788	2 725	2 135	1 889	-0.2	-1.3
Heavy-duty trucks	1 420	1 673	1 532	2 040	1 865	1 734	2.9	0.4
Aviation	751	1 027	606	1 147	1 205	1 145	6.6	2.1
Shipping	796	866	811	909	781	702	1.1	-0.5
Buildings	2 891	2 941	2 917	2 476	1 902	1 589	-1.6	-2.0
Residential	1 963	2 023	1 958	1 670	1 235	1 027	-1.6	-2.1
Services	928	918	960	806	667	562	-1.7	-1.8
Total CO_2 removals	-	0	1	67	409	885	54	26
Total CO_2 captured	4	40	40	350	2 501	3 813	24	16

*Includes industrial process emissions.

Table A.1c: World energy supply

	Sustainable Development Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	544.7	613.0	589.1	599.2	580.5	577.9	100	100	100	0.2	-0.1
Renewables	47.7	65.8	68.5	142.7	238.6	316.4	12	24	55	7.6	5.2
Solar	0.8	4.0	4.7	23.8	55.2	86.3	1	4	15	17	10
Wind	1.2	5.1	5.7	21.6	45.7	62.9	1	4	11	14	8.3
Hydro	12.4	15.2	15.6	19.4	23.8	28.5	3	3	5	2.2	2.0
Modern solid bioenergy	27.3	31.1	31.8	48.8	66.5	74.4	5	8	13	4.4	2.9
Modern liquid bioenergy	2.4	4.1	3.8	12.3	16.3	18.7	1	2	3	12	5.5
Modern gaseous bioenergy	1.0	2.1	2.2	4.9	9.1	13.5	0	1	2	8.2	6.2
Other renewables	2.6	4.2	4.5	12.0	22.0	32.1	1	2	6	10	6.8
Traditional use of biomass	26.2	24.2	24.1	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30.1	30.5	29.4	37.0	46.8	51.4	5	6	9	2.3	1.9
Unabated natural gas	115.1	141.4	138.7	134.6	93.2	59.4	24	22	10	-0.3	-2.8
Natural gas with CCUS	0.1	0.4	0.4	4.7	14.7	25.8	0	1	4	27	14
Oil	172.1	187.9	171.4	168.3	124.8	89.4	29	28	15	-0.2	-2.1
of which non-energy use	23.6	28.5	28.5	32.7	32.6	31.0	5	5	5	1.4	0.3
Unabated coal	153.0	162.2	155.8	107.6	46.6	16.9	26	18	3	-3.6	-7.1
Coal with CCUS	-	0.0	0.0	3.4	15.0	17.9	0	1	3	84	29
Electricity and heat sectors	199.8	233.5	230.5	242.4	277.1	327.6	100	100	100	0.5	1.2
Renewables	21.2	35.7	38.1	88.1	165.0	234.1	17	36	71	8.8	6.2
Solar PV	0.1	2.5	3.0	18.0	40.6	62.8	1	7	19	20	11
Wind	1.2	5.1	5.7	21.6	45.7	62.9	2	9	19	14	8.3
Hydro	12.4	15.2	15.6	19.4	23.8	28.5	7	8	9	2.2	2.0
Bioenergy	5.1	9.5	10.1	18.0	29.2	38.7	4	7	12	6.0	4.6
Other renewables	2.4	3.4	3.6	11.2	25.7	41.2	2	5	13	12	8.5
Hydrogen	-	-	-	0.6	2.4	3.3	-	0	1	n.a.	n.a.
Ammonia	-	-	-	0.0	0.3	3.2	-	0	1	n.a.	n.a.
Nuclear	30.1	30.5	29.4	37.0	46.8	51.4	13	15	16	2.3	1.9
Unabated natural gas	46.7	55.7	55.1	51.3	29.9	17.1	24	21	5	-0.7	-3.8
Natural gas with CCUS	-	-	-	0.7	3.2	5.1	-	0	2	n.a.	n.a.
Oil	10.9	8.2	7.9	3.8	2.2	1.6	3	2	0	-7.1	-5.2
Unabated coal	91.0	103.3	100.0	58.3	16.5	0.7	43	24	0	-5.3	-15
Coal with CCUS	-	0.0	0.0	2.5	10.9	11.1	0	1	3	86	29
Other energy sector	54.2	59.1	58.1	61.6	69.2	77.5	100	100	100	0.6	1.0
Hydrogen production	-	-	-	4.0	17.3	34.6	-	7	45	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	10.3	16.0	19.9	8	17	26	8.6	5.1

Table A.2c: World final consumption

	Sustainable Development Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total final consumption	382.5	432.9	412.8	434.3	411.0	392.3	100	100	100	0.5	-0.2
Electricity	64.5	82.4	81.8	104.3	131.0	155.8	20	24	40	2.5	2.2
Liquid fuels	152.5	173.3	157.3	168.8	135.4	107.3	38	39	27	0.7	-1.3
Biofuels	2.4	4.1	3.8	12.3	16.3	18.7	1	3	5	12	5.5
Ammonia	-	-	-	0.2	1.3	2.7	-	0	1	n.a.	n.a.
Synthetic oil	-	-	-	0.2	1.1	2.2	-	0	1	n.a.	n.a.
Oil	150.1	169.3	153.5	156.2	116.6	83.8	37	36	21	0.2	-2.0
Gaseous fuels	57.6	70.2	68.7	73.3	66.9	59.6	17	17	15	0.6	-0.5
Biomethane	0.0	0.1	0.2	1.2	3.6	6.5	0	0	2	22	13
Hydrogen	0.0	0.0	0.0	1.6	6.1	11.4	0	0	3	73	28
Synthetic methane	-	-	-	-	-	-	-	-	-	n.a.	n.a.
Natural gas	57.2	69.7	68.2	69.6	56.0	40.4	17	16	10	0.2	-1.7
Solid fuels	95.6	91.8	89.2	68.1	56.0	46.6	22	16	12	-2.7	-2.1
Solid bioenergy	38.8	37.8	37.9	23.0	24.0	23.8	9	5	6	-4.9	-1.5
Coal	56.4	53.4	50.6	44.5	31.5	22.3	12	10	6	-1.3	-2.7
Heat	11.5	12.8	13.1	13.1	10.9	8.5	3	3	2	0.0	-1.4
Other	0.9	2.3	2.6	6.7	10.9	14.5	1	2	4	9.7	5.8
Industry	146.9	158.6	156.1	175.9	172.9	164.5	100	100	100	1.2	0.2
Electricity	26.8	34.4	34.4	44.8	54.5	61.8	22	25	38	2.7	2.0
Liquid fuels	31.3	31.3	31.3	33.2	30.5	26.7	20	19	16	0.6	-0.5
Oil	31.3	31.3	31.3	33.2	30.5	26.7	20	19	16	0.6	-0.5
Gaseous fuels	26.1	29.5	29.1	34.6	34.4	31.3	19	20	19	1.8	0.2
Biomethane	0.0	0.0	0.1	0.5	1.6	3.3	0	0	2	24	15
Hydrogen	-	-	-	0.7	1.8	2.4	-	0	1	n.a.	n.a.
Unabated natural gas	26.1	29.4	29.0	32.7	28.2	20.4	19	19	12	1.2	-1.2
Natural gas with CCUS	-	0.0	0.0	0.7	2.7	5.3	0	0	3	31	17
Solid fuels	57.4	57.2	54.9	56.1	46.9	38.6	35	32	23	0.2	-1.2
Solid bioenergy	8.1	9.3	9.5	13.6	15.9	16.7	6	8	10	3.7	1.9
Unabated coal	49.3	47.9	45.5	41.8	27.1	15.2	29	24	9	-0.8	-3.6
Coal with CCUS	-	0.0	0.0	0.7	3.9	6.8	0	0	4	74	30
Heat	5.3	6.1	6.3	6.3	4.8	3.3	4	4	2	0.1	-2.1
Other	0.0	0.0	0.0	0.8	1.8	2.6	0	0	2	35	15
Iron and steel	31.2	36.0	36.1	39.7	36.7	34.3	23	23	21	1.0	-0.2
Chemicals	19.0	21.5	21.4	25.3	25.2	23.2	14	14	14	1.7	0.3
Cement	9.5	11.0	11.3	12.1	10.8	9.9	7	7	6	0.7	-0.4

Table A.2c: World final consumption (continued)

	Sustainable Development Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Transport	**101.7**	**120.9**	**105.1**	**121.6**	**108.0**	**101.2**	**100**	**100**	**100**	**1.5**	**-0.1**
Electricity	1.1	1.5	1.5	5.6	15.2	25.7	1	5	25	14	9.9
Liquid fuels	96.9	114.3	98.6	110.2	85.0	64.4	94	91	64	1.1	-1.4
Biofuels	2.4	4.0	3.7	11.5	14.7	16.8	4	9	17	12	5.2
Oil	94.5	110.3	94.9	98.3	67.8	42.8	90	81	42	0.3	-2.6
Gaseous fuels	3.7	5.0	4.9	5.8	7.8	11.1	5	5	11	1.6	2.7
Biomethane	0.0	0.1	0.1	0.3	0.7	1.3	0	0	1	18	11
Hydrogen	0.0	0.0	0.0	0.5	2.9	7.0	0	0	7	54	26
Natural gas	3.7	5.0	4.9	5.1	4.2	2.8	5	4	3	0.4	-1.8
Road	75.9	89.5	80.5	89.2	74.7	65.6	77	73	65	1.0	-0.7
Passenger cars	38.6	47.7	41.7	40.8	29.6	22.6	40	34	22	-0.2	-2.0
Heavy-duty trucks	20.3	24.5	22.5	30.3	29.1	29.3	21	25	29	3.0	0.9
Aviation	10.5	14.4	8.5	16.2	18.3	20.4	8	13	20	6.7	3.0
Shipping	10.4	11.4	10.7	11.5	10.6	10.4	10	9	10	0.8	-0.1
Buildings	**117.9**	**128.8**	**127.2**	**110.3**	**104.6**	**103.1**	**100**	**100**	**100**	**-1.4**	**-0.7**
Electricity	34.6	43.2	42.6	49.9	57.1	64.2	33	45	62	1.6	1.4
Liquid fuels	13.3	13.1	12.8	10.4	5.7	3.4	10	9	3	-2.1	-4.4
Biofuels	0.0	0.0	0.0	0.2	0.3	0.3	0	0	0	21	9.1
Oil	13.3	13.1	12.8	10.2	5.4	3.0	10	9	3	-2.2	-4.7
Gaseous fuels	26.6	30.6	29.8	26.9	18.7	11.6	23	24	11	-1.0	-3.1
Biomethane	0.0	0.0	0.1	0.4	1.2	1.8	0	0	2	23	12
Hydrogen	-	-	-	0.3	1.4	2.0	-	0	2	n.a.	n.a.
Natural gas	26.2	30.1	29.4	25.4	15.2	6.7	23	23	7	-1.4	-4.8
Solid fuels	36.5	33.1	32.8	10.9	8.6	7.6	26	10	7	-10	-4.8
Modern biomass	4.5	4.5	4.5	9.5	8.4	7.4	4	9	7	7.7	1.7
Traditional use of biomass	26.2	24.2	24.1	-	-	-	19	-	-	n.a.	n.a.
Coal	5.7	4.4	4.1	1.3	0.0	0.0	3	1	0	-11	-20
Heat	6.1	6.6	6.7	6.7	6.0	5.1	5	6	5	-0.1	-0.9
Other	0.9	2.2	2.5	5.5	8.6	11.2	2	5	11	8.3	5.1
Residential	84.3	90.4	89.4	71.7	67.5	67.8	70	65	66	-2.2	-0.9
Services	33.6	38.4	37.9	38.6	37.1	35.3	30	35	34	0.2	-0.2
Other	**15.9**	**24.7**	**24.3**	**26.6**	**25.5**	**23.5**	**100**	**100**	**100**	**0.9**	**-0.1**

Table A.3c: World electricity sector

	Sustainable Development Scenario (TWh)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total generation	21 520	26 959	26 762	34 424	45 885	57 950	100	100	100	2.5	2.6
Renewables	4 250	7 114	7 593	18 283	34 349	48 436	28	53	84	9.2	6.4
Solar PV	32	681	833	4 989	11 273	17 433	3	14	30	20	11
Wind	342	1 421	1 596	6 115	12 817	17 577	6	18	30	14	8.3
Hydro	3 446	4 236	4 347	5 387	6 599	7 921	16	16	14	2.2	2.0
Bioenergy	360	672	709	1 362	2 336	3 199	3	4	6	6.8	5.2
of which BECCS	-	-	-	42	328	593	-	0	1	n.a.	n.a.
CSP	2	13	13	129	717	1 377	0	0	2	26	17
Geothermal	68	91	94	284	538	801	0	1	1	12	7.4
Marine	1	1	1	16	69	129	0	0	0	28	16
Nuclear	2 756	2 790	2 692	3 395	4 293	4 714	10	10	8	2.3	1.9
Hydrogen and ammonia	-	-	-	100	389	805	-	0	1	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	323	1 480	1 790	0	1	3	91	31
Coal with CCUS	-	1	1	226	1 019	1 046	0	1	2	84	29
Natural gas with CCUS	-	-	-	97	460	744	-	0	1	n.a.	n.a.
Unabated fossil fuels	14 480	17 019	16 440	12 290	5 341	2 172	61	36	4	-2.9	-6.5
Coal	8 671	9 911	9 467	5 618	1 559	42	35	16	0	-5.1	-17
Natural gas	4 843	6 356	6 257	6 345	3 610	2 011	23	18	3	0.1	-3.7
Oil	966	752	716	327	172	119	3	1	0	-7.5	-5.8

	Sustainable Development Scenario (GW)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total capacity	5 192	7 467	7 782	12 728	19 883	25 996	100	100	100	5.0	4.1
Renewables	1 346	2 710	2 989	8 017	14 725	20 304	38	63	78	10	6.6
Solar PV	39	605	739	3 582	7 421	10 865	9	28	42	17	9.4
Wind	181	623	737	2 378	4 471	5 881	9	19	23	12	7.2
Hydro	1 027	1 306	1 327	1 679	2 032	2 360	17	13	9	2.4	1.9
Bioenergy	87	154	163	281	456	599	2	2	2	5.6	4.4
of which BECCS	-	-	-	9	63	107	-	0	0	n.a.	n.a.
CSP	1	6	6	46	232	424	0	0	2	22	15
Geothermal	11	15	16	44	86	124	0	0	0	11	7.2
Marine	0	1	1	7	28	51	0	0	0	25	15
Nuclear	402	415	415	475	607	669	5	4	3	1.4	1.6
Hydrogen and ammonia	-	-	-	-	360	528	-	-	2	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	53	288	384	0	0	1	84	31
Coal with CCUS	-	0	0	37	170	203	0	0	1	78	28
Natural gas with CCUS	-	-	-	16	118	181	-	0	1	n.a.	n.a.
Unabated fossil fuels	3 443	4 331	4 361	3 843	2 782	1 988	56	30	8	-1.3	-2.6
Coal	1 622	2 105	2 109	1 564	782	283	27	12	1	-2.9	-6.5
Natural gas	1 384	1 793	1 822	2 023	1 798	1 548	23	16	6	1.0	-0.5
Oil	437	433	430	256	202	157	6	2	1	-5.1	-3.3
Battery storage	1	12	17	341	1 122	2 123	0	3	8	35	17

Table A.4c: World CO_2 emissions

	Sustainable Development Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	32 345	35 966	34 156	28 487	16 441	8 170	-1.8	-4.7
Combustion activities (+)	30 447	33 464	31 617	26 049	14 924	7 807	-1.9	-4.6
Coal	13 828	14 768	14 240	9 493	4 034	1 395	-4.0	-7.5
Oil	10 530	11 344	10 123	9 571	6 413	3 986	-0.6	-3.1
Natural gas	6 040	7 270	7 165	6 931	4 645	2 799	-0.3	-3.1
Bioenergy and waste	49	82	89	54	- 168	- 373	-5.0	n.a.
Industry removals (-)	-	0	1	73	234	643	57	25
Biofuels production	-	0	1	64	181	419	55	23
Direct air capture	-	-	-	10	53	224	n.a.	n.a.
Electricity and heat sectors	12 380	13 933	13 530	8 891	3 376	887	-4.1	-8.7
Coal	8 933	10 171	9 832	5 741	1 733	179	-5.2	-12
Oil	826	626	601	290	168	121	-7.0	-5.2
Natural gas	2 621	3 136	3 097	2 888	1 698	990	-0.7	-3.7
Bioenergy and waste	-	-	-	- 28	- 223	- 403	n.a.	n.a.
Other energy sector*	1 434	1 565	1 435	1 296	681	101	-1.0	-8.5
Final consumption*	18 530	20 467	19 191	18 311	12 437	7 406	-0.5	-3.1
Coal	4 692	4 464	4 288	3 637	2 226	1 190	-1.6	-4.2
Oil	9 075	10 106	8 967	8 850	5 996	3 719	-0.1	-2.9
Natural gas	2 836	3 395	3 380	3 345	2 461	1 462	-0.1	-2.8
Bioenergy and waste	48	82	89	82	56	30	-0.8	-3.5
Industry*	8 191	8 876	8 736	8 377	5 874	3 447	-0.4	-3.1
Iron and steel	1 989	2 500	2 591	2 574	1 745	1 027	-0.1	-3.0
Chemicals	1 143	1 182	1 160	1 169	873	440	0.1	-3.2
Cement	1 921	2 455	2 534	2 552	1 635	755	0.1	-4.0
Transport	7 010	8 211	7 102	7 348	5 112	3 239	0.3	-2.6
Road	5 217	6 043	5 419	5 343	3 468	1 996	-0.1	-3.3
Passenger cars	2 615	3 192	2 788	2 425	1 356	617	-1.4	-4.9
Heavy-duty trucks	1 420	1 673	1 532	1 866	1 457	1 076	2.0	-1.2
Aviation	751	1 027	606	1 028	968	797	5.4	0.9
Shipping	796	866	811	809	564	372	-0.0	-2.6
Buildings	2 891	2 941	2 917	2 249	1 238	599	-2.6	-5.1
Residential	1 963	2 023	1 958	1 582	891	419	-2.1	-5.0
Services	928	918	960	667	347	180	-3.6	-5.4
Total CO_2 removals	-	0	1	103	466	1 076	60	27
Total CO_2 captured	4	40	40	892	3 461	5 404	36	18

*Includes industrial process emissions.

Table A.1d: World energy supply

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	**544.7**	**613.0**	**589.1**	**547.1**	**534.5**	**543.0**	**100**	**100**	**100**	**-0.7**	**-0.3**
Renewables	47.7	65.8	68.5	166.6	294.6	362.1	12	30	67	9.3	5.7
Solar	0.8	4.0	4.7	32.0	78.3	109.1	1	6	20	21	11
Wind	1.2	5.1	5.7	28.5	67.3	88.9	1	5	16	17	9.6
Hydro	12.4	15.2	15.6	21.1	26.8	30.5	3	4	6	3.1	2.2
Modern solid bioenergy	27.3	31.1	31.8	53.8	73.3	73.5	5	10	14	5.4	2.8
Modern liquid bioenergy	2.4	4.1	3.8	12.5	14.3	14.6	1	2	3	13	4.6
Modern gaseous bioenergy	1.0	2.1	2.2	5.4	10.0	13.7	0	1	3	9.4	6.3
Other renewables	2.6	4.2	4.5	13.2	24.5	31.8	1	2	6	11	6.7
Traditional use of biomass	26.2	24.2	24.1	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30.1	30.5	29.4	41.4	54.3	60.6	5	8	11	3.5	2.4
Unabated natural gas	115.1	141.4	138.7	116.1	43.6	17.4	24	21	3	-1.8	-6.7
Natural gas with CCUS	0.1	0.4	0.4	13.3	31.0	43.3	0	2	8	40	16
Oil	172.1	187.9	171.4	137.4	79.2	42.2	29	25	8	-2.2	-4.6
of which non-energy use	23.6	28.5	28.5	31.7	30.9	29.3	5	6	5	1.1	0.1
Unabated coal	153.0	162.2	155.8	67.5	16.0	3.3	26	12	1	-8.0	-12
Coal with CCUS	-	0.0	0.0	4.4	15.6	13.9	0	1	3	89	28
Electricity and heat sectors	**199.8**	**233.5**	**230.5**	**239.9**	**307.7**	**370.7**	**100**	**100**	**100**	**0.4**	**1.6**
Renewables	21.2	35.7	38.1	106.7	220.4	284.4	17	44	77	11	6.9
Solar PV	0.1	2.5	3.0	25.1	61.3	84.5	1	10	23	24	12
Wind	1.2	5.1	5.7	28.5	67.3	88.9	2	12	24	17	9.6
Hydro	12.4	15.2	15.6	21.1	26.8	30.5	7	9	8	3.1	2.2
Bioenergy	5.1	9.5	10.1	18.4	34.7	38.6	4	8	10	6.2	4.6
Other renewables	2.4	3.4	3.6	13.5	30.2	41.9	2	6	11	14	8.5
Hydrogen	-	-	-	5.1	11.5	10.5	-	2	3	n.a.	n.a.
Ammonia	-	-	-	1.0	1.9	1.6	-	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	41.4	54.3	60.6	13	17	16	3.5	2.4
Unabated natural gas	46.7	55.7	55.1	49.3	4.3	1.8	24	21	0	-1.1	-11
Natural gas with CCUS	-	-	-	1.2	4.9	4.7	-	1	1	n.a.	n.a.
Oil	10.9	8.2	7.9	2.2	0.1	0.1	3	1	0	-12	-14
Unabated coal	91.0	103.3	100.0	29.7	0.0	0.0	43	12	0	-11	-34
Coal with CCUS	-	0.0	0.0	3.2	10.4	7.1	0	1	2	91	27
Other energy sector	**54.2**	**59.1**	**58.1**	**61.3**	**75.9**	**90.6**	**100**	**100**	**100**	**0.5**	**1.5**
Hydrogen production	-	-	-	21.4	49.2	69.7	-	35	77	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	12.2	16.1	15.4	8	20	17	10	4.2

Table A.2d: World final consumption

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total final consumption	382.5	432.9	412.8	393.6	362.5	343.6	100	100	100	-0.5	-0.6
Electricity	64.5	82.4	81.8	103.2	139.8	169.2	20	26	49	2.3	2.5
Liquid fuels	152.5	173.3	157.3	142.6	96.2	65.8	38	36	19	-1.0	-2.9
Biofuels	2.4	4.1	3.8	12.5	14.2	14.4	1	3	4	13	4.5
Ammonia	-	-	-	0.9	2.9	4.6	-	0	1	n.a.	n.a.
Synthetic oil	-	-	-	0.4	2.3	4.8	-	0	1	n.a.	n.a.
Oil	150.1	169.3	153.5	128.8	76.7	42.1	37	33	12	-1.7	-4.2
Gaseous fuels	57.6	70.2	68.7	67.9	60.3	53.0	17	17	15	-0.1	-0.9
Biomethane	0.0	0.1	0.2	2.0	5.0	7.6	0	1	2	29	14
Hydrogen	0.0	0.0	0.0	6.4	12.4	19.7	0	2	6	99	31
Synthetic methane	-	-	-	0.2	1.1	4.0	-	0	1	n.a.	n.a.
Natural gas	57.2	69.7	68.2	58.3	40.3	19.8	17	15	6	-1.6	-4.0
Solid fuels	95.6	91.8	89.2	64.4	49.9	38.7	22	16	11	-3.2	-2.7
Solid bioenergy	38.8	37.8	37.9	23.7	25.3	25.3	9	6	7	-4.6	-1.3
Coal	56.4	53.4	50.6	37.6	20.7	9.7	12	10	3	-2.9	-5.4
Heat	11.5	12.8	13.1	11.7	8.7	5.9	3	3	2	-1.2	-2.7
Other	0.9	2.3	2.6	3.8	7.6	11.1	1	1	3	3.8	4.9
Industry	146.9	158.6	156.1	170.1	169.4	160.4	100	100	100	0.9	0.1
Electricity	26.8	34.4	34.4	46.8	62.5	73.8	22	28	46	3.1	2.6
Liquid fuels	31.3	31.3	31.3	30.6	27.2	23.4	20	18	15	-0.2	-1.0
Oil	31.3	31.3	31.3	30.6	27.2	23.4	20	18	15	-0.2	-1.0
Gaseous fuels	26.1	29.5	29.1	35.2	34.1	28.1	19	21	18	1.9	-0.1
Biomethane	0.0	0.0	0.1	0.5	2.0	4.3	0	0	3	26	16
Hydrogen	-	-	-	3.1	4.3	4.8	-	2	3	n.a.	n.a.
Unabated natural gas	26.1	29.4	29.0	30.1	22.0	9.2	19	18	6	0.4	-3.8
Natural gas with CCUS	-	0.0	0.0	1.3	5.1	6.5	0	1	4	39	18
Solid fuels	57.4	57.2	54.9	50.7	39.5	29.6	35	30	18	-0.8	-2.0
Solid bioenergy	8.1	9.3	9.5	14.9	19.1	20.2	6	9	13	4.6	2.6
Unabated coal	49.3	47.9	45.5	34.6	15.1	2.6	29	20	2	-2.7	-9.2
Coal with CCUS	-	0.0	0.0	1.2	5.3	6.8	0	1	4	84	30
Heat	5.3	6.1	6.3	5.5	3.4	1.6	4	3	1	-1.2	-4.5
Other	0.0	0.0	0.0	1.2	2.6	3.8	0	1	2	41	16
Iron and steel	31.2	36.0	36.1	36.7	35.7	31.4	23	22	20	0.2	-0.5
Chemicals	19.0	21.5	21.4	25.4	25.3	23.7	14	15	15	1.7	0.3
Cement	9.5	11.0	11.3	11.1	10.7	10.5	7	7	7	-0.2	-0.3

Table A.2d: World final consumption (continued)

	Net Zero Emissions by 2050 Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Transport	101.7	120.9	105.1	102.4	84.5	79.5	100	100	100	-0.3	-0.9
Electricity	1.1	1.5	1.5	7.3	22.1	34.8	1	7	44	17	11
Liquid fuels	96.9	114.3	98.6	89.0	52.7	30.2	94	87	38	-1.0	-3.9
Biofuels	2.4	4.0	3.7	11.5	12.0	11.4	4	11	14	12	3.8
Oil	94.5	110.3	94.9	76.2	35.5	9.4	90	74	12	-2.2	-7.4
Gaseous fuels	3.7	5.0	4.9	6.1	9.7	14.5	5	6	18	2.1	3.7
Biomethane	0.0	0.1	0.1	0.5	1.2	1.5	0	0	2	25	12
Hydrogen	0.0	0.0	0.0	1.4	6.2	12.8	0	1	16	71	29
Natural gas	3.7	5.0	4.9	4.2	2.3	0.1	5	4	0	-1.5	-11
Road	75.9	89.5	80.5	73.2	56.5	50.0	77	72	63	-0.9	-1.6
Passenger cars	38.6	47.7	41.7	29.7	18.7	16.7	40	29	21	-3.3	-3.0
Heavy-duty trucks	20.3	24.5	22.5	27.8	24.3	22.1	21	27	28	2.1	-0.1
Aviation	10.5	14.4	8.5	13.2	12.8	14.0	8	13	18	4.5	1.7
Shipping	10.4	11.4	10.7	11.3	10.2	9.9	10	11	12	0.5	-0.3
Buildings	117.9	128.8	127.2	99.0	88.7	86.0	100	100	100	-2.5	-1.3
Electricity	34.6	43.2	42.6	45.3	51.2	56.9	33	46	66	0.6	1.0
Liquid fuels	13.3	13.1	12.8	9.5	4.4	2.0	10	10	2	-3.0	-5.9
Biofuels	0.0	0.0	0.0	0.3	0.6	0.9	0	0	1	28	13
Oil	13.3	13.1	12.8	9.2	3.8	1.2	10	9	1	-3.3	-7.6
Gaseous fuels	26.6	30.6	29.8	23.0	12.5	6.3	23	23	7	-2.6	-5.1
Biomethane	0.0	0.0	0.1	0.8	1.7	1.5	0	1	2	32	12
Hydrogen	-	-	-	1.8	1.9	2.1	-	2	2	n.a.	n.a.
Natural gas	26.2	30.1	29.4	19.3	7.5	0.7	23	20	1	-4.1	-12
Solid fuels	36.5	33.1	32.8	10.2	7.0	6.1	26	10	7	-11	-5.5
Modern biomass	4.5	4.5	4.5	9.0	6.9	6.0	4	9	7	7.1	1.0
Traditional use of biomass	26.2	24.2	24.1	-	-	-	19	-	-	n.a.	n.a.
Coal	5.7	4.4	4.1	1.1	0.1	0.0	3	1	0	-12	-21
Heat	6.1	6.6	6.7	6.0	5.1	4.2	5	6	5	-1.2	-1.6
Other	0.9	2.2	2.5	5.1	8.3	10.6	2	5	12	7.4	4.9
Residential	84.3	90.4	89.4	66.8	58.6	58.0	70	67	67	-2.9	-1.4
Services	33.6	38.4	37.9	32.3	30.1	28.0	30	33	33	-1.6	-1.0
Other	15.9	24.7	24.3	22.1	20.0	17.7	100	100	100	-1.0	-1.1

Table A.3d: World electricity sector

	Net Zero Emissions by 2050 Scenario (TWh)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total generation	21 520	26 959	26 762	37 316	56 553	71 164	100	100	100	3.4	3.3
Renewables	4 250	7 114	7 593	22 817	47 521	62 333	28	61	88	12	7.3
Solar PV	32	681	833	6 970	17 031	23 469	3	19	33	24	12
Wind	342	1 421	1 596	8 008	18 787	24 785	6	21	35	18	9.6
Hydro	3 446	4 236	4 347	5 870	7 445	8 461	16	16	12	3.0	2.2
Bioenergy	360	672	709	1 407	2 676	3 279	3	4	5	7.1	5.2
of which BECCS	-	-	-	129	673	842	-	0	1	n.a.	n.a.
CSP	2	13	13	204	880	1 386	0	1	2	32	17
Geothermal	68	91	94	330	625	821	0	1	1	13	7.5
Marine	1	1	1	27	77	132	0	0	0	34	16
Nuclear	2 756	2 790	2 692	3 777	4 855	5 497	10	10	8	3.4	2.4
Hydrogen and ammonia	-	-	-	875	1 857	1 713	-	2	2	n.a.	n.a.
Fossil fuels with CCUS	-	1	1	459	1 659	1 332	0	1	2	97	30
Coal with CCUS	-	1	1	289	966	663	0	1	1	89	27
Natural gas with CCUS	-	-	-	170	694	669	-	0	1	n.a.	n.a.
Unabated fossil fuels	14 480	17 019	16 440	9 358	632	259	61	25	0	-5.5	-13
Coal	8 671	9 911	9 467	2 947	0	0	35	8	0	-11	-40
Natural gas	4 843	6 356	6 257	6 222	626	253	23	17	0	-0.1	-10
Oil	966	752	716	189	6	6	3	1	0	-12	-15

	Net Zero Emissions by 2050 Scenario (GW)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total capacity	5 192	7 467	7 782	14 933	26 384	33 415	100	100	100	6.7	5.0
Renewables	1 346	2 710	2 989	10 293	20 732	26 568	38	69	80	13	7.6
Solar PV	39	605	739	4 956	10 980	14 458	9	33	43	21	10
Wind	181	623	737	3 101	6 525	8 265	9	21	25	15	8.4
Hydro	1 027	1 306	1 327	1 804	2 282	2 599	17	12	8	3.1	2.3
Bioenergy	87	154	163	297	534	640	2	2	2	6.2	4.7
of which BECCS	-	-	-	28	125	152	-	0	0	n.a.	n.a.
CSP	1	6	6	73	281	426	0	0	1	27	15
Geothermal	11	15	16	52	98	126	0	0	0	13	7.2
Marine	0	1	1	11	32	55	0	0	0	31	15
Nuclear	402	415	415	515	730	812	5	3	2	2.2	2.3
Hydrogen and ammonia	-	-	-	139	1 455	1 867	-	1	6	n.a.	n.a.
Fossil fuels with CCUS	-	0	0	81	312	394	0	1	1	92	31
Coal with CCUS	-	0	0	53	182	222	0	0	1	84	29
Natural gas with CCUS	-	-	-	28	130	171	-	0	1	n.a.	n.a.
Unabated fossil fuels	3 443	4 331	4 361	3 320	1 151	677	56	22	2	-2.7	-6.0
Coal	1 622	2 105	2 109	1 192	432	158	27	8	0	-5.5	-8.3
Natural gas	1 384	1 793	1 822	1 950	679	495	23	13	1	0.7	-4.3
Oil	437	433	430	178	39	25	6	1	0	-8.4	-9.0
Battery storage	1	12	17	585	2 005	3 097	0	4	9	43	19

Table A.4d: World CO_2 emissions

	Net Zero Emissions by 2050 Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	32 345	35 966	34 156	21 147	6 316	0	-4.7	n.a.
Combustion activities (+)	30 447	33 464	31 617	19 254	6 030	940	-4.8	-11
Coal	13 828	14 768	14 240	5 915	1 299	195	-8.4	-13
Oil	10 530	11 344	10 123	7 426	3 329	928	-3.1	-7.7
Natural gas	6 040	7 270	7 165	5 960	1 929	566	-1.8	-8.1
Bioenergy and waste	49	82	89	- 48	- 528	- 748	n.a.	n.a.
Industry removals (-)	-	0	1	214	914	1 186	75	28
Biofuels production	-	0	1	142	385	553	68	24
Direct air capture	-	-	-	71	528	633	n.a.	n.a.
Electricity and heat sectors	12 380	13 933	13 530	5 816	- 81	- 369	-8.1	n.a.
Coal	8 933	10 171	9 832	2 950	102	69	-11	-15
Oil	826	626	601	173	6	6	-12	-14
Natural gas	2 621	3 136	3 097	2 781	268	128	-1.1	-10
Bioenergy and waste	-	-	-	- 87	- 457	- 572	n.a.	n.a.
Other energy sector*	1 434	1 565	1 435	679	- 85	- 368	-7.2	n.a.
Final consumption*	18 530	20 467	19 191	13 574	6 438	1 139	-3.4	-9.0
Coal	4 692	4 464	4 288	2 935	1 186	117	-3.7	-11
Oil	9 075	10 106	8 967	6 973	3 242	880	-2.5	-7.4
Natural gas	2 836	3 395	3 380	2 668	1 453	303	-2.3	-7.7
Bioenergy and waste	48	82	89	40	- 70	- 176	-7.8	n.a.
Industry*	8 191	8 876	8 736	6 892	3 485	519	-2.3	-9.0
Iron and steel	1 989	2 500	2 591	1 996	909	112	-2.6	-9.9
Chemicals	1 143	1 182	1 160	1 078	634	65	-0.7	-9.1
Cement	1 921	2 455	2 534	1 899	906	133	-2.8	-9.4
Transport	7 010	8 211	7 102	5 719	2 686	689	-2.1	-7.5
Road	5 217	6 043	5 419	4 077	1 793	340	-2.8	-8.8
Passenger cars	2 615	3 192	2 788	1 626	547	85	-5.2	-11
Heavy-duty trucks	1 420	1 673	1 532	1 614	890	198	0.5	-6.6
Aviation	751	1 027	606	783	469	210	2.6	-3.5
Shipping	796	866	811	705	348	122	-1.4	-6.1
Buildings	2 891	2 941	2 917	1 809	685	122	-4.7	-10
Residential	1 963	2 023	1 958	1 377	541	108	-3.5	-9.2
Services	928	918	960	432	144	14	-7.7	-13
Total CO_2 removals	-	0	1	317	1 457	1 936	80	29
Total CO_2 captured	4	40	40	1 665	5 619	7 602	45	19

*Includes industrial process emissions.

Table A.5: Total energy supply (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	544.7	613.0	589.1	671.0	743.9	651.1	674.4	599.2	577.9
North America	112.6	115.8	107.7	112.1	106.2	101.9	82.7	101.3	80.3
United States	94.1	94.8	88.3	90.9	83.6	82.3	64.4	82.6	64.5
Central and South America	26.6	28.5	26.9	31.4	41.0	29.8	35.9	28.7	33.3
Brazil	12.1	13.5	13.1	15.3	19.8	13.9	15.4	14.2	15.8
Europe	89.2	82.4	77.5	75.5	69.9	71.8	61.6	70.2	56.5
European Union	64.5	59.5	55.5	52.4	45.1	48.9	37.8	48.8	37.6
Africa	28.0	34.6	34.0	42.4	61.8	41.7	59.5	29.6	43.1
Middle East	26.2	32.9	32.2	39.3	53.6	39.5	55.2	34.9	45.0
Eurasia	35.2	39.8	38.3	42.4	47.2	42.6	47.2	40.0	37.1
Russia	28.5	32.2	31.0	34.1	35.6	34.2	35.6	32.5	29.9
Asia Pacific	211.8	261.4	259.4	306.7	335.6	303.8	309.1	276.2	265.1
China	107.3	143.4	146.1	163.4	157.3	162.5	133.4	149.9	125.1
India	29.3	39.1	37.2	52.1	70.5	52.0	70.4	43.6	52.7
Japan	20.9	17.4	16.2	15.8	13.3	15.0	12.1	15.0	12.1
Southeast Asia	22.7	29.9	29.1	39.5	51.9	39.6	51.8	36.1	40.2

Table A.6: Renewables energy supply (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	47.7	65.8	68.5	109.0	192.5	120.6	248.4	142.7	316.4
North America	9.4	12.6	12.8	18.8	29.0	24.9	43.8	26.0	46.6
United States	6.9	9.8	9.9	15.0	23.6	20.2	36.8	20.8	37.6
Central and South America	7.7	9.5	9.5	12.6	19.5	12.9	20.4	14.0	23.5
Brazil	5.6	6.6	6.6	8.4	12.0	8.5	11.8	8.8	12.2
Europe	10.3	13.8	14.3	20.2	27.9	22.8	34.0	23.8	37.4
European Union	8.1	10.3	10.5	15.0	19.9	17.1	25.7	17.1	25.7
Africa	3.3	4.5	4.6	7.9	16.5	8.3	17.6	10.2	27.0
Middle East	0.1	0.2	0.2	1.0	4.8	1.0	6.2	3.0	17.9
Eurasia	1.1	1.3	1.3	1.9	4.7	1.9	4.6	3.3	11.2
Russia	0.9	1.0	1.0	1.5	3.9	1.5	3.8	2.4	8.1
Asia Pacific	15.7	23.9	25.8	46.0	88.0	47.9	117.8	61.1	146.6
China	4.7	11.7	12.9	24.7	43.0	25.3	67.7	30.5	67.4
India	2.6	4.2	4.4	7.9	20.3	7.9	20.3	10.7	29.9
Japan	0.9	1.3	1.4	1.9	3.2	2.5	5.2	2.5	5.2
Southeast Asia	2.8	4.9	5.1	7.7	12.9	7.6	12.9	10.9	26.1

Table A.7: Oil production (mb/d)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World supply	85.5	97.9	91.3	103.0	103.0	96.1	76.7	87.6	47.0
Processing gains	2.2	2.4	2.1	2.6	3.0	2.4	2.3	2.2	1.4
World production	83.4	95.5	89.2	100.4	99.9	93.7	74.4	85.4	45.6
Conventional crude oil	66.8	65.1	59.6	64.1	61.2	59.9	46.6	53.6	25.1
Tight oil	0.7	7.7	7.3	10.6	10.9	9.8	7.8	8.7	6.4
Natural gas liquids	12.7	18.1	18.1	20.4	21.4	19.3	17.2	18.6	11.7
Extra-heavy oil & bitumen	2.6	3.8	3.3	4.1	5.0	3.8	2.3	3.5	2.2
Other	0.6	0.8	0.9	1.2	1.4	0.9	0.5	1.0	0.2
Non-OPEC	50.1	60.5	58.3	63.8	56.2	59.1	39.1	53.6	25.9
OPEC	33.3	35.0	30.9	36.6	43.7	34.6	35.4	31.7	19.6
North America	14.2	24.7	23.8	27.7	23.2	25.2	15.6	23.7	13.3
Central and South America	7.4	6.3	5.9	7.9	10.9	7.5	6.2	6.7	3.4
Europe	4.4	3.6	3.8	3.2	1.6	2.9	0.7	2.6	0.7
European Union	0.7	0.5	0.5	0.4	0.3	0.3	0.1	0.3	0.1
Africa	10.2	8.5	7.0	6.9	7.3	6.5	4.1	6.0	3.4
Middle East	25.4	30.2	27.7	34.0	39.7	32.1	34.3	29.3	17.9
Eurasia	13.4	14.6	13.4	14.4	12.5	13.9	10.2	11.9	5.1
Asia Pacific	8.4	7.7	7.5	6.2	4.7	5.6	3.2	5.1	1.9
Southeast Asia	2.6	2.3	2.1	1.4	0.9	1.4	0.8	1.3	0.4

Table A.8: Oil demand (mb/d)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	86.7	96.6	87.9	103.0	103.0	96.1	76.7	87.6	47.0
North America	22.2	22.7	20.1	21.3	16.7	18.0	7.7	17.7	6.8
United States	17.8	18.4	16.4	17.4	13.4	14.7	5.4	14.6	5.4
Central and South America	5.5	5.5	5.0	5.4	6.0	4.8	4.0	4.5	2.4
Brazil	2.3	2.4	2.3	2.4	2.5	1.9	1.1	1.9	1.0
Europe	13.9	13.0	11.9	10.4	6.4	9.0	3.6	8.7	2.2
European Union	10.6	9.7	8.9	7.4	4.1	6.2	1.4	6.2	1.3
Africa	3.3	4.0	3.6	5.1	8.4	5.0	7.9	4.6	4.3
Middle East	6.6	7.4	6.7	8.2	10.2	8.2	10.2	7.2	6.1
Eurasia	3.2	3.8	3.7	4.4	4.5	4.4	4.5	4.0	2.6
Russia	2.6	3.1	3.0	3.5	3.1	3.5	3.1	3.2	2.0
Asia Pacific	25.0	32.0	30.8	38.5	38.8	37.8	30.1	33.0	17.2
China	8.8	13.1	13.3	15.7	13.4	15.7	6.4	13.6	5.9
India	3.3	4.8	4.4	7.2	9.2	7.2	9.2	6.0	4.1
Japan	4.2	3.4	3.1	2.8	1.8	2.4	0.8	2.4	0.8
Southeast Asia	4.0	5.1	4.7	6.6	7.7	6.6	7.6	5.6	3.2
International bunkers	7.0	8.3	6.1	9.6	11.9	8.9	8.8	7.9	5.4

Table A.9: World liquids demand (mb/d)

	Historical		Stated Policies		Announced Pledges		Sustainable Development	
	2019	2020	2030	2050	2030	2050	2030	2050
Total liquids	**98.6**	**89.7**	**106.4**	**108.7**	**100.8**	**83.3**	**93.3**	**55.1**
Biofuels	2.0	1.9	3.5	5.7	4.7	6.6	5.8	8.1
Total oil	96.6	87.9	103.0	103.0	96.1	76.7	87.6	47.0
CTL, GTL and additives	0.8	0.8	1.1	1.3	1.0	0.5	0.9	0.2
Direct use of crude oil	1.0	0.7	0.4	0.2	0.4	0.2	0.2	0.0
Oil products	94.8	86.3	101.5	101.5	94.8	76.1	86.4	46.7
LPG and ethane	12.7	12.5	15.1	15.3	14.3	12.9	13.2	7.6
Naphtha	6.3	6.3	7.6	9.0	7.4	7.6	7.3	7.6
Gasoline	24.6	21.8	24.2	20.5	22.1	14.1	19.9	5.6
Kerosene	7.8	5.6	9.1	11.6	8.4	8.1	7.4	5.6
Diesel	27.3	24.9	29.4	30.0	27.3	20.6	24.3	10.7
Fuel oil	6.2	5.8	5.7	5.7	5.2	4.0	4.6	2.1
Other products	11.7	11.1	11.9	10.8	11.5	9.3	10.8	7.9
Products from NGLs	11.4	11.4	13.1	12.9	12.2	10.2	12.1	7.2
Refinery products	83.4	75.0	88.4	88.6	82.6	65.9	74.4	39.5
Refinery market share	*85%*	*84%*	*83%*	*82%*	*82%*	*79%*	*80%*	*72%*

Note: CTL = coal-to-liquids; GTL = gas-to-liquids; NGLs = natural gas liquids; LPG = liquefied petroleum gas.

Table A.10: Refining capacity and runs (mb/d)

	Refining capacity				Refinery runs				Capacity at risk
	2019	2020	2030	2050	2019	2020	2030	2050	2050
World (Stated Policies)	**101.7**	**101.8**	**104.7**	**105.8**	**81.6**	**74.4**	**85.8**	**85.5**	**16.4**
North America	22.3	22.0	21.2	20.9	18.9	16.4	18.5	17.5	1.8
Europe	16.4	16.2	14.2	13.2	13.4	11.8	10.7	8.8	5.7
Asia Pacific	36.8	36.9	40.6	42.3	29.8	28.3	33.3	34.8	5.2
Japan and Korea	7.0	6.9	6.2	5.7	6.0	5.2	4.9	4.1	2.1
China	16.8	17.0	18.9	18.9	13.0	13.4	14.7	14.0	2.9
India	5.2	5.3	6.9	8.2	5.1	4.5	6.4	7.7	-
Southeast Asia	5.5	5.4	6.6	7.3	3.9	3.8	5.7	6.8	0.2
Middle East	9.1	9.6	11.9	12.3	7.7	6.8	10.1	10.7	0.7
Russia	6.7	6.7	6.5	6.4	5.7	5.4	5.3	5.0	1.0
Africa	3.5	3.5	4.0	4.3	2.0	1.9	3.1	3.6	0.6
Brazil	2.2	2.2	2.3	2.3	1.8	1.8	2.2	2.2	-
Other	4.7	4.7	4.1	4.1	2.3	2.0	2.6	3.0	1.3
Atlantic Basin	55.3	54.7	52.0	51.0	43.7	38.9	42.1	39.8	10.4
East of Suez	46.4	47.1	52.7	54.9	37.9	35.4	43.7	45.7	6.0
Announced Pledges	**101.7**	**101.8**	**99.8**	**80.3**	**81.6**	**74.4**	**80.2**	**63.6**	**38.1**
Sustainable Development	**101.7**	**101.8**	**93.2**	**60.8**	**81.6**	**74.4**	**72.2**	**38.1**	**61.7**

Table A.11: Natural gas production (bcm)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	3 275	4 115	4 014	4 554	5 113	4 249	3 852	4 038	2 452
Conventional gas	2 771	3 003	2 899	3 177	3 634	3 084	3 047	2 975	1 899
Tight gas	272	298	290	279	223	229	71	277	113
Shale gas	155	731	742	1 013	1 136	853	650	705	373
Coalbed methane	77	79	80	62	94	59	84	57	68
Other	-	5	3	24	25	24	0	24	0
North America	811	1 182	1 165	1 305	1 188	1 071	549	1 006	433
Central and South America	160	174	151	154	209	150	162	133	98
Europe	341	259	241	200	181	179	96	172	41
European Union	148	70	55	41	34	32	5	32	5
Africa	203	249	244	305	446	305	399	278	252
Middle East	463	646	645	800	1 124	805	1 018	742	577
Eurasia	807	971	926	1 088	1 183	1 038	990	1 006	601
Asia Pacific	489	635	643	702	782	701	639	700	450
Southeast Asia	216	213	196	199	246	199	238	199	103

Table A.12: Natural gas demand (bcm)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	3 336	4 076	3 999	4 554	5 113	4 249	3 852	4 038	2 452
North America	835	1 122	1 096	1 154	1 073	933	418	900	328
United States	678	895	876	905	813	720	248	711	233
Central and South America	148	164	148	154	191	152	154	134	98
Brazil	29	37	35	32	41	28	22	27	21
Europe	696	611	596	587	497	504	234	483	118
European Union	446	413	401	392	297	315	60	314	57
Africa	106	164	164	208	319	210	308	193	170
Middle East	391	554	559	658	839	665	841	541	435
Eurasia	574	624	597	663	711	668	712	634	419
Russia	467	507	481	536	531	541	533	516	348
Asia Pacific	588	837	839	1 114	1 442	1 105	1 164	1 146	880
China	111	305	322	454	521	443	314	438	359
India	64	64	63	133	207	133	206	173	142
Japan	107	104	99	74	59	64	34	63	34
Southeast Asia	150	172	164	226	333	230	333	231	141
International bunkers	-	0	1	16	40	12	21	8	5

Table A.13: Coal production (Mtce)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	5 231	5 717	5 462	5 132	4 020	4 828	2 672	3 786	1 189
Steam coal	4 065	4 485	4 296	3 944	3 057	3 703	1 982	2 839	771
Coking coal	866	973	940	1 005	843	971	605	850	406
Lignite and peat	300	260	226	182	119	154	86	97	13
North America	818	542	410	262	110	153	58	138	34
Central and South America	75	87	63	48	34	35	0	35	0
Europe	330	218	178	88	41	65	29	51	8
European Union	220	151	124	53	13	34	5	34	5
Africa	210	225	213	199	170	151	67	149	46
Middle East	1	1	1	1	2	1	0	1	0
Eurasia	309	430	394	411	417	391	428	249	131
Asia Pacific	3 487	4 213	4 203	4 123	3 245	4 034	2 091	3 164	972
Southeast Asia	318	510	484	479	443	457	458	325	148

Table A.14: Coal demand (Mtce)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	5 221	5 536	5 317	5 132	4 020	4 828	2 672	3 786	1 189
North America	768	430	346	192	59	84	35	79	28
United States	716	393	318	177	47	71	24	71	24
Central and South America	37	47	44	42	49	27	25	23	16
Brazil	21	22	19	24	31	15	12	15	12
Europe	538	385	330	197	151	157	124	116	54
European Union	360	250	204	96	48	57	22	57	22
Africa	155	168	156	168	159	139	72	118	29
Middle East	3	5	4	11	15	11	15	5	3
Eurasia	203	234	221	221	211	221	211	137	46
Russia	151	178	168	166	147	166	147	107	40
Asia Pacific	3 516	4 268	4 216	4 301	3 375	4 189	2 191	3 310	1 014
China	2 567	2 968	2 986	2 847	1 980	2 814	879	2 389	614
India	399	597	557	729	691	728	688	468	215
Japan	166	165	153	116	72	107	46	107	46
Southeast Asia	122	255	257	338	393	338	388	214	79

Table A.15: Electricity generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	21 520	26 959	26 762	33 575	46 703	34 362	54 716	34 424	57 950
North America	5 233	5 364	5 221	5 619	6 726	6 066	9 063	6 048	9 155
United States	4 354	4 371	4 243	4 490	5 175	4 874	7 435	4 874	7 435
Central and South America	1 130	1 307	1 277	1 616	2 435	1 584	2 637	1 575	2 987
Brazil	516	626	605	752	1 148	702	1 216	702	1 216
Europe	4 121	4 080	3 952	4 601	5 594	4 911	7 091	4 926	7 267
European Union	2 957	2 884	2 757	3 145	3 577	3 411	5 040	3 411	5 040
Africa	670	839	827	1 215	2 384	1 239	2 542	1 400	3 488
Middle East	829	1 202	1 189	1 616	2 764	1 625	3 130	1 485	3 724
Eurasia	1 251	1 394	1 335	1 617	2 057	1 617	2 057	1 630	2 114
Russia	1 036	1 120	1 057	1 253	1 488	1 253	1 488	1 255	1 508
Asia Pacific	8 284	12 773	12 961	17 292	24 743	17 320	28 195	17 360	29 215
China	4 236	7 509	7 787	10 232	13 187	10 193	15 947	10 232	15 329
India	972	1 637	1 609	2 545	5 000	2 545	5 000	2 596	5 812
Japan	1 164	1 037	1 003	984	1 055	1 031	1 362	1 031	1 362
Southeast Asia	684	1 132	1 111	1 682	2 843	1 682	2 843	1 623	3 045

Table A.16: Renewables generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	4 250	7 114	7 593	14 056	27 883	15 917	38 959	18 283	48 436
North America	867	1 258	1 340	2 270	4 045	3 367	7 416	3 422	7 748
United States	452	777	842	1 615	3 036	2 618	6 227	2 618	6 227
Central and South America	744	871	870	1 277	2 102	1 274	2 378	1 323	2 815
Brazil	437	518	515	681	1 035	650	1 141	650	1 141
Europe	976	1 496	1 617	2 743	4 068	3 130	5 737	3 260	6 247
European Union	672	1 001	1 082	1 887	2 680	2 252	4 307	2 252	4 307
Africa	114	162	173	438	1 396	510	1 639	776	3 095
Middle East	18	28	26	153	878	162	1 244	464	3 157
Eurasia	229	264	264	323	580	323	580	479	1 320
Russia	170	200	195	234	432	234	432	332	867
Asia Pacific	1 303	3 035	3 303	6 852	14 814	7 150	19 965	8 559	24 055
China	791	2 025	2 222	4 540	8 076	4 641	12 418	5 186	12 340
India	160	339	360	922	3 587	922	3 587	1 386	5 202
Japan	115	204	234	328	593	384	796	384	796
Southeast Asia	104	254	255	463	1 121	463	1 121	701	2 608

Table A.17: Solar PV generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	32	681	833	3 492	9 667	4 190	14 194	4 989	17 433
North America	3	105	134	534	1 492	974	2 851	1 002	3 061
United States	3	94	117	497	1 300	929	2 648	929	2 648
Central and South America	0	18	22	133	346	152	410	175	530
Brazil	-	7	8	70	172	74	205	74	205
Europe	23	151	176	504	714	583	903	601	1 017
European Union	23	120	142	421	541	499	728	499	728
Africa	0	7	10	82	370	100	449	215	1 191
Middle East	-	7	11	80	445	88	775	209	1 560
Eurasia	-	2	4	14	37	14	37	15	49
Russia	-	1	1	6	19	6	19	6	22
Asia Pacific	6	390	476	2 146	6 263	2 281	8 770	2 772	10 026
China	1	224	270	1 304	3 140	1 355	5 378	1 523	5 286
India	0	51	64	415	2 107	415	2 107	636	2 651
Japan	4	69	79	133	188	155	241	155	241
Southeast Asia	-	12	18	91	348	91	348	164	732

Table A.18: Wind generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	342	1 421	1 596	4 102	8 805	5 115	14 384	6 115	17 577
North America	105	344	391	787	1 399	1 349	3 109	1 362	3 199
United States	95	298	340	688	1 179	1 187	2 759	1 187	2 759
Central and South America	4	78	78	190	393	224	665	247	835
Brazil	2	56	57	118	221	129	353	129	353
Europe	154	463	517	1 148	1 945	1 401	3 317	1 475	3 659
European Union	140	367	398	844	1 365	1 083	2 706	1 083	2 706
Africa	2	17	17	78	271	124	427	156	605
Middle East	0	2	2	27	261	28	299	185	1 033
Eurasia	-	1	2	28	121	28	121	69	345
Russia	-	0	1	20	99	20	99	32	212
Asia Pacific	77	516	588	1 845	4 414	1 961	6 446	2 622	7 901
China	45	406	471	1 414	2 631	1 445	4 249	1 778	4 236
India	20	68	68	200	916	200	916	382	1 557
Japan	4	8	8	45	205	68	306	68	306
Southeast Asia	0	6	7	50	201	50	201	126	620

Table A.19: Nuclear generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	2 756	2 790	2 692	3 115	3 711	3 282	4 449	3 395	4 714
North America	936	956	933	812	642	886	895	886	898
United States	839	843	823	721	517	794	817	794	817
Central and South America	22	25	25	34	67	35	69	35	77
Brazil	15	16	14	24	39	26	42	26	42
Europe	1 032	931	838	776	710	842	821	841	832
European Union	855	765	681	592	519	656	625	656	625
Africa	12	13	13	29	44	29	54	29	72
Middle East	-	7	7	51	96	51	96	47	148
Eurasia	173	211	218	221	283	221	283	256	427
Russia	170	209	216	219	275	219	275	254	409
Asia Pacific	582	647	658	1 193	1 871	1 220	2 232	1 302	2 260
China	74	348	366	675	1 222	675	1 528	751	1 450
India	26	47	46	109	292	109	292	113	303
Japan	288	64	42	195	193	212	259	212	259
Southeast Asia	-	-	-	-	24	-	24	-	40

Table A.20: Natural gas generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	4 843	6 356	6 257	7 121	8 432	6 611	6 307	6 442	2 755
North America	1 217	1 926	1 955	2 046	1 967	1 571	531	1 509	290
United States	1 018	1 640	1 676	1 681	1 555	1 236	177	1 236	177
Central and South America	178	252	242	230	234	223	162	179	86
Brazil	37	60	55	31	62	25	27	25	27
Europe	947	864	846	802	633	742	292	734	103
European Union	590	569	556	535	356	459	41	459	41
Africa	220	331	329	431	705	430	689	366	209
Middle East	527	869	844	1 149	1 574	1 149	1 574	816	375
Eurasia	603	642	598	835	951	835	951	807	367
Russia	521	514	471	654	653	654	653	620	232
Asia Pacific	1 151	1 472	1 443	1 628	2 367	1 662	2 108	2 032	1 325
China	93	226	230	308	539	288	494	413	703
India	107	65	69	120	172	120	172	316	124
Japan	332	386	367	213	139	204	102	204	102
Southeast Asia	336	376	360	537	857	537	857	557	149

Table A.21: Coal generation (TWh)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	8 671	9 912	9 468	8 744	6 293	7 969	4 160	5 843	1 088
North America	2 106	1 144	912	462	58	156	53	146	51
United States	1 994	1 070	858	450	55	144	50	144	50
Central and South America	43	66	66	34	21	13	13	6	-
Brazil	11	21	17	12	9	0	-	0	-
Europe	1 068	726	593	254	173	179	177	75	22
European Union	755	491	386	110	15	35	20	35	20
Africa	259	260	241	251	175	204	74	166	31
Middle East	0	1	3	17	29	17	29	7	7
Eurasia	236	267	247	235	242	235	242	86	-
Russia	166	188	168	144	127	144	127	46	-
Asia Pacific	4 958	7 448	7 406	7 491	5 594	7 165	3 572	5 357	977
China	3 264	4 899	4 958	4 704	3 349	4 579	1 410	3 867	738
India	658	1 181	1 127	1 389	947	1 389	947	777	110
Japan	317	329	316	202	65	192	50	192	50
Southeast Asia	185	483	479	667	830	667	830	358	29

Table A.22: Total final consumption (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	382.5	432.9	412.8	488.6	550.3	473.2	479.3	434.3	392.3
North America	76.6	80.5	74.3	80.7	77.3	73.0	52.7	72.6	51.1
United States	63.8	66.9	62.0	66.8	62.4	60.3	40.6	60.3	40.6
Central and South America	19.2	20.4	19.2	22.9	29.5	21.6	24.6	20.3	21.3
Brazil	9.0	9.7	9.5	11.0	13.7	9.9	9.9	9.9	9.9
Europe	62.9	60.0	56.7	57.2	52.2	53.8	42.4	52.9	38.3
European Union	45.9	43.5	40.9	40.0	34.0	37.1	25.2	37.1	25.2
Africa	20.4	24.9	24.4	30.9	45.8	30.5	44.8	21.1	27.9
Middle East	18.3	23.2	22.4	28.6	39.5	28.6	39.5	25.9	29.2
Eurasia	23.6	27.4	26.2	30.6	33.5	30.6	33.5	28.2	24.1
Russia	19.0	22.5	21.5	24.6	24.7	24.6	24.7	23.1	18.8
Asia Pacific	146.5	179.1	176.6	216.5	244.0	215.0	216.6	194.7	179.6
China	76.2	96.6	98.0	114.4	112.4	114.4	88.9	105.2	85.6
India	20.5	26.8	25.2	36.8	53.9	36.8	53.9	31.5	38.1
Japan	14.2	12.6	11.7	11.7	10.3	10.9	8.1	10.9	8.1
Southeast Asia	16.0	19.9	19.3	26.7	34.9	26.7	34.9	23.7	25.2

Table A.23: Industry consumption (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	**146.9**	**158.6**	**156.1**	**188.2**	**206.8**	**184.0**	**182.3**	**175.9**	**164.5**
North America	19.7	18.4	17.9	20.8	21.3	18.9	15.9	18.8	15.6
United States	15.8	14.5	14.1	16.4	16.5	14.8	11.5	14.8	11.5
Central and South America	7.5	6.7	6.5	7.9	9.6	7.6	8.4	7.6	8.3
Brazil	4.0	3.7	3.6	4.3	5.2	4.0	4.3	4.0	4.3
Europe	19.7	18.7	18.1	19.0	18.0	17.9	15.6	17.6	14.4
European Union	14.4	13.8	13.3	13.5	11.7	12.5	9.6	12.5	9.6
Africa	4.1	4.0	3.9	5.6	8.6	5.5	8.2	5.2	6.9
Middle East	7.6	9.7	9.5	11.4	14.4	11.4	14.4	11.1	12.6
Eurasia	10.1	9.0	8.8	11.3	12.2	11.3	12.2	10.8	10.1
Russia	8.6	7.8	7.6	9.6	9.7	9.6	9.7	9.2	8.2
Asia Pacific	78.3	92.1	91.5	112.0	122.7	111.4	107.5	104.8	96.5
China	49.2	57.3	58.0	66.1	63.1	66.1	49.7	61.8	49.4
India	7.9	10.7	10.1	16.6	26.0	16.6	26.0	15.4	19.6
Japan	6.0	5.5	5.1	5.4	4.8	5.1	4.0	5.1	4.0
Southeast Asia	6.5	8.5	8.7	11.9	15.6	11.9	15.6	11.3	12.7

Table A.24: Transport consumption (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	**101.7**	**120.9**	**105.1**	**136.4**	**157.1**	**129.9**	**131.4**	**121.6**	**101.2**
North America	29.6	31.7	27.1	30.0	26.6	26.6	15.7	26.5	15.1
United States	24.9	26.7	23.0	25.4	22.2	22.4	12.1	22.4	12.1
Central and South America	6.1	7.4	6.6	8.0	11.2	7.6	8.9	7.2	6.8
Brazil	2.9	3.6	3.4	3.9	4.9	3.6	3.0	3.6	3.0
Europe	15.6	16.6	14.5	14.4	11.5	13.5	8.7	13.2	7.6
European Union	11.7	12.1	10.7	10.1	7.4	9.3	4.9	9.3	4.9
Africa	3.6	5.0	4.5	6.6	11.2	6.5	10.8	6.2	7.8
Middle East	4.9	5.9	5.1	6.9	9.5	6.9	9.5	6.1	5.9
Eurasia	4.7	5.1	4.7	5.6	6.6	5.6	6.6	5.0	4.3
Russia	4.0	4.2	3.8	4.3	4.4	4.3	4.4	3.9	3.0
Asia Pacific	22.1	31.8	29.7	43.5	51.9	43.2	46.0	39.0	33.0
China	8.3	13.7	13.5	19.2	18.0	19.2	13.1	17.3	12.4
India	2.7	4.4	3.8	7.5	12.3	7.5	12.3	6.6	8.0
Japan	3.3	2.9	2.6	2.4	1.9	2.2	1.2	2.2	1.2
Southeast Asia	3.7	5.7	5.1	8.3	10.7	8.3	10.7	7.4	6.5

Table A.25: Buildings consumption (EJ)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	**117.9**	**128.8**	**127.2**	**136.1**	**157.8**	**131.6**	**139.0**	**110.3**	**103.1**
North America	23.8	24.8	24.0	23.7	23.5	21.5	15.8	21.3	15.3
United States	20.5	21.1	20.4	19.9	19.0	18.2	12.7	18.2	12.7
Central and South America	4.3	4.9	4.8	5.5	7.0	5.0	5.8	4.2	4.7
Brazil	1.4	1.7	1.7	2.0	2.8	1.5	1.9	1.5	1.9
Europe	24.3	21.6	21.0	20.5	19.6	19.3	15.4	19.0	13.8
European Union	17.6	15.3	14.8	14.2	12.9	13.2	9.2	13.2	9.2
Africa	11.9	14.9	15.1	17.4	24.0	17.2	23.8	8.5	11.5
Middle East	5.3	6.5	6.5	8.9	14.2	8.9	14.2	7.6	10.0
Eurasia	8.4	10.3	9.9	10.5	11.3	10.5	11.3	9.3	6.5
Russia	6.2	7.7	7.5	7.8	7.5	7.8	7.5	7.0	4.7
Asia Pacific	39.9	45.8	46.0	49.6	58.2	49.1	52.7	40.3	41.2
China	15.6	21.4	22.2	24.3	27.0	24.3	22.6	21.7	20.5
India	8.7	9.2	8.9	9.1	12.1	9.1	12.1	6.1	7.8
Japan	4.3	3.8	3.7	3.6	3.3	3.4	2.7	3.4	2.7
Southeast Asia	5.2	4.5	4.4	5.0	7.0	5.0	7.0	3.7	4.6

Table A.26: Total CO_2 emissions* (Mt CO_2)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	**32 345**	**35 966**	**34 156**	**36 267**	**33 903**	**33 640**	**20 726**	**28 487**	**8 170**
North America	6 423	5 867	5 229	4 944	3 881	3 616	655	3 497	280
United States	5 418	4 826	4 303	3 969	2 936	2 834	129	2 817	107
Central and South America	1 144	1 185	1 093	1 179	1 370	1 041	889	933	485
Brazil	411	443	421	461	532	356	189	354	185
Europe	4 633	3 977	3 642	3 036	2 218	2 518	1 045	2 283	376
European Union	3 236	2 744	2 485	1 957	1 208	1 488	134	1 482	128
Africa	1 109	1 370	1 297	1 617	2 287	1 529	1 948	1 352	883
Middle East	1 572	1 886	1 849	2 150	2 644	2 159	2 626	1 687	822
Eurasia	2 017	2 165	2 068	2 247	2 332	2 258	2 336	1 896	935
Russia	1 565	1 691	1 612	1 727	1 619	1 737	1 624	1 489	710
Asia Pacific	14 326	18 220	18 007	19 569	17 245	19 115	9 836	15 585	3 556
China	8 766	11 198	11 356	11 385	8 341	11 263	1 748	9 375	1 331
India	1 683	2 475	2 304	3 305	3 687	3 301	3 676	2 441	969
Japan	1 159	1 071	996	797	513	682	20	683	20
Southeast Asia	1 152	1 712	1 674	2 238	2 704	2 245	2 695	1 726	659

* Includes industrial process emissions.

Table A.27: Electricity and heat sectors CO_2 emissions (Mt CO_2)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	12 380	13 933	13 530	12 425	9 915	11 375	5 506	8 891	887
North America	2 579	1 911	1 707	1 214	767	670	17	637	- 74
United States	2 329	1 682	1 501	1 053	607	526	- 108	526	- 108
Central and South America	235	261	242	157	115	128	76	99	33
Brazil	46	64	51	30	36	11	10	11	10
Europe	1 694	1 216	1 089	666	484	528	271	419	33
European Union	1 154	811	715	388	196	243	- 7	243	- 7
Africa	419	501	478	488	475	448	371	378	148
Middle East	550	681	682	692	789	692	789	466	152
Eurasia	1 014	976	951	975	962	975	962	779	250
Russia	871	791	762	785	706	785	706	635	194
Asia Pacific	5 890	8 388	8 381	8 234	6 323	7 935	3 022	6 113	345
China	3 486	5 242	5 362	5 019	3 684	4 914	615	4 009	220
India	785	1 172	1 124	1 344	915	1 344	915	844	- 24
Japan	488	483	456	270	106	238	- 5	238	- 5
Southeast Asia	397	702	688	887	1 042	887	1 042	612	69

Table A.28: Total final consumption CO_2 emissions* (Mt CO_2)

	Historical			Stated Policies		Announced Pledges		Sustainable Development	
	2010	2019	2020	2030	2050	2030	2050	2030	2050
World	18 530	20 467	19 191	22 118	22 202	20 696	14 650	18 311	7 407
North America	3 444	3 530	3 149	3 278	2 694	2 615	687	2 576	507
United States	2 837	2 892	2 591	2 664	2 113	2 127	348	2 127	348
Central and South America	811	843	777	931	1 135	826	749	764	438
Brazil	344	356	348	402	463	321	180	321	180
Europe	2 768	2 605	2 409	2 231	1 631	1 873	728	1 782	332
European Union	1 970	1 830	1 674	1 475	946	1 175	124	1 175	124
Africa	576	749	707	982	1 636	945	1 513	848	721
Middle East	919	1 058	1 043	1 290	1 643	1 290	1 643	1 079	647
Eurasia	887	1 107	1 047	1 188	1 281	1 188	1 281	1 052	653
Russia	635	849	806	888	858	888	858	811	493
Asia Pacific	8 006	9 278	9 088	10 692	10 257	10 554	6 659	8 954	3 275
China	5 021	5 623	5 670	5 997	4 352	5 996	1 225	5 074	1 226
India	866	1 242	1 122	1 869	2 661	1 869	2 661	1 523	949
Japan	643	568	524	514	398	434	93	434	93
Southeast Asia	690	933	913	1 267	1 535	1 267	1 535	1 047	582

* Includes industrial process emissions.

Design of the scenarios

The *World Energy Outlook-2021* (*WEO-2021)* explores three main scenarios in the analyses in the chapters and also includes projections for our Sustainable Development Scenario (SDS) for continuity with previous editions of the *WEO* and to provide pathways that are compliant with the Paris Agreement for regions that have not yet announced net zero pledges. These scenarios are not predictions – the IEA does not have a single view on the future of the energy system. In contrast to the 2020 edition of the *WEO*, we do not vary the assumptions about public health and economic recovery implications across the scenarios. The scenarios are:

- The **Net Zero Emissions by 2050 Scenario (NZE)** shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular achieving universal energy access by 2030. The NZE does not rely on emissions reductions from outside the energy sector to achieve its goals, but assumes that non-energy emissions will be reduced in the same proportion as energy emissions. It is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability).
- The **Announced Pledges Scenario (APS)** takes account of all of the climate commitments made by governments around the world, including Nationally Determined Contributions as well as longer term net zero targets, and assumes that they will be met in full and on time. The global trends in this scenario represent the cumulative extent of the world's ambition to tackle climate change as of mid-2021. The remaining difference in global emissions between the APS and the goals in the NZE or the Sustainable Development Scenario shows the "ambition gap" that needs to be closed to achieve the goals agreed in the Paris Agreement in 2015.
- The **Stated Policies Scenario (STEPS)** does not take for granted that governments will reach all announced goals. Instead, the STEPS explores where the energy system might go without additional policy implementation. As with the APS, it is not designed to achieve a particular outcome. It takes a granular, sector-by-sector look at existing policies and measures and those under development. The remaining difference in global emissions between the STEPS and the APS, represents the "implementation gap" that needs to be closed for countries to achieve their announced decarbonisation targets.
- The **Sustainable Development Scenario (SDS)** is a "well below 2 °C" pathway, and represents a gateway to achieving the outcomes targeted by the Paris Agreement. The SDS assumes all energy-related SDGs are met, all current net zero pledges are achieved in full, and there are increased efforts to realise near-term emissions reductions; advanced economies reach net zero emissions by 2050, China around 2060, and all other countries by 2070 at the latest. Without assuming extensive net negative emissions, this scenario is consistent with limiting the global temperature rise to 1.65 °C (with a 50% probability). With some level of net negative emissions after 2070, the temperature rise could be reduced to 1.5 °C in 2100.

B.1 Population

Table B.1 ▷ Population assumptions by region

	Compound average annual growth rate			Population (million)			Urbanisation (share of population)		
	2000-20	2020-30	2020-50	2020	2030	2050	2020	2030	2050
North America	1.0%	0.7%	0.5%	496	526	578	82%	84%	89%
United States	0.8%	0.6%	0.5%	330	349	379	83%	85%	89%
C & S America	1.1%	0.8%	0.5%	522	562	603	81%	84%	88%
Brazil	1.0%	0.6%	0.3%	213	224	229	87%	89%	92%
Europe	0.4%	0.0%	0.0%	699	701	690	75%	78%	84%
European Union	0.2%	-0.1%	-0.2%	451	447	429	75%	77%	84%
Africa	2.7%	2.6%	2.2%	1 340	1 688	2 489	43%	48%	59%
Middle East	2.3%	1.7%	1.2%	247	289	348	72%	76%	81%
Eurasia	0.4%	0.3%	0.2%	236	244	253	65%	67%	73%
Russia	-0.1%	-0.2%	-0.2%	144	142	134	75%	77%	83%
Asia Pacific	1.1%	0.7%	0.4%	4 210	4 488	4 727	47%	53%	63%
China	0.6%	0.2%	-0.1%	1 411	1 436	1 375	62%	71%	80%
India	1.4%	1.0%	0.6%	1 380	1 504	1 639	34%	40%	53%
Japan	0.0%	-0.5%	-0.6%	126	120	105	92%	93%	95%
Southeast Asia	1.3%	0.9%	0.6%	667	726	792	50%	56%	66%
World	**1.3%**	**1.0%**	**0.8%**	**7 749**	**8 501**	**9 687**	**56%**	**60%**	**68%**

Notes: C & S America = Central and South America. See Annex C for composition of regional groupings.

Sources: UN DESA (2018, 2019); World Bank (2021a); IEA databases and analysis.

- Population is a major determinant of many of the trends in the *Outlook*. We use the medium variant of the United Nations projections as the basis for population growth in all scenarios, but this is naturally subject to a degree of uncertainty.
- The rate of population growth is assumed to slow over time, but the global population nonetheless exceeds 9.6 billion by 2050 (Table B.1).
- More than half of the increase over the projection period to 2050 is in Africa and around a further third is in the Asia Pacific region.
- India adds around 260 million people to its population, overtaking China (where the population is projected to decrease by around 35 million) to become the world’s most populous country.
- The share of the world’s population living in towns and cities has been rising steadily, a trend that is projected to continue over the period to 2050. In aggregate, this means that *all* of the 2.2 billion increase in global population over the period is added to cities and towns.

B.2 CO_2 prices

Table B.2 ⊳ **CO_2 prices for electricity, industry and energy production in selected regions by scenario**

USD (2020) per tonne of CO_2	2030	2040	2050
Stated Policies			
Canada	55	60	75
Chile, Colombia	15	20	30
China	30	45	55
European Union	65	75	90
Korea	40	65	90
Announced Pledges			
Advanced economies with net zero pledges[1]	120	170	200
China	30	95	160
Emerging market and developing economies with net zero pledges	40	110	160
Sustainable Development[2]			
Other advanced economies	100	140	160
Other selected emerging market and developing economies	-	35	95
Net Zero Emissions by 2050			
Advanced economies	130	205	250
Major emerging economies[3]	90	160	200
Other emerging market and developing economies	15	35	55

Note: The values are rounded.

[1] The CO_2 price for Canada reaches USD 135 per tonne of CO_2 in 2030 as stated in its Healthy Environment and Healthy Economy Plan.

[2] All regions with net zero pledges have the same pricing as in the APS. China's CO_2 pricing rises to the levels of other emerging market and developing economies with net zero pledges in the SDS.

[3] Includes China, Russia, Brazil and South Africa.

- More than 60 carbon pricing schemes are in place today, covering over 40 countries (World Bank, 2021b). With the formal launch of the national emissions trading system in China in 2021, the share of global emissions covered by carbon prices increased to 21.5% (from 15.1% in 2020).
- Existing and planned CO_2 pricing schemes are reflected in the STEPS, covering electricity generation, industry, energy production sectors and end-use sectors (e.g. aviation, road transport and buildings) where applicable.

- In the APS, higher CO_2 prices are introduced across all regions with net zero pledges. In the SDS, carbon pricing is expanded to all advanced economies and most emerging market and developing economies, while no explicit pricing is assumed in the Africa, Middle East and Other Asia regions. Instead, these regions rely on direct policy interventions to drive decarbonisation in the SDS.
- In the NZE, CO_2 prices cover all regions and rise rapidly across all advanced economies and in a number of other major economies, including China, Brazil, Russia and South Africa. CO_2 prices are lower in all other emerging market and developing economies, as it is assumed they pursue more direct policies to adapt and transform their energy systems.
- All scenarios consider the effects of other policy measures alongside CO_2 pricing, such as coal phase-out plans, efficiency standards and renewable targets (Tables B.6-B.12). These policies interact with carbon pricing; therefore CO_2 pricing is not the marginal cost of abatement as is often the case in other modelling approaches (NGFS, 2021).

B.3 Fossil fuel resources

Table B.3 ▷ Remaining technically recoverable fossil fuel resources, end-2020

Oil (billion barrels)	Proven reserves	Resources	Conventional crude oil	Tight oil	NGLs	EHOB	Kerogen oil
North America	238	2 416	239	217	160	799	1 000
Central and South America	292	860	255	59	49	493	3
Europe	15	114	58	19	28	3	6
Africa	125	446	306	54	84	2	-
Middle East	887	1 146	895	29	178	14	30
Eurasia	146	945	232	85	58	552	18
Asia Pacific	50	279	124	72	64	3	16
World	**1 753**	**6 206**	**2 109**	**536**	**622**	**1 866**	**1 073**

Natural gas (trillion cubic metres)	Proven reserves	Resources	Conventional gas	Tight gas	Shale gas	Coalbed methane
North America	17	149	50	10	81	7
Central and South America	8	84	28	15	41	-
Europe	5	46	18	5	18	5
Africa	19	101	51	10	40	0
Middle East	81	121	101	9	11	-
Eurasia	70	169	131	10	10	17
Asia Pacific	21	139	45	21	53	20
World	**221**	**809**	**425**	**80**	**253**	**49**

Coal (billion tonnes)	Proven reserves	Resources	Coking coal	Steam coal	Lignite
North America	257	8 389	1 031	5 839	1 519
Central and South America	14	60	3	32	25
Europe	137	982	166	413	403
Africa	15	343	45	297	0
Middle East	1	41	19	23	-
Eurasia	191	2 015	343	1 041	632
Asia Pacific	461	8 974	1 509	6 037	1 428
World	**1 076**	**20 803**	**3 115**	**13 682**	**4 007**

Notes: NGLs = natural gas liquids; EHOB = extra-heavy oil and bitumen. The breakdown of coal resources by type is an IEA estimate. Coal world resources exclude Antarctica.

Sources: BGR (2019); BP (2021); Cedigaz (2020); OGJ (2020); US DOE/EIA (2019, 2020); US DOE/EIA/ARI (2013, 2015); USGS (2012a, 2012b); IEA databases and analysis.

- The *World Energy Outlook* supply modelling relies on estimates of the remaining technically recoverable resource, rather than the (often more widely quoted) numbers for proven reserves. Resource estimates are subject to a considerable degree of uncertainty, as well as the distinction in the analysis between conventional and unconventional resource types.
- Overall, the remaining technical recoverable resources of fossil fuels remain almost unchanged from the *World Energy Outlook-2020*. All fuels are at a level comfortably sufficient to meet the projections of global energy demand growth to 2050 in all scenarios.
- The Covid-19 pandemic has slowed exploration and reserve replacement ratios, although there has been an upward revision to the Middle East proven reserves by around 50 billion barrels compared with the *WEO-2020*. Remaining technically recoverable resources of US tight oil (crude plus condensate) in this *Outlook* are unchanged, totalling more than 200 billion barrels. Natural gas resource numbers remain broadly similar to those of last year. Most of the proven reserves lie in the Middle East and Eurasia.
- World coal resources are made up of various types of coal: around 80% is steam and coking coal and the remainder is lignite. Coal resources are more available in parts of the world without substantial gas and oil resources, notably in Asia.
- Overall, the gradual depletion of resources (at a pace that varies by scenario) means that operators have to develop more difficult and complex reservoirs. This tends to push up production costs over time, although this effect is offset by the assumed continuous adoption of new, more efficient production technologies and practices.

B.4 Electricity generation technology costs

Table B.4a ▷ Technology costs in selected regions in the Stated Policies Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)			VALCOE (USD/MWh)		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
United States															
Nuclear	5 000	4 800	4 500	90	90	90	30	30	30	105	100	95	105	100	95
Coal	2 100	2 100	2 100	50	60	60	25	25	25	75	70	70	75	70	65
Gas CCGT	1 000	1 000	1 000	50	45	40	30	35	40	50	65	70	50	60	60
Solar PV	1 100	710	530	21	22	22	10	10	10	50	30	30	55	40	45
Wind onshore	1 390	1 310	1 270	42	43	44	10	10	10	35	30	30	35	35	40
Wind offshore	4 040	2 560	1920	42	46	48	35	25	15	115	70	55	110	70	60
European Union															
Nuclear	6 600	5 100	4 500	75	75	75	35	35	35	150	125	110	145	125	110
Coal	2 000	2 000	2 000	35	40	40	90	120	135	170	185	200	160	165	165
Gas CCGT	1 000	1 000	1 000	45	35	25	80	105	115	110	140	170	100	115	115
Solar PV	840	550	430	13	14	14	10	10	10	55	40	30	60	70	70
Wind onshore	1 500	1 420	1 370	29	29	30	15	15	15	50	45	45	55	60	60
Wind offshore	3 480	2 260	1 720	51	55	58	15	10	10	75	45	35	75	50	45
China															
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60	65	65	60
Coal	800	800	800	55	45	40	45	60	75	60	80	95	60	70	70
Gas CCGT	560	560	560	25	20	20	80	90	100	100	120	130	90	105	95
Solar PV	650	420	310	17	18	19	10	5	5	35	20	15	40	45	50
Wind onshore	1 260	1 190	1 140	26	27	27	15	15	10	50	45	40	50	50	45
Wind offshore	2 960	1 860	1 280	34	40	43	25	15	10	100	55	35	100	60	40
India															
Nuclear	2 800	2 800	2 800	75	80	80	30	30	30	70	70	70	70	70	70
Coal	1 200	1 200	1 200	60	60	50	30	35	30	55	55	55	55	55	50
Gas CCGT	700	700	700	45	50	45	75	75	80	90	90	95	90	80	75
Solar PV	600	380	270	20	21	21	5	5	5	35	20	15	40	35	55
Wind onshore	1 040	1 020	1 000	26	28	29	10	10	10	50	45	40	55	50	50
Wind offshore	2 980	1960	1 440	32	36	38	25	20	15	135	80	55	135	85	65

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; VALCOE = value-adjusted LCOE; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine. Cost components, LCOE and VALCOE figures are rounded. Lower values for VALCOE indicate improved competitiveness.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2021).

Table B.4b ▷ Technology costs in selected regions in the Announced Pledges Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
United States												
Nuclear	5 000	4 800	4 500	90	85	80	30	30	30	105	105	105
Coal	2 100	2 100	2 100	30	10	n.a.	65	125	155	150	410	n.a.
Gas CCGT	1 000	1 000	1 000	50	25	n.a.	40	65	75	65	110	n.a.
Solar PV	1 100	660	460	21	22	23	10	10	10	50	30	25
Wind onshore	1 390	1 290	1 220	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 440	1 680	42	46	48	35	20	15	115	70	45
European Union												
Nuclear	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	2000	2000	2000	25	n.a.	n.a.	105	165	210	200	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	50	40	n.a.	70	95	105	95	120	n.a.
Solar PV	840	530	380	13	14	14	10	10	10	55	35	30
Wind onshore	1 500	1 410	1 340	29	29	30	15	15	15	50	45	45
Wind offshore	3 480	2 240	1 540	51	55	58	15	10	10	75	45	30
China												
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	800	800	800	55	45	5	45	95	150	60	115	290
Gas CCGT	560	560	560	25	25	25	80	105	115	100	125	135
Solar PV	650	400	270	17	18	19	10	5	5	35	20	15
Wind onshore	1 260	1 180	1 110	26	27	27	15	15	10	50	45	40
Wind offshore	2 960	1 820	1 120	34	40	43	25	15	10	100	55	30
India												
Nuclear	2 800	2 800	2 800	75	80	80	30	30	30	70	70	70
Coal	1 200	1 200	1 200	60	60	50	30	35	30	55	55	60
Gas CCGT	700	700	700	45	50	45	75	75	80	90	90	95
Solar PV	600	360	240	20	21	21	5	5	5	35	20	15
Wind onshore	1 040	1 010	990	26	28	29	10	10	10	50	45	40
Wind offshore	2 980	1 880	1 260	32	36	38	25	15	10	135	75	50

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2021).

Table B.4c ▻ Technology costs in selected regions in the Sustainable Development Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
United States												
Nuclear	5 000	4 800	4 500	90	85	80	30	30	30	105	105	105
Coal	2 100	2 100	2 100	30	10	n.a.	65	125	155	150	410	n.a.
Gas CCGT	1 000	1 000	1 000	50	25	n.a.	40	65	75	65	110	n.a.
Solar PV	1 100	640	440	21	22	23	10	10	10	50	30	25
Wind onshore	1 390	1 280	1 200	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 420	1 660	42	46	48	35	20	15	115	70	45
European Union												
Nuclear	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	2 000	2 000	2 000	25	n.a.	n.a.	105	165	210	200	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	50	40	n.a.	70	95	105	95	120	n.a.
Solar PV	840	510	370	13	14	14	10	10	10	55	35	30
Wind onshore	1 500	1 390	1 310	29	29	30	15	15	15	50	45	45
Wind offshore	3 480	2 220	1 520	51	55	58	15	10	10	75	45	30
China												
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	800	800	800	55	45	5	65	115	150	80	135	290
Gas CCGT	560	560	560	30	30	30	80	100	115	100	120	135
Solar PV	650	380	260	17	18	19	10	5	5	35	20	15
Wind onshore	1 260	1 160	1 090	26	27	27	15	15	10	50	45	40
Wind offshore	2 960	1 760	1 100	34	40	43	25	15	10	100	55	30
India												
Nuclear	2 800	2 800	2 800	75	80	80	30	30	30	70	70	70
Coal	1 200	1 200	1 200	50	40	20	30	30	30	55	65	95
Gas CCGT	700	700	700	50	55	10	60	45	45	75	60	125
Solar PV	600	340	230	20	21	21	5	5	5	35	20	15
Wind onshore	1 040	990	960	26	28	29	10	10	10	50	45	40
Wind offshore	2 980	1 800	1 220	32	36	38	25	15	10	135	75	50

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2021).

Table B.4d ▷ Technology costs in selected regions in the Net Zero Emissions by 2050 Scenario

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
United States												
Nuclear	5 000	4 800	4 500	90	80	75	30	30	30	105	110	110
Coal	2 100	2 100	2 100	20	n.a.	n.a.	90	170	235	220	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	55	25	n.a.	50	80	105	70	125	n.a.
Solar PV	1 140	620	420	21	22	23	10	10	10	50	30	20
Wind onshore	1 540	1 420	1 320	42	43	44	10	10	10	35	35	30
Wind offshore	4 040	2 080	1 480	42	46	48	35	20	15	115	60	40
European Union												
Nuclear	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	2 000	2 000	2 000	20	n.a.	n.a.	120	205	275	250	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	40	20	n.a.	65	95	120	100	150	n.a.
Solar PV	790	460	340	13	14	14	10	10	10	55	35	25
Wind onshore	1 540	1 420	1 300	29	30	31	15	15	15	55	45	40
Wind offshore	3 600	2 020	1 420	51	56	59	15	10	5	75	40	25
China												
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	800	800	800	60	n.a.	n.a.	75	135	195	90	n.a.	n.a.
Gas CCGT	560	560	560	45	35	n.a.	75	100	120	90	115	n.a.
Solar PV	750	400	280	17	18	19	10	5	5	40	25	15
Wind onshore	1 220	1 120	1 040	26	27	27	15	10	10	45	40	40
Wind offshore	2 840	1 560	1 000	34	41	43	25	15	10	95	45	30
India												
Nuclear	2 800	2 800	2 800	70	70	70	30	30	30	75	75	75
Coal	1 200	1 200	1 200	50	n.a.	n.a.	35	50	75	65	n.a.	n.a.
Gas CCGT	700	700	700	55	50	n.a.	45	45	50	55	60	n.a.
Solar PV	580	310	220	20	21	21	5	5	5	35	20	15
Wind onshore	1 040	980	940	26	28	29	10	10	10	50	45	40
Wind offshore	2 980	1 680	1 180	32	37	38	25	15	10	130	70	45

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2021).

- Major contributors to the levelised cost of electricity (LCOE) include: overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided); cost of fuel inputs; plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, and onshore and offshore wind.
- Weighted average cost of capital (WACC) reflects analysis for utility-scale solar PV in the *World Energy Outlook 2020* (IEA, 2020a), with a range of 3-6%, and for offshore wind analysis from the *Offshore Wind Outlook 2019* (IEA, 2019)*,* with a range of 4-7%. Onshore wind was assumed to have the same WACC as utility-scale solar PV. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (7-8% based on the stage of economic development).
- The value-adjusted levelised cost of electricity (VALCOE) incorporates information on both costs and the value provided to the system. Based on the LCOE, estimates of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies (IEA, 2021a).
- All power generation technology costs for the Net Zero Emissions by 2050 Scenario are from the *Net Zero by 2050: A Roadmap for the Global Energy Sector* report (IEA, 2021b) and are in USD 2019.
- Fuel, CO_2 and O&M costs reflect the average over the ten years following the indicated date in the projections (and therefore vary by scenario in 2020).
- Solar PV and wind costs do not include the cost of energy storage technologies, such as utility-scale batteries.
- The capital costs for nuclear power represent the “nth-of-a-kind” costs for new reactor designs, with substantial cost reductions from the first-of-a-kind projects.
- Additional cost information and projections for power generation technologies are available at: https://www.iea.org/reports/world-energy-model/techno-economic-inputs.

B.5 Other key technology costs

Table B.5 ⊳ Capital costs for selected technologies by scenario

		Stated Policies		Announced Pledges		Sustainable Development		Net Zero Emissions by 2050	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Buildings (USD/kW)									
Air source heat pumps									
Advanced economies	610	570	490	530	400	530	390	520	370
Emerging market and developing economies	320	300	260	300	220	280	210	280	200
Industry (USD/tpa)									
Primary steel production									
Conventional	640	650	660	650	670	650	680	650	680
Innovative	n.a.	1 400	1 050	1 330	980	1 020	910	980	900
Vehicles (USD/vehicle)									
Hybrid cars	15 710	14 280	13 110	14 100	11 750	13 510	12 100	13 490	12 090
Battery electric cars	21 760	15 370	13 210	14 920	13 010	14 740	12 680	14 520	12 590
Batteries and hydrogen									
Hydrogen electrolysers (USD/kW)	1 480	850	630	590	430	560	410	460	360
Utility-scale stationary batteries (USD/kWh)	310	180	130	170	120	170	115	155	110
Fuel cells (USD/kW)	110	58	39	50	32	49	31	43	28

Notes: kW = kilowatt; tpa = tonne per annum; kWh = kilowatt-hour; n.a. = not applicable. All values are in USD (2020).

Sources: IEA analysis; Bloomberg New Energy Finance (2020); Cole *et al.* (2020); Tsiropoulos *et al.* (2018).

- All costs represent fully installed/delivered technologies, not solely the module cost, and includes engineering, procurement and construction costs to install *the* module.
- Industry costs reflect production costs in the iron and steel sub-sector and differentiate between conventional and innovative production routes. Conventional routes are blast furnace- basic oxygen furnace (BF-BOF) and direct reduced iron-electric arc furnace (DRI-EAF). The innovative routes are Hisarna with CCUS, DRI-EAF with CCUS and hydrogen-based DRI-EAF. Costs for conventional primary steel increase over time reflecting a growing shift toward DRI-EAF in new capacity, which is more capital intensive.
- Vehicle costs reflect production costs, not retail prices, to better reflect the cost declines in production, which move independently of final marketed prices for electric vehicles to customers.
- Utility-scale stationary battery costs reflect the average installed costs of all battery systems rated to provide maximum power output for a four-hour period.
- Electrolyser costs reflect a projected weighted average of installed electrolyser technologies, including inverters. However, inverter costs are not included in the *WEO* modelling of non-grid connected electrolysers.

B.6 Policies

The policy actions assumed to be taken by governments are a key variable in this *World Energy Outlook (WEO)* and the main reason for the differences in outcomes across the scenarios. An overview of the policies and measures that are considered in the various scenarios is included in Tables B.6 – B.12.

In addition, Table B.11 lays out policy assumptions in the Sustainable Development Scenario (SDS), which are achieved in all regions in order to achieve the SDS trajectory. Table B.12 provides an abbreviated list of policy assumptions in the Net Zero Emissions by 2050 Scenario (NZE). Additional policy and milestones by sector can be found in *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA, 2021b).

The policies are additive: measures listed under the Announced Pledges Scenario (APS) supplement those in the Stated Policies Scenario (STEPS). The tables begin with broad cross-cutting policy frameworks, followed by more detailed policies by sector: power, industry, buildings and transport. The tables for the STEPS list only the "new policies" enacted, implemented or revised since the publication of the *WEO-2020*. Policies already considered in previous editions of the *WEO* are not listed due to space constraints. However, we do restate major long-term policies to be clear which targets and goals are met in the STEPS and which are only met in the APS. Some regional policies have been included if they play a significant role in shaping energy at a global scale, e.g. regional carbon markets, standards in very large provinces or states. The tables do not include all policies and measures, rather they highlight the policies most prominent in shaping global energy demand today, while being derived from an exhaustive examination of announcements and plans in countries around the world. A more comprehensive list of energy-related policies by country can be viewed on the IEA Policies and Management Database (PAMS), https://www.iea.org/policies.

Table B.6 ⊳ Cross-cutting policy assumptions for selected regions/countries by scenario

Region/ country	Scenario	Assumptions
United States	STEPS	• Energy provisions in the CARES Act, other Covid-19 recovery measures and the Consolidated Appropriations Act 2021.
	APS	• Updated NDC and national target for net zero GHG emissions by 2050. • Energy provisions in the Infrastructure Investment and Jobs Act (not yet signed into law) and additional elements in the proposed American Jobs Plan.
Canada	STEPS	• Energy provisions in the 2020 Healthy Environment and a Healthy Economy Plan. • Spending in the Hydrogen Strategy and Strategic Innovation Fund Net Zero Accelerator. • 2021 Covid19--related recovery public investment in public transit infrastructure, EV infrastructure and other measures.
	APS	• Immediate targets and plans established to meet net zero GHG emissions target by 2050.
Central and South America	STEPS	• Colombia: Energy provisions in the Ten Milestones in 2021 Plan.
	APS	• Brazil: Long-term objective of reaching climate neutrality in 2050. • Chile, Costa Rica and Colombia: Full implementation of net zero emission targets by 2050.
European Union	STEPS	• European Green Deal provisions related to clean energy transitions and detailed spending and implementation measures in the Fit for 55 package. • Horizon Europe research and innovation funding programme. • Energy provisions in the Recovery and Resilience Facility and other recovery plans are taken into account at EU member country level, including major provisions for renewables, efficiency in buildings and low-carbon transport.
	APS	• Full implementation of the targets in the Fit for 55 package. • Target for climate neutrality by 2050 (to be embedded in the European Climate Law). • Targets in the EU Hydrogen Strategy for a Climate Neutral Europe. • European Union and country-level targets for climate neutrality.
Other Europe	STEPS	• United Kingdom: All spending in the UK Ten Point Plan and the 2020 Energy White Paper. Provisions of the North Sea Transition Deal.
	APS	• United Kingdom: Full implementation of the target for net zero GHG emissions by 2050, and 2021 announcements on ramping up emissions reductions by 2037. • Norway, Iceland and Switzerland: Climate neutrality targets.
Australia and New Zealand	STEPS	• Australia: Energy-related recovery measures, notably public investment in hydrogen and CCUS.
	APS	• New Zealand: Full implementation of the NZ Zero Carbon amendment to the Climate Change Response Act setting a net zero emission target for all GHG except biogenic methane by 2050.

Table B.6 ▷ Cross-cutting policy assumptions for selected regions/countries by scenario (continued)

Region/ country	Scenario	Assumptions
China	STEPS	• “Made in China 2025” transition from heavy industry to higher value-added manufacturing. • 14th Five-Year Plan: ○ Reduce CO_2 intensity of economy by 18% from 2021 to 2025. ○ Reduce energy intensity of economy by 13.5% from 2021 to 2025. ○ 20% non-fossil share of energy mix by 2025. ○ 25% non-fossil share of energy mix by 2030. • NDC: ○ Aim to peak CO_2 emissions before 2030. ○ Lower CO_2 emissions per unit of GDP by 60% from 2005 levels.
	APS	• Announced pledge to strive to be carbon neutral by 2060.
India	STEPS	• 450 GW renewables capacity by 2030 and 60% of total installed capacity being renewables by 2030. • National Mission on Enhanced Energy Efficiency. • “Make in India” campaign to increase the share of manufacturing in the national economy. • National Hydrogen Mission. • New power distribution scheme reforms and public investment. • Covid-19-related recovery measures, notably those ensuring energy access for vulnerable households and firms, and public investment in urban transport infrastructure. • Draft LNG policy targets.
Southeast Asia	STEPS	• Indonesia: 23% share of renewable energy in primary energy supply by 2025 and 31% by 2050.
Japan	STEPS	• Achieve lower range targets for renewables in the draft 6th Strategic Energy Plan under the Basic Act on Energy Policy. • Public spending on clean energy innovation - 2021 national budget.
	APS	• Achieves efficiency targets and upper range targets for renewables in the draft 6th Strategic Energy Plan under the Basic Act on Energy Policy. • Announced pledge to strive to be carbon neutral by 2050.
Korea	STEPS	• Korean New Deal clean energy spending. • 14th long-term natural gas supply and demand plan (2021-2034).
	APS	• Carbon Neutrality and Green Growth Act for Climate Change committing to CO_2 neutrality by 2050.

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; APS = Announced Pledges Scenario. NDC = Nationally Determined Contributions (Paris Agreement); CCUS = carbon capture, utilisation and storage; GHG = greenhouse gases; GW = gigawatts; LNG = liquefied natural gas.

Table B.7 ⊳ Electricity sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• 100% carbon-free electricity or energy targets by 2050 in 20 states plus Puerto Rico and Washington D.C. • 30 GW offshore wind capacity by 2030. • Extension of renewable tax credits for solar, and onshore and offshore wind. • Nuclear compensated with zero emissions credits in five states.
	APS	• 100% carbon pollution-free electricity by 2035.
Canada	STEPS	• Reach nearly 90% non-emitting renewables generation by 2030. • Phase out conventional coal-fired plants by 2030.
European Union	STEPS	• Coal phase-out plans considered in 16 member states, notably in Germany, Greece, Hungary, Romania and Spain. • Early retirement of all nuclear plants in Germany by end-2022. • Strengthening National Energy and Climate Plans, notably offshore wind targets.
	APS	• 40% renewables share of gross final consumption by 2030 proposed under EU Renewable Energy Directive.
Other Europe	STEPS	• United Kingdom: Phase out of traditional coal-fired power by 2024. • United Kingdom: Ten Point Plan, with up to 40 GW offshore wind capacity by 2030.
Africa	STEPS	• Partial implementation of national electrification strategies. • South Africa: Increased renewables capacity and reduced coal-fired capacity under 2019 Integrated Resource Plan.
China	STEPS	• Indicative target of 26% of electricity consumption from non-hydro renewables and 40% from total renewables sources by 2030. • Over 1 200 GW solar and wind installed capacity by 2030. • 70 GW nuclear generation by 2025 under the 14th Five-Year Plan.
	APS	• Overall coal use to decline in the 15th Five-Year Plan period (2025-2030).
India	STEPS	• 450 GW renewables capacity installed by 2030 and 60% of total installed capacity from renewables by 2030.
Japan	STEPS	• Achieve electricity generation targets by 2030 in the draft 6th Strategic Energy Plan, excluding additional policies under consideration (as of August 2021).
	APS	• Green Growth Strategy: 10 GW offshore wind capacity in 2030, 30-45 GW in 2040. • Draft 6th Strategic Energy Plan, with additional policies to support renewables in power generation to reach 2030 targets: 36-38% renewables; 20-22% nuclear; 20% gas; 19% coal; 2% oil; 1% hydrogen and ammonia in electricity generation.
Korea	STEPS	• Increase renewable power capacity to 35% and decrease coal-fired and nuclear power capacity by 2034 under 9th Basic Energy Plan.
Southeast Asia	STEPS	• Indonesia: 30% of capacity additions from new and renewable energy sources under National Electricity Supply Business Plan (RUPTL) 2019-2028. • Philippines: No new coal builds except for those already approved or under construction. • Viet Nam: 18 GW installed wind capacity by 2030 under draft Power Development Plan VIII.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. ETS = emissions trading system; GW = gigawatts. RUPTL = Rencana Usaha Penyediaan Tenaga Listrik, the utility plan for electricity development in Indonesia.

Table B.8 ⊳ Industry sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• Investments from a Department of Energy programme to decarbonise manufacturing in the United States.
	APS	• Carbon Capture Improvement Act: allows facilities to finance CCUS equipment with private activity bonds.
Canada	STEPS	• Funding to decarbonise the industry sector, includes scaling up clean technology, supporting the production of low-carbon fuels and introducing a hydrogen strategy. • Strategic Innovation Fund to spur innovation of clean technologies and emissions reduction solutions and their large-scale deployment.
Central and South America	STEPS	• Brazil: Energy efficiency guarantee fund.
European Union	STEPS	• Spending provisions for the New Industrial Strategy to support green and digital infrastructure, boost industry competitiveness and enhance strategic autonomy. • Country-level incentives for industrial efficiency incentives and targets. • Country-level spending on green industry pilots, circular economy and hydrogen.
	APS	• Country-level hydrogen targets for electrolyser capacity and production volumes. • Country-level targets for industrial GHG emissions reductions (e.g. France declines by 35% by 2030 compared with 2015).
Other Europe	STEPS	• United Kingdom: Electrification component of the 6th Carbon Budget. • United Kingdom: Industrial Energy Transformation Fund provides grant funding for energy efficiency projects.
	APS	• United Kingdom: Full implementation of the 6th Carbon Budget (in addition to the electrification component, it promotes deployment of CCUS and low-carbon manufacturing technologies).
Australia and New Zealand	STEPS	• Australia: Investments from the Modern Manufacturing Initiative. • New Zealand: Investment supported by the Decarbonising Industry Fund.
China	STEPS	• "Made in China 2025" targets for industrial energy intensity.
Japan	STEPS	• Subsidies for industry and commercial energy efficiency investments.
Korea	STEPS	• Funding for smart and green industrial complexes, including monitoring of emissions and energy generation/consumption (Korean New Deal).

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; CCUS = carbon capture, utilisation and storage.

Table B.9 ⊳ Buildings sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• Updated minimum energy performance standards for central air conditioning and heat pumps. • Training programme for workforce that enables energy efficiency improvements.
	APS	• American Jobs Plan objective for building energy retrofits implemented in full. • Funding for retrofits of housing and federal buildings, and construction of energy-efficient childcare facilities and public schools (American Jobs Plan).
Canada	STEPS	• Efficiency financing (second phase - financing for community energy transitions). • Implementation of updated appliance efficiency standards. • Large-scale energy-efficient retrofits as part of the Canada Infrastructure Bank growth plan. • Greener Homes Grant and interest-free loans for deep home retrofits.
	APS	• All new buildings meet zero carbon-ready building standards by 2030.
Central and South America	STEPS	• Argentina: Strengthened energy efficiency building codes and mandatory efficiency labelling for new social housing.
European Union	STEPS	• EU Recovery and Resilience Facility flagship area “Renovate” for energy efficiency in buildings. • Country-level incentives for renovation and appliance upgrades, new building codes, and clean heating incentives and investment.
	APS	• EU Energy Performance of Buildings Directive objective to achieve a highly energy-efficient and decarbonised building stock by 2050. • Renovation Wave objective to double the rate of building energy retrofits by 2030.
Other Europe	STEPS	• United Kingdom: Low Carbon Heat Support and Heat Networks Investment Project; various retrofit incentive schemes for improving buildings efficiency as part of Plan for Jobs.
	APS	• United Kingdom: Future Homes standard banning fossil fuel heating in new home construction by 2025.
Africa	STEPS	• Egypt: Minimum performance standards for incandescent lamps. • Morocco: Minimum performance standards and labelling for appliances. Mandatory energy efficiency audits for services. • Nigeria: Minimum performance standards for refrigerators, air conditioners, central heating/cooling systems and space heating. • Benin: Minimum performance standards and energy labelling system for lamps and unit air conditioners. • Rwanda: Minimum performance standards for air conditioners and refrigerators.
Australia and New Zealand	STEPS	• Australia: Funding for energy efficiency measures, including energy rating labels; State of Victoria 2020-2021 budget for funding includes energy-efficient retrofits and rooftop solar expansion via the Solar Homes programme. • New Zealand: Incentives for clean heating in the Warmer Kiwi Homes programme.

Table B.9 ⊳ **Buildings sector policies and measures as modelled by scenario for selected regions/countries** (continued)

Region/ country	Scenario	Assumptions
China	STEPS	- Standard for maximum energy consumption per square metre in buildings. - Green and High-Efficiency Cooling Action Plan. - Minimum performance standards and energy efficiency labelling for room air conditioners.
India	STEPS	- Cooling Action Plan. Standards and labelling for light commercial air conditioners, freezers and light bulbs. - Energy efficiency labelling for residential buildings for renters and homeowners.
Japan	STEPS	- Support for the introduction of high-performance ventilation equipment. - Revised retailer labelling system.
	APS	- New residential and services buildings meet the net zero energy home or net zero energy building standard on average by 2030.
Korea	STEPS	- Support for energy audits in older buildings. - Rebate for purchase of appliances entitled to energy efficiency grade 1. - Korean New Deal: Retrofit of school buildings to integrate solar power; retrofit of public rental homes, recreational and healthcare facilities; and construction of energy-efficient day-care centres and sports facilities.
	APS	- All new buildings meet zero carbon-ready building standards by 2030.
Southeast Asia	STEPS	- Viet Nam: Minimum performance standards and labelling for appliances and lighting in residential and commercial buildings.

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

Table B.10 ▷ Transport sector policies and measures as modelled by scenario for selected regions/countries

Region/ country	Scenario	Assumptions
United States	STEPS	• In California, the target is to achieve zero emissions passenger cars and light truck sales by 2035, as well as to achieve a zero emissions medium- and heavy-duty truck fleet by 2045.
	APS	• Announced executive order for a target of 50% of all new passenger cars and light-duty trucks to be zero emissions vehicles by 2030. • Fuel-economy standards to improve 8% annually for passenger cars and light trucks for model years 2024-2026, relative to 2021 levels. • Budget plans such as Infrastructure Investment and Jobs Act and American Jobs Plan that aim to enhance the shift towards electric vehicles.
Canada	STEPS	• Public transport infrastructure fund to improve and expand public transit, including buses. • Provinces of Quebec and British Columbia aim to phase out all new sales and registrations of internal combustion engine passenger vehicles by 2035 and 2040 respectively.
	APS	• 100% of all passenger cars and light trucks sales to be zero emissions by 2035.
European Union	STEPS	• The national recovery and resilience plans of EU member states support green mobility, railways, electric vehicles and charging infrastructure.
	APS	• European Union and country-level and automotive manufacturing target dates for 100% EV sales. • Average emissions of new cars to reduce emissions by 55% from 2030 and 100% from 2035 relative to 2021 levels. • Electromobility trends aligned with the net zero target of the European Union by 2050.
Other Europe	STEPS	• United Kingdom: In 2030, implementation of a ban on new gasoline and diesel cars and vans. Hybrid vehicles to be phased out from 2035. Ten Point Plan support for zero emissions vehicles, green ships and aircraft, and public transport. Active Travel England investment in walking and cycling infrastructure. • Norway: National Transport Plan supporting railways and the maritime sector.
	APS	• United Kingdom: Full implementation of aviation net zero emissions target by 2050.
Australia and New Zealand	STEPS	• In the State of Victoria (Australia), government net zero emissions vehicles roadmap and Electric Vehicle Action Plan supporting recharging infrastructure.
Japan	STEPS	• Eco-car tax break and subsidies for vehicles, and national budget 2021 for supporting electric and fuel cell vehicles.
	APS	• Green Growth Strategy and the draft 6th Strategic Energy Plan aiming for 100% zero emissions vehicles (including hybrids) for passenger vehicles by 2035 and for light commercial vehicles by 2040.
Korea	STEPS	• Subsidy scheme for supporting electric vehicles. • Investment in urban and mass transit. • Partial implementation of target for zero emissions vehicles: one-third of new passenger car sales in 2030 are electric vehicles or FCEVs.
	APS	• Target to increase the number of FCEVs to 200 000 by 2025 (Green New Deal).

Table B.10 ▷ Transport sector policies and measures as modelled by scenario for selected regions/countries (continued)

Region/ country	Scenario	Assumptions
China	STEPS	• Corporate average fuel consumption (CAFC) target of 4.0 litres/100 km for 2025 and 3.2 litres/100 km for 2030. • Pilot/demonstration cities reward scheme for FCEVs and exemption of vehicle purchase tax for zero emissions vehicles. • New Energy Automobile Industry Development Plan (2021-2035). • National railway investments.
	APS	• New energy vehicle car sales reach more than half by 2035.
India	STEPS	• Urban and public transit investments. • Partial implementation of 20% bioethanol blending target for gasoline and 5% biodiesel in 2030.
	APS	• National railways target of net zero by 2030.
Southeast Asia	STEPS	• Indonesia: Introduction of the B30 programme to increase biodiesel blends to 30% in gasoil.

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; FCEVs: fuel cell electric vehicles.

Table B.11 ⊳ All regions: Sustainable Development Scenario assumptions

Sector	Assumptions
Cross-cutting policies	• Universal access to electricity and clean cooking by 2030. • Staggered introduction of CO_2 prices (see Table B.2). • Fossil fuel subsidies phased out by 2025 in net-importing countries and by 2035 in net-exporting countries. • Maximum sulphur content of oil products capped at 1% for heavy fuel oil, 0.1% for gas, oil and 10 ppm for gasoline and diesel. • Policies promoting production and use of alternative fuels and technologies such as hydrogen, biogas, biomethane and CCUS across sectors. • Investments included in the *Sustainable Recovery: World Energy Outlook Special Report* (IEA, 2020b).
Power sector policies	• Increased deployment of renewables. • Lifetime extensions of nuclear power plants and some new builds, where applicable and with public acceptance. • Expanded support for the deployment of CCUS. • Efficiency and emissions standards that prevent the refurbishment of old inefficient fossil fuel plants. • Stringent pollution emissions limits for industrial facilities above 50 MW_{th} input using solid fuels set at 200 mg/m^3 for SO_2 and NO_X, and 30 mg/m^3 for $PM_{2.5}$.
Buildings sector policies	• Phase out least efficient appliances, light bulbs and heating/cooling equipment by 2030 at the latest. • Emissions limits for biomass boilers set at 40-60 mg/m^3 for $PM_{2.5}$ and 200 mg/m^3 for NO_X. • Introduction of mandatory energy performance standards for all appliances and space cooling equipment. • Mandatory energy conservation building codes, including net zero emissions requirement for all new buildings by 2030 at the latest. • Increased support for energy efficiency and CO_2 emissions reduction measures in existing buildings, including retrofits, heat pumps, direct use of solar thermal and geothermal energy in some countries. • Digitalisation of electricity demand in the buildings sector to increase demand-side response potential through increased flexibility and control of end-use devices.
Transport sector policies	• PLDVs: On-road vehicle stock emissions intensity limited to 50 g CO_2/km in countries with net zero pledges and around 130 g CO_2/km elsewhere by 2040. • Two/three-wheelers: Phase out two-stroke engines. • Light-duty gasoline vehicles: Three-way catalysts and tight evaporative controls required. • Light-duty diesel vehicles: Limit emissions to 0.1 g/km NO_X and 0.01 g/km $PM_{2.5}$. • New medium and heavy freight trucks are around 20% more efficient by 2040 than in the STEPS. • Heavy-duty diesel vehicles: Limit emissions to 3.5 g/km NO_X and 0.03 g/km $PM_{2.5}$. • Aviation: Fuel intensity reduced by around 3% per year; scale up of biofuels driven by long-term CO_2 emissions target (50% below 2005 levels in 2050). • International shipping: Annual GHG emissions trajectory consistent with 50% below 2008 levels in 2050 in line with IMO GHG emissions reduction strategy.
Industry sector policies	• Policies to support increasing deployment of CCUS and hydrogen in various industry and fuel transformation sub-sectors. • Policies to support circular economies through increased recycling of aluminium, steel, paper and plastics, and materials efficiency strategies. • Enhanced minimum energy performance standards by 2025, in particular for electric motors; incentives for the introduction of variable speed drives in variable load systems and implementation of system-wide efficiency measures. • Mandatory energy management systems or energy audits.

Notes: CCUS = carbon capture, utilisation and storage; g CO_2/km = grammes of carbon dioxide per kilometre; g/km = gramme per kilometre; PLDVs = passenger light-duty vehicles. MW_{th} = megawatts thermal; SO_2 = sulphur dioxide; NO_X = nitrogen oxides; $PM_{2.5}$ = fine particulate matter 2.5 microns or less in diameter; mg/m^3 = milligrammes per cubic metre. IMO = International Maritime Organization.

Table B.12 ⊳ All regions: Net Zero Emissions by 2050 assumptions

Sector	Assumptions
Buildings	• 2025: No new sales of fossil fuel boilers. • 2030: Universal energy access and all new buildings are zero carbon-ready. • 2035: Most appliances and cooling systems sold are "best in class". • 2040: 50% of existing buildings retrofitted to zero carbon-ready levels. • 2045: 50% of heating demand met by heat pumps. • 2050: More than 85% of buildings are zero carbon-ready.
Transport	• 2030: 60% of global car sales are electric vehicles. • 2035: 50% of heavy truck sales are electric and there are no new ICE car sales. • 2040: 50% of fuels used in aviation are low emissions.
Industry	• 2030: Most new clean technologies in heavy industry demonstrated at scale. • 2035: All industrial electric motor sales are "best in class". • 2040: Around 90% of existing capacity in heavy industries reach end of investment cycle. • 2050: More than 90% of heavy industrial production is low emissions.
Electricity and heat	• 2021: No new unabated coal plants approved for development. • 2030: 1 020 GW annual solar and wind additions and phase-out of unabated coal in advanced economies. • 2035: Overall net zero emissions electricity in advanced economies. • 2040: Net zero emissions electricity globally and phase-out of all unabated coal- and oil-fired power plants. • 2050: Almost 70% of electricity generation globally from solar PV and wind.
Other	• 2021: No new oil and gas fields approved for development; no new coal mines or mine extensions. • 2030: Target 150 Mt low-carbon hydrogen and 850 GW electrolysers. • 2035: Target of 4 Gt of CO_2 captured. • 2045: Targets of 435 Mt low-carbon hydrogen and 3 000 GW electrolysers. • 2050: Target of 7.6 Gt CO_2 captured.

Note: ICE = internal combustion engine; GW = gigawatts; PV = photovoltaic; Mt = million tonnes; Gt = gigatonnes.

Definitions

This annex provides general information on terminology used throughout this report including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Area	km^2	square kilometre
	Mha	million hectares
Batteries	Wh/kg	watt hours per kilogramme
Coal	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
Distance	km	kilometre
Emissions	ppm	parts per million (by volume)
	t CO_2	tonnes of carbon dioxide
	Gt CO_2-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
	g CO_2/km	grammes of carbon dioxide per kilometre
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	EJ	exajoule
	PJ	petajoule
	TJ	terajoule
	GJ	gigajoule
	MJ	megajoule
	boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	MBtu	million British thermal units
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
	Gcal	gigacalorie
Gas	bcm	billion cubic metres
	tcm	trillion cubic metres
Mass	kg	kilogramme (1 000 kg = 1 tonne)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonnes (1 tonne x 10^9)

Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/t CO_2	US dollars per tonne of carbon dioxide
Oil	kb/d	thousand barrels per day
	mb/d	million barrels per day
	mboe/d	million barrels of oil equivalent per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

		Multiplier to convert to:				
		EJ	**Gcal**	**Mtoe**	**MBtu**	**GWh**
Convert from:	**EJ**	1	2.388 x 10^8	23.88	9.478 x 10^8	2.778 x 10^5
	Gcal	4.1868 x 10^{-9}	1	10^{-7}	3.968	1.163 x 10^{-3}
	Mtoe	4.1868 x 10^{-2}	10^7	1	3.968 x 10^7	11 630
	MBtu	1.0551 x 10^{-9}	0.252	2.52 x 10^{-8}	1	2.931 x 10^{-4}
	GWh	3.6 x 10^{-6}	860	8.6 x 10^{-5}	3 412	1

Note: There is no generally accepted definition of boe; typically the conversion factors used vary from 7.15 to 7.40 boe per toe.

Currency conversions

Exchange rates *(2020 annual average)*	**1 US dollar (USD) equals:**
British Pound	0.78
Chinese Yuan Renminbi	6.90
Euro	0.88
Indian Rupee	74.10
Indonesian Rupiah	14 582.20
Japanese Yen	106.77
Russian Ruble	72.10
South African Rand	16.47

Source: OECD National Accounts Statistics (database): purchasing power parities and exchange rates dataset (period-average), https://doi.org/10.1787/data-00004-en, accessed September 2021.

Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant lifecycle greenhouse gas emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. This definition differs from the one used for "advanced biofuels" in US legislation, which is based on a minimum 50% lifecycle greenhouse gas reduction and which, therefore, includes sugar cane ethanol.

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Agriculture, forestry and other land use (AFOLU) emissions: Includes greenhouse gas emissions from agriculture, forestry and other land use.

Ammonia (NH_3): Is a compound of nitrogen and hydrogen. It can be used directly as a fuel in direct combustion processes, as well as in fuel cells or as a hydrogen carrier. To be a low emissions fuel, ammonia must be produced from low-carbon hydrogen, the nitrogen separated via the Haber process with electricity generated from low-carbon sources.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to the main power grid may also have some form of back-up power generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline. Capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off-grid systems that are not connected to a main power grid.

Battery storage: Energy storage technology that uses reversible chemical reactions to absorb and release electricity on demand.

Biodiesel: Diesel-equivalent, processed fuel made from the transesterification (a chemical process that converts triglycerides in oils) of vegetable oils and animal fats.

Bioenergy: Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases.

Biogas: A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Include both biogas and biomethane.

Biomethane: Biomethane is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. It is also known as renewable natural gas.

Buildings: The buildings sector includes energy used in residential, commercial and institutional buildings and non-specified other. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Bunkers: Includes both international marine bunkers and international aviation bunkers.

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS)**:** The process of capturing CO_2 emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore or used as an input or feedstock in manufacturing.

Carbon dioxide (CO_2)**:** Is a gas consisting of one part carbon and two parts oxygen. It is an important greenhouse (heat-tapping) gas.

Clean energy: In *power*, clean energy includes: generation from renewable sources, nuclear and fossil fuels fitted with CCUS; battery storage; and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry and transport, excluding aviation bunkers and domestic navigation. In *end-use* applications, clean energy includes: direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; use of hydrogen and hydrogen-based fuels; CCUS in industry and direct air capture. In *fuel supply*, clean energy includes low emissions fuels liquid biofuels and biogases, low-carbon hydrogen and hydrogen-based fuels.

Clean cooking systems: Cooking solutions that release less harmful pollutants, are more efficient and environmentally sustainable than traditional cooking options that make use of solid biomass (such as a three-stone fire), coal or kerosene. This refers primarily to improved solid biomass cookstoves, biogas/biodigester systems, electric stoves, liquefied petroleum gas, natural gas or ethanol stoves.

Coal: Includes both primary coal (i.e. lignite, coking and steam coal) and derived fuels (e.g. patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas works gas, coke-oven gas, blast furnace gas and oxygen steel furnace gas). Peat is also included.

Coalbed methane (CBM)**:** Category of unconventional natural gas, which refers to methane found in coal seams.

Coal-to-gas (CTG)**:** Process in which mined coal is first turned into syngas (a mixture of hydrogen and carbon monoxide) and then into synthetic methane.

Coal-to-liquids (CTL)**:** Transformation of coal into liquid hydrocarbons. It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined using the Fischer-Tropsch or methanol-to-gasoline synthesis process to produce liquid fuels, or through the less developed direct-coal liquefaction technologies in which coal is directly reacted with hydrogen.

Coking coal: Type of coal that can be used for steel making (as a chemical reductant and a source of heat), where it produces coke capable of supporting a blast furnace charge. Coal of this quality is also commonly known as metallurgical coal.

Concentrating solar power (CSP)**:** Solar thermal power generation technology that collects and concentrates sunlight to produce high temperature heat to generate electricity.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. Commonly referred to as first generation biofuels and include sugar cane ethanol, starch-based ethanol, fatty acid methyl ester (FAME), straight vegetable oil (SVO) and hydrotreated vegetable oil (HVO) produced from palm, rapeseed or soybean oil.

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. The *World Energy Outlook* uses an additive index decomposition of the type Logarithmic Mean Divisia Index (LMDI).

Demand-side integration (DSI)**:** Consists of two types of measures: actions that influence load shape such as energy efficiency and electrification; and actions that manage load such as demand-side response.

Demand-side response (DSR)**:** Describes actions which can influence the load profile such as shifting the load curve in time without affecting total electricity demand, or load shedding such as interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time.

Direct air capture (DAC)**:** Technology to capture CO_2 from the atmosphere and permanently store it in deep geological formations or to be used in the production of fuels, chemicals, building materials or other products that use CO_2. When the CO_2 is geologically stored it is permanently removed from the atmosphere resulting in negative emissions.

Dispatchable generation: Refers to technologies whose power output can be readily controlled, i.e. increased to maximum rated capacity or decreased to zero, in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmission and distribution losses.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

End-use sectors: Includes industry (i.e. manufacturing, mining, chemical production, blast furnaces and coke ovens), transport, buildings (i.e. residential and services) and other (i.e. agriculture and other non-energy use).

Energy-related and industrial process CO_2 emissions: Carbon dioxide emissions from fuel combustion and from industrial processes. Note that this does not include fugitive emissions from fuels, flaring or CO_2 from transport and storage. Unless otherwise stated, CO_2 emissions in the *World Energy Outlook* refer to energy-related and industrial process CO_2 emissions.

Energy sector greenhouse gas (GHG) emissions: Energy-related and industrial process CO_2 emissions plus fugitive and vented methane (CH_4) and nitrous dioxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Currently, ethanol is made from starches and sugars, but second generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

Fischer-Tropsch synthesis: Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.

Fossil fuels: Include coal, natural gas, oil and peat.

Gases: Include natural gas, biogases, synthetic methane and hydrogen.

Gaseous fuels: Include natural gas, biogas, biomethane, hydrogen and synthetic methane.

Gas-to-liquids (GTL): Process featuring reaction of methane with oxygen or steam to produce syngas (a mixture of hydrogen and carbon monoxide) followed by synthesis of liquid products (such as diesel and naphtha) from the syngas using Fischer-Tropsch catalytic synthesis. The process is similar to that used in coal-to-liquids.

Geothermal: Geothermal energy is heat derived from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use): Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply): Obtained from the combustion of fuels, nuclear reactors, geothermal resources and the capture of sunlight. It may be used for heating or cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation.

Hydrogen: In this report, hydrogen refers to low-carbon hydrogen unless otherwise stated. To be low-carbon hydrogen, either the emissions associated with fossil fuel-based hydrogen production must be prevented (e.g. by carbon capture, utilisation and storage) or the electricity for hydrogen production from water must be low-carbon electricity. Hydrogen is used in the energy system to refine hydrocarbon fuels and as an energy carrier in its own right. It is also produced from other energy products for use in chemicals production. In this report, total hydrogen demand includes gaseous hydrogen for all uses, including transformation into hydrogen-based fuels and biofuels, power generation, oil refining, and on site production and consumption. Final consumption of hydrogen includes gaseous hydrogen in end-use sectors, excluding transformation into hydrogen-based fuels and biofuels, power generation, oil refining and on site production and consumption.

Hydrogen-based fuels: Include ammonia and synthetic hydrocarbons (gases and liquids). Hydrogen-based is used in the figures in this *World Energy Outlook* to refer to hydrogen and hydrogen-based fuels.

Hydropower: The energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, aluminium, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under other energy sector. There is an exception for fuel transformation in blast furnaces and coke ovens, which are reported within iron and steel. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Covers those quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and instead included in the residential, services and agriculture category.

Investment: Investment is measured as the ongoing capital spending in energy supply capacity, energy infrastructure and energy end-use and efficiency. All investment data and projections reflect spending across the lifecycle of a project, i.e. the capital spent is assigned to the year when it is incurred. Fuel supply investments include production, transformation and transportation for oil, gas, coal and low emissions fuels. Power sector investments include new builds and refurbishments of generation, electricity grids (transmission, distribution and public electric vehicle chargers), and battery storage. Energy efficiency investments include those made in buildings, industry and transport. Other end-use investments include direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; use of hydrogen and hydrogen-based fuels; fossil fuel-based industrial facilities; CCUS in industry and DAC. Investment data are presented in real terms in year-2020 US dollars unless otherwise stated.

Light-duty vehicles (LDVs)**:** Includes passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Lignite: Type of coal that is used in the power sector mostly in regions near lignite mines due to its low energy content and typically high moisture levels, which generally makes long-distance transport uneconomic. Data on lignite in the *World Energy Outlook* includes peat, a solid formed from the partial decomposition of dead vegetation under conditions of high humidity and limited air access.

Liquid biofuels: Liquid fuels derived from biomass or waste feedstock and include ethanol, biodiesel and biojet fuels. They can be classified as conventional and advanced biofuels according to the combination of feedstock and technologies used to produce them and their respective maturity. Unless otherwise stated, biofuels are expressed in energy-equivalent volumes of gasoline, diesel and kerosene.

Liquid fuels: Includes oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-carbon electricity: Includes renewable energy technologies, hydrogen-based generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Lower heating value: Heat liberated by the complete combustion of a unit of fuel when the water produced is assumed to remain as a vapour and the heat is not recovered.

Low emissions fuels: Include liquid biofuels, biogas and biomethane, hydrogen, and hydrogen-based fuels that do not emit any CO_2 from fossil fuels directly when used and also emit very little when being produced.

Marine: Represents the mechanical energy derived from tidal movement, wave motion or ocean currents and exploited for electricity generation.

Middle distillates: Include jet fuel, diesel and heating oil.

Mini-grids: Small electric grid systems, not connected to main electricity networks, linking a number of households and/or other consumers.

Modern energy access: Includes household access to a minimum level of electricity; household access to less harmful and more sustainable cooking and heating fuels, and stoves; access that enables productive economic activity; and access for public services.

Modern gaseous bioenergy: See biogases.

Modern liquid bioenergy: Includes bio-gasoline, biodiesel, biojet kerosene and other liquid biofuels.

Modern renewables: Include all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid bioenergy: Refers to the use of solid bioenergy in improved cook stoves and modern technologies using processed biomass such as pellets.

Natural gas: Comprises gases occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both non-associated gas originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids, manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg (Standard Conditions). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporization of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Natural gas liquids (NGLs): Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilisation of natural gas. NGLs are portions of natural gas recovered as liquids in separators, field facilities or gas processing plants. NGLs include, but are not limited to, ethane (when it is removed from the natural gas stream), propane, butane, pentane, natural gasoline and condensates.

Network gases: Include natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: Fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, asphalt, bitumen, coal tars and oils as timber preservatives.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear power plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Stand-alone systems for individual households or groups of consumers.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Includes both conventional and unconventional oil production. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirits, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses by gas works, petroleum refineries, coal and gas transformation and liquefaction. It also includes energy own use in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category. Fuel transformation in blast furnaces and coke ovens are not accounted in other energy sector.

Passenger cars: A road motor vehicle, other than a moped or a motorcycle, intended to transport passengers. It includes vans designed and used primarily to transport passengers. Excluded are light commercial vehicles, motor coaches, urban buses, and mini-buses/mini-coaches.

Power generation: Refers to fuel use in electricity plants, heat plants and combined heat and power plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Process emissions: CO_2 emissions produced from industrial processes which chemically or physically transform materials. A notable example is cement production, in which CO_2 is emitted when calcium carbonate is transformed into lime, which in turn is used to produce clinker.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector (e.g. freight) could be considered as productive, but is treated separately.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking.

Road transport: Includes all road vehicle types (passenger cars, two/three-wheelers, light commercial vehicles, buses and medium and heavy freight trucks).

Self-sufficiency: Corresponds to indigenous production divided by total primary energy demand.

Services: Energy used in commercial facilities, e.g. offices, shops, hotels, restaurants, and in institutional buildings, e.g. schools, hospitals, public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking and desalination.

Shale gas: Natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability of gas to flow through the rock than is the case within a conventional reservoir. Shale gas is generally produced using hydraulic fracturing.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or people on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar: Includes solar photovoltaics and concentrating solar power.

Solar photovoltaics (PV)**:** Electricity produced from solar photovoltaic cells.

Solid bioenergy: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

Solid fuels: Include coal, modern solid bioenergy, traditional use of biomass and industrial and municipal wastes.

Steam coal: Type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic methane: Low-carbon synthetic methane is produced through the methanation of low-carbon hydrogen and carbon dioxide from a biogenic or atmospheric source.

Synthetic oil: Low-carbon synthetic oil produced through Fischer-Tropsch conversion or methanol synthesis from syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO).

Tight oil: Oil produced from shale or other very low permeability formations, generally using hydraulic fracturing. This is also sometimes referred to as light tight oil. Tight oil includes tight crude oil and condensate production except for the United States, which includes tight crude oil only (US tight condensate volumes are included in natural gas liquids).

Total energy supply (TES)**:** Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens), transport, buildings (including residential and services) and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the United Nations Sustainable Development Goals. It incorporates total final consumption by end-use sectors but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (indicator 7.2.1 of the Sustainable Development Goals), where TFEC is the denominator.

Total primary energy demand (TPED): See total energy supply.

Traditional use of biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes all size categories of commercial vehicles: light trucks (gross vehicle weight less than 3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (>15 tonnes).

Unabated coal: Consumption of coal in facilities without CCUS.

Unabated fossil fuels: Consumption of fossil fuels in facilities without CCUS.

Unabated gas: Consumption of natural gas in facilities without CCUS.

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

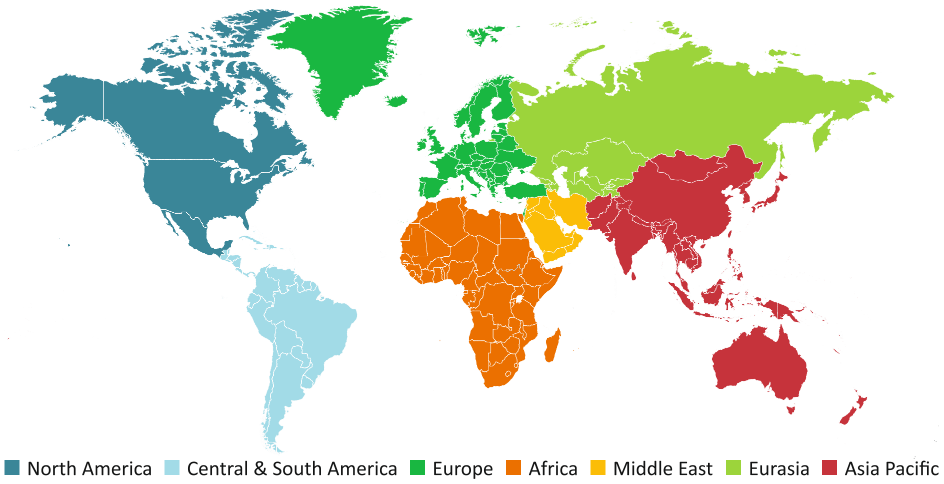
Variable renewable energy (VRE): Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero carbon-ready buildings: A zero carbon-ready building is highly energy efficient and either uses renewable energy directly or an energy supply that can be fully decarbonised, such as electricity or district heat.

Zero emissions vehicles (ZEVs): Vehicles that are capable of operating without tailpipe CO_2 emissions (battery electric and fuel cell vehicles).

Regional and country groupings

Figure C.1 ▷ Main country groupings



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Iceland, Israel, Latvia, Lithuania and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Czech Republic, Colombia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. Costa Rica became a member of the OECD in May 2021; its membership is not yet reflected in the *World Energy Outlook* projections for the OECD grouping.

OPEC (Organisation of the Petroleum Exporting Countries)**:** Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and Acronyms

APEC	Asia-Pacific Economic Cooperation
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy equipped with CCUS
BEV	battery electric vehicles
CAAGR	compound average annual growth rate
CAFE	corporate average fuel economy standards (United States)
CBM	coalbed methane
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CEM	Clean Energy Ministerial
CH4	methane
CHP	combined heat and power; the term co-generation is sometimes used
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power

CTG	coal-to-gas
CTL	coal-to-liquids
DAC	direct air capture
DER	distributed energy resources
DRI	direct reduced iron
DSI	demand-side integration
DSO	distribution system operator
DSR	demand-side response
EHOB	extra-heavy oil and bitumen
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (United States)
ESG	environmental, social and governance
EU	European Union
EU ETS	European Union Emissions Trading System
EV	electric vehicle
FAO	Food and Agriculture Organization of the United Nations
FCEV	fuel cell electric vehicle
FDI	foreign direct investment
FiT	feed-in tariff
FOB	free on board
GDP	gross domestic product
GHG	greenhouse gases
GTL	gas-to-liquids
HEFA	hydrogenated esters and fatty acids
HFO	heavy fuel oil
IAEA	International Atomic Energy Agency
ICE	internal combustion engine
ICT	information and communication technologies
IEA	International Energy Agency
IGCC	integrated gasification combined-cycle
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IMO	International Maritime Organization
IOC	international oil company
IPCC	Intergovernmental Panel on Climate Change
LCOE	levelised cost of electricity
LCV	light commercial vehicle
LDV	light-duty vehicle
LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LULUCF	land use, land-use change and forestry
MEPS	minimum energy performance standards
MER	market exchange rate

NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (an agency within the OECD)
NGLs	natural gas liquids
NGV	natural gas vehicle
NOC	national oil company
NPV	net present value
NO_X	nitrogen oxides
N_2O	nitrous dioxide
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	plug-in hybrid electric vehicles
PLDV	passenger light-duty vehicle
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PPA	power purchase agreement
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SDG	Sustainable Development Goals (United Nations)
SDS	Sustainable Development Scenario
SME	small and medium enterprises
SMR	steam methane reformation
SO_2	sulphur dioxide
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	thermal energy storage
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
TSO	transmission system operator
UAE	United Arab Emirates
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USGS	United States Geological Survey
VALCOE	value-adjusted levelised cost of electricity
VRE	variable renewable energy
WACC	weighted average cost of capital
WEM	World Energy Model
WEO	*World Energy Outlook*

WHO	World Health Organization
ZEV	zero emissions vehicle
ZCRB	zero carbon-ready building

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Inputs to the World Energy Model

General note

This annex includes references of databases and publications used to provide input data to the World Energy Model (WEM). The IEA's own databases of energy and economic statistics provide much of the data used in the WEM, with IEA statistics on energy supply, transformation and demand, carbon dioxide emissions from fuel combustion, energy efficiency indicators and splits of energy demand, forming the bedrock of *World Energy Outlook* modelling and analysis.

Additional data from a wide range of external sources are also used to compliment IEA data and provide additional detail. This list of databases and publications is comprehensive, but not exhaustive.

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World Energy Outlook 2021

Against the backdrop of turbulent markets and a crucial meeting of the COP26 conference on climate change in Glasgow, the 2021 *World Energy Outlook (WEO)* provides an indispensable guide to the opportunities, benefits and risks ahead at this vital moment for clean energy transitions.

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