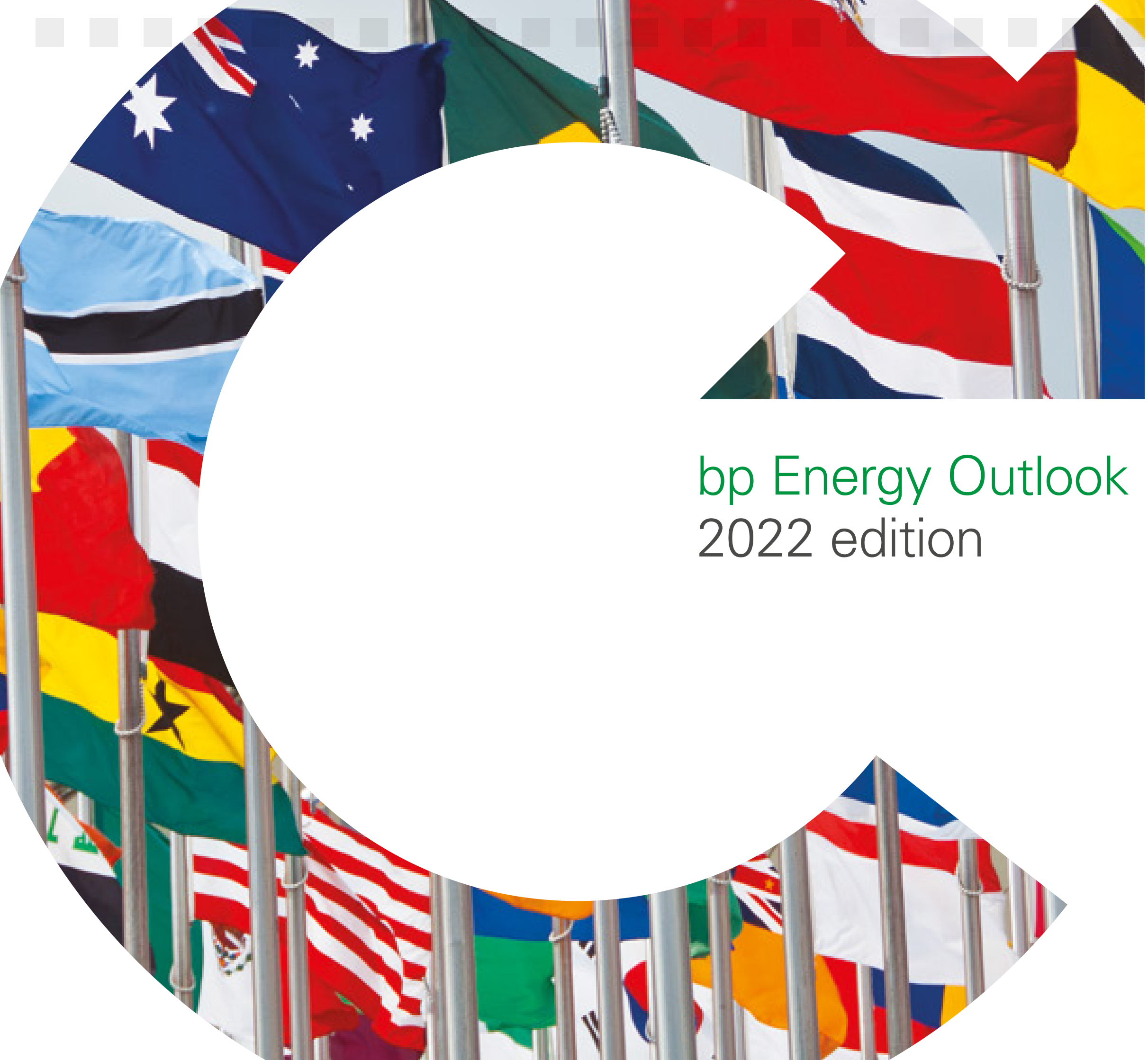

bp Energy Outlook

2022 edition

Energy Outlook 2022 explores the key uncertainties surrounding the energy transition

Energy Outlook 2022 is focussed on three main scenarios: *Accelerated*, *Net Zero* and *New Momentum*. These scenarios are not predictions of what is likely to happen or what bp would like to happen. Rather they explore the possible implications of different judgements and assumptions concerning the nature of the energy transition. The scenarios are based on existing and developing technologies and do not consider the possibility of entirely new or unknown technologies emerging.

The many uncertainties mean that the probability of any one of these scenarios materializing exactly as described is negligible. Moreover, the three scenarios do not provide a comprehensive description of all possible outcomes. However, they do span a wide range of possible outcomes and so might help to inform a judgement about the uncertainty surrounding energy markets out to 2050.

The *Outlook* was largely prepared before the military action by Russia in Ukraine and does not include any analysis of the possible implications of those developments on economic growth or global energy markets.

The *Energy Outlook* is produced to inform bp's strategy and is published as a contribution to the wider debate about the factors shaping the energy transition. But the *Outlook* is only one source among many when considering the future of global energy markets and bp considers a wide range of other external scenarios, analysis and information when forming its long-term strategy.

The content published in this initial version of the *Outlook* summarizes some of the key highlights and findings from the updated scenarios. More detailed material is planned to be released in the future and will be available at bp.com

Welcome to the 2022 edition of bp's *Energy Outlook*

At the time of writing, the world's attention is focussed on the terrible events taking place in Ukraine. Our thoughts and hopes are with all those affected.

The scenarios included in *Energy Outlook 2022* were largely prepared before the outbreak of the military action and do not include any analysis of its possible implications for economic growth and global energy markets. Those implications could have lasting impacts on global economic and energy systems and the energy transition. We will update the scenarios as the possible impacts become clearer.

In the meantime, this year's *Outlook* describes three main scenarios – *Accelerated*, *Net Zero* and *New Momentum* – which explore a wide span of possible outcomes as the world transitions to a lower carbon energy system. Understanding this range of uncertainty helps to shape bp's strategy, increasing its resilience to the different speeds and ways in which the energy system may transition over the next 30 years.

Developments since the previous *Outlook* was published in 2020 show some signs of progress. Government ambitions globally to tackle climate change have increased markedly. And key elements of the low-carbon energy system critical for the world to transition successfully to *Net Zero* – installation of new wind and solar power capacity; sales of electric vehicles; announcements of blue and green hydrogen and CCUS projects – have all expanded rapidly. There are signs of a *New Momentum* in tackling climate change.

Despite that, other than the COVID-19-induced dip in 2020, carbon emissions have risen in every year since 2015, the year of the Paris COP. The carbon budget is finite, and it is running out: further delays in reducing CO_2 emissions could greatly increase the economic and social costs associated with trying to remain within the carbon budget.

Although there is considerable uncertainty, some features of the energy transition are common across all the main scenarios in this year's *Outlook* and so may provide a guide as to how the energy system may change over the next few decades:

- Wind and solar power expand rapidly, supported by an increasing electrification of the world
- A range of energy sources and technologies is required to support deep decarbonization of the global energy system, including electric vehicles, blue and green hydrogen, bioenergy, and CCUS
- Oil and natural gas continue to play a critical role for decades, but in lower volumes as society reduces its reliance on fossil fuels
- The energy mix becomes more diverse, with increasing customer choice and growing demands for integration across different fuels and energy services.

The importance of the world making a decisive shift towards a net-zero future has never been clearer. The opportunities and risks associated with that transition are significant. I hope this year's *Energy Outlook* is useful to everyone trying to navigate this uncertain future and accelerate the transition to *Net Zero*.

As always, any feedback on the *Outlook* and how we can improve would be most welcome.

Spencer Dale
Chief economist

Key themes from *Energy Outlook 2022*

The Outlook can be used to identify aspects of the energy transition which are common across the main scenarios and so may provide a guide as to how the energy system may evolve over the next 30 years.

- The carbon budget is running out: CO_2 emissions have increased in every year since the Paris COP in 2015, except in 2020. Delaying decisive action to reduce emissions sustainably could lead to significant economic and social costs.
- Government ambitions globally have grown markedly in the past few years pointing to new, increased momentum in tackling climate change. But there is significant uncertainty as to how successful countries and regions will be in achieving those aims and pledges.
- The structure of energy demand changes, with the importance of fossil fuels gradually declining, replaced by a growing share of renewable energy and increasing electrification. The transition to a low-carbon world requires a range of other energy sources and technologies, including low-carbon hydrogen, modern bioenergy, and carbon capture, use and storage (CCUS).
- The movement to a lower carbon energy system leads to a fundamental restructuring of global energy markets, with a more diversified energy mix, increased levels of competition, shifting economic rents, and a greater role for customer choice.
- Oil demand increases to above its pre-COVID-19 level before falling further out. Declines in oil demand are driven by the increasing efficiency and electrification of road transportation. Natural declines in existing hydrocarbon production imply continuing investment in new upstream oil and gas is required over the next 30 years.

- The use of natural gas is supported, at least for a period, by increasing demand in fast-growing emerging economies as they continue to industrialize and reduce their reliance on coal. Growth in liquefied natural gas plays a central role in increasing emerging markets' access to natural gas.
- Wind and solar power expand rapidly, accounting for all or most of the increase in global power generation, underpinned by continuing falls in their costs and an increasing ability of power systems to integrate high concentrations of variable power sources. The growth in wind and solar power requires a substantial increase in the pace of investment in both new capacity and enabling technologies and infrastructure.
- The use of modern bioenergy increases substantially, providing a low-carbon alternative to fossil fuels in hard-to-abate sectors.
- The use of low-carbon hydrogen increases as the energy system progressively decarbonizes, carrying energy to activities and processes which are difficult to electrify, especially in industry and transport. The production of low-carbon hydrogen is dominated by green and blue hydrogen, with green hydrogen growing in importance over time.
- CCUS plays a central role in supporting a low-carbon energy system: capturing emissions from industrial processes, providing a source of carbon dioxide removals, and abating emissions from fossil fuels.
- A range of carbon dioxide removals – including bioenergy combined with carbon capture and storage, natural climate solutions, and direct air capture with storage – may be needed for the world to achieve a deep and rapid decarbonization.

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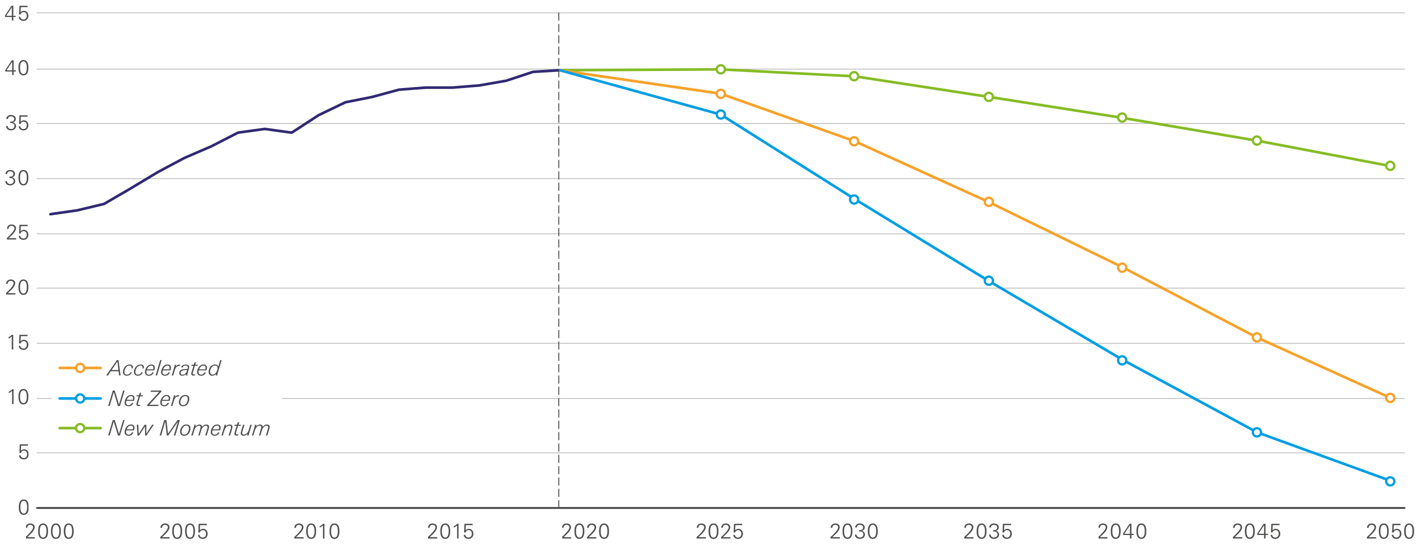
Accelerated and *Net Zero* are broadly in line with 'Paris consistent' IPCC scenarios

Final energy demand peaks in all three scenarios as gains in energy efficiency accelerate

Three scenarios to explore the energy transition to 2050: *Accelerated*, *Net Zero*, and *New Momentum*

Carbon emissions

Gt of CO_2e



Carbon emissions include CO_2 emissions from energy use, industrial processes, natural gas flaring, and methane emissions from energy production.

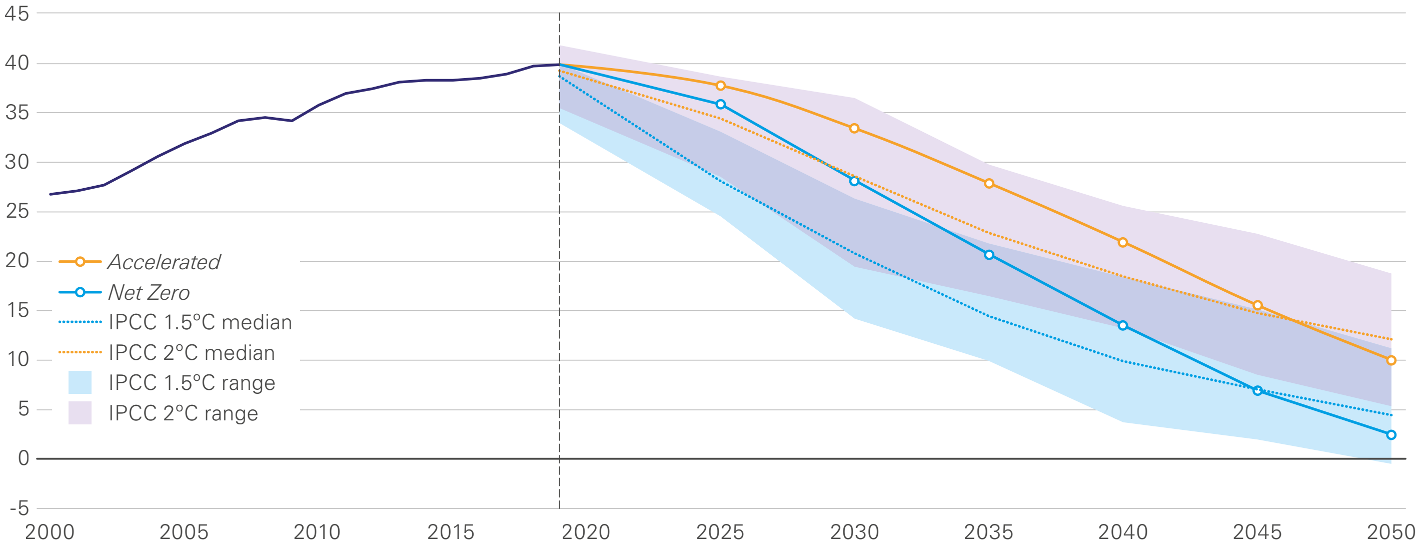
bp's *Energy Outlook 2022* uses three main scenarios (*Accelerated*, *Net Zero*, and *New Momentum*) to explore the range of possible pathways for the global energy system to 2050 and help shape a resilient strategy for bp.

- The scenarios are not predictions of what is likely to happen or what bp would like to happen. Rather, the scenarios taken collectively are used to explore the range of possible outcomes over the next 30 years.
- Importantly, the scenarios were largely prepared before the outbreak of military action in Ukraine and do not include any analysis of its possible implications for economic growth and global energy markets.
- Although the scenarios do not provide a comprehensive description of future uncertainty, they are intended to encompass a significant range of the possible outcomes for the energy system out to 2050. As such, the scenarios are used to inform bp's core beliefs about the energy transition and help shape a strategy which is resilient to that uncertainty.
- The scenarios consider carbon emissions from energy production and use, most non-energy related industrial processes, and natural gas flaring plus methane emissions from the production, transmission and distribution of fossil fuels.
- Accelerated and Net Zero explore how different elements of the energy system might change in order to achieve a substantial reduction in carbon emissions. They are conditioned on the assumption that there is a significant tightening of climate policies leading to a pronounced and sustained fall in CO_2-equivalent (CO_2e) emissions. The fall in emissions in Net Zero is aided by a shift in societal behaviour and preferences which further supports gains in energy efficiency and the adoption of low-carbon energy sources.
- New Momentum is designed to capture the broad trajectory along which the global energy system is currently progressing. It places weight both on the marked increase in global ambition for decarbonisation seen in recent years and the likelihood that those aims and ambitions will be achieved, and on the manner and speed of progress seen over the recent past.
- CO_2e emissions in all three scenarios increase above pre-Covid levels. Emissions in Accelerated and Net Zero peak in the early 2020s and by 2050 are around 75% and 95% below 2019 levels respectively. CO_2e emissions in New Momentum peak in the late 2020s and by 2050 are around 20% below 2019 levels.

Accelerated and *Net Zero* are broadly in line with 'Paris consistent' IPCC scenarios

Carbon emissions

Gt of CO_2e



Carbon emissions include CO_2 emissions from energy use, industrial processes, natural gas flaring, and methane emissions from energy production. Ranges show 10th and 90th percentiles of the IPCC scenarios.

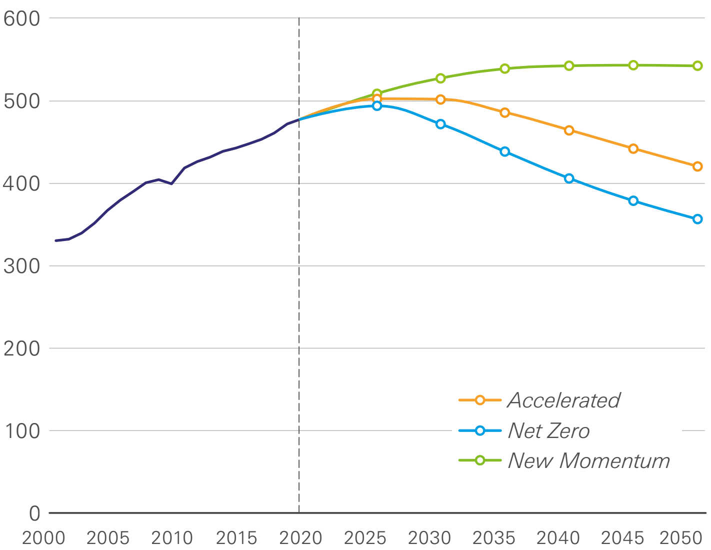
The pace and extent of decarbonization in *Accelerated* and *Net Zero* are broadly aligned with a range of IPCC scenarios which are consistent with maintaining global average temperature rises to well below 2°C and 1.5°C respectively.

- Since the *Energy Outlook* scenarios extend only to 2050 and do not model all forms of greenhouse gases it is not possible to map directly between the scenarios and their implications for the increase in average global temperatures in 2100.
- However, for *Net Zero* and *Accelerated* it is possible to provide an indirect inference by comparing their trajectories for CO_2e emissions with the range of corresponding pathways taken from the scenarios included in the 2018 IPCC Special Report on Global Warming of 1.5°C (SR15). For details of the construction of the IPCC scenario ranges (see pages 98-99).
- CO_2e emissions in *Accelerated* fall by around 75% by 2050 (relative to 2019 levels). The extent and pace of this fall is broadly in the middle of the range of IPCC scenarios corresponding to a rise in average global temperatures of well below 2°C by 2100, with cumulative CO_2e emissions (2019-2050) around the 75th percentile of the range of well below 2°C IPCC scenarios.
- CO_2e emissions in *Accelerated* fall to around 10 $GtCO_2e$ by 2050. The remaining emissions are concentrated in the hardest-to-abate sectors, with industry accounting for close to 50% of the residual emissions and transport around 35%.
- CO_2e emissions in *Net Zero* fall by around 95% relative to 2019 levels to around 2.5 $GtCO_2e$ by 2050. The initial pace of decline is slower than the range of IPCC 1.5°C scenarios, but by the second half of the outlook, the emissions pathway is towards the bottom end of the range. Cumulative CO_2e emissions (2019-to-2050) in *Net Zero* are between the 75th and 90th percentile of the range of 1.5°C IPCC scenarios.
- The CO_2e emissions remaining in *Net Zero* in 2050 could be further reduced either by additional changes to the energy system or by the use of carbon dioxide removal (CDR) options (see pages 92-93), such as natural climate solutions (NCS) or direct air carbon capture with storage (DACCS).

Final energy demand peaks in all three scenarios as gains in energy efficiency accelerate

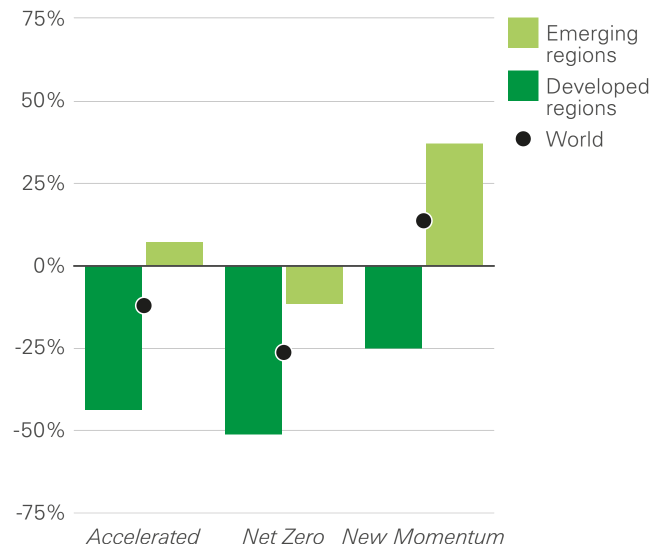
Total final consumption

EJ



Change in total final consumption

2019-2050 change



Global energy demand measured at the final point of use (total final consumption, TFC) peaks in all three scenarios as gains in energy efficiency accelerate. TFC peaks in the early 2020s in *Net Zero*, around 2030 in *Accelerated* and in the mid-2040s in *New Momentum*. By 2050, TFC is 10-25% lower in *Accelerated* and *Net Zero* than 2019 levels and around 15% higher in *New Momentum*.

- The global pace of improvement in energy efficiency over the outlook – measured by comparing growth in final energy demand and economic activity – is much quicker in all three scenarios than over the past 20 years. This acceleration in energy efficiency reflects increasing process and material efficiency as well as the increasing use of electricity at the final point of use.

- The average rates of improvement in energy efficiency over the outlook are similar across developed and emerging economies. However, the increasing prosperity and stronger economic growth in emerging economies means the outlook for energy demand within emerging economies is far stronger than in the developed world.

- Total final consumption across all emerging economies grows by around 35% and 5% by 2050 in *New Momentum* and *Accelerated* and falls by 10% in *Net Zero*. In comparison, TFC within the developed world falls by 25-50% by 2050 across the three scenarios.

- The increasing importance of electricity and hydrogen means the outlook for total primary energy depends importantly on the method used to equate the energy content of non-fossil fuels with traditional hydrocarbons. (See pages 106-107).
  - The *substitution method* – which grosses up energy derived from non-fossil power generation to reflect the losses associated with converting fossil fuels to electricity – implies that primary energy grows by 5-20% by 2050 across the three scenarios.
  - The *physical content method* – which uses the output of non-fossil power generation directly – implies a lower range for primary energy of between growth of 10% (*New Momentum*) and a fall of around 25% (*Net Zero*) by 2050.

Changes since *Energy Outlook 2020*

Economic impact of COVID-19 in near-term less than previously feared

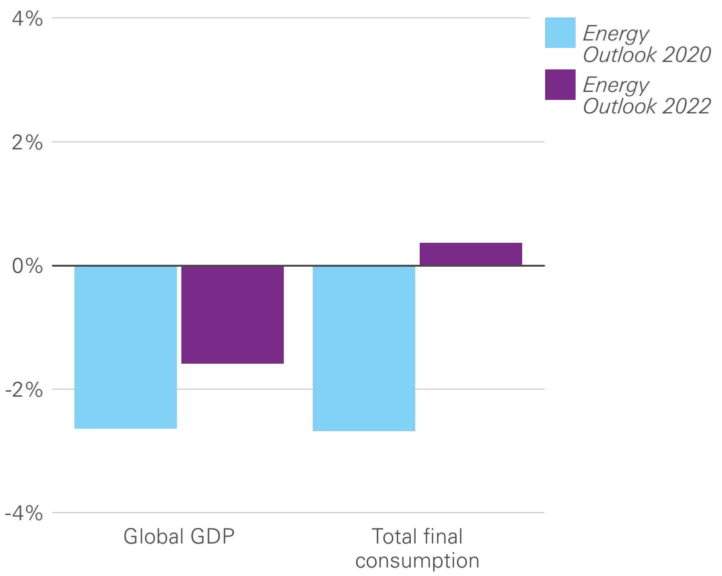
Growing government ambition points to increased momentum in tackling climate change

Increased focus on speed of global decarbonization to 2030

Economic impact of COVID-19 in near-term less than previously feared

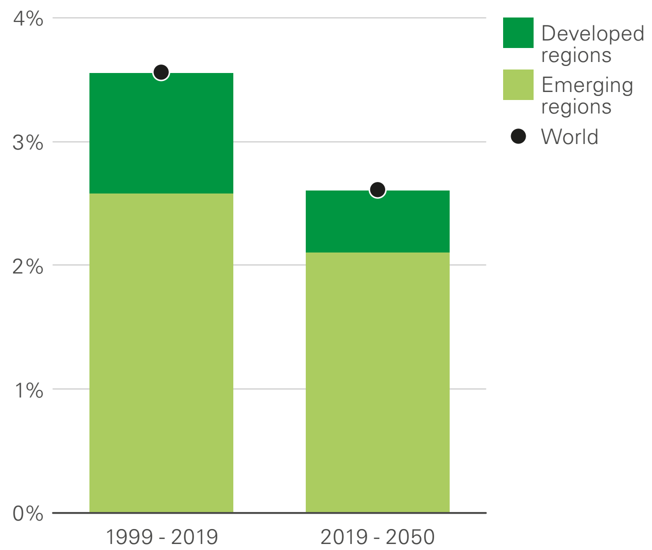
Impact of COVID-19 on global GDP and total final consumption of energy

2019 - 2025 Change



Global GDP growth

Contributions to annual average growth rate

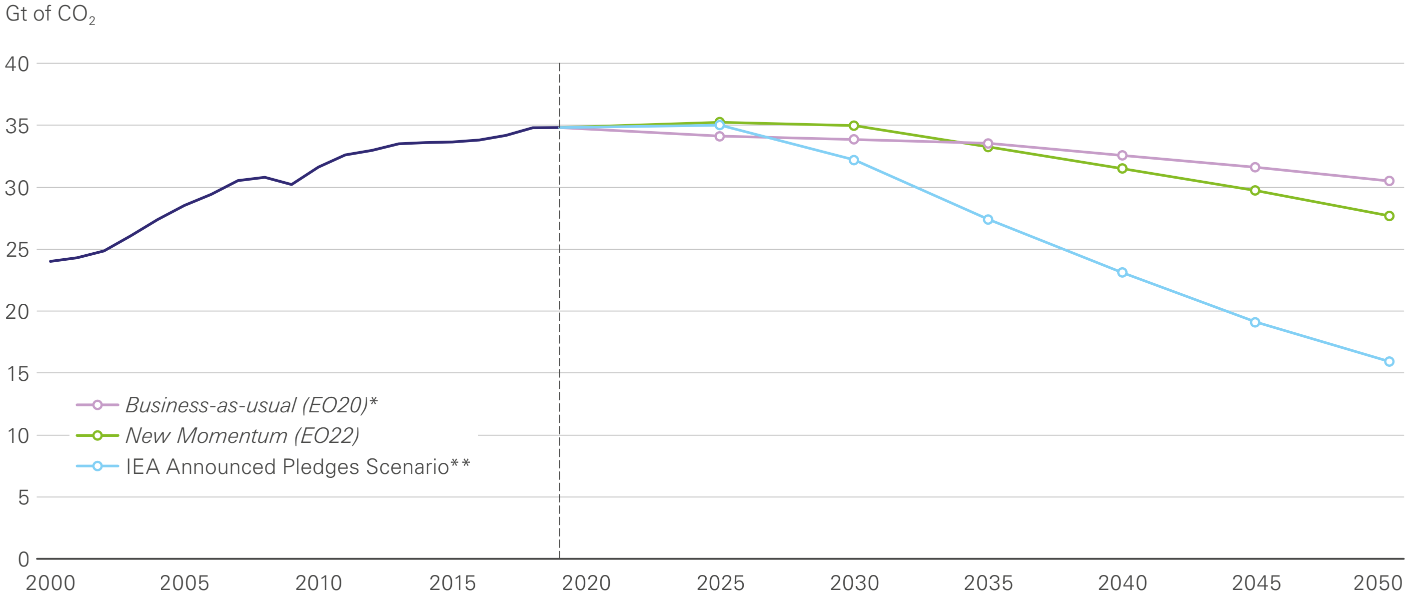


The COVID-19 pandemic is foremost a humanitarian crisis. The scale of the economic cost and disruption means it is also likely to have a significant and persistent impact on the global economy and energy system

- Although considerable uncertainty remains, the near-term economic impact of COVID-19 on global GDP looks set to be less severe than previously anticipated, pointing to a stronger-than-expected outlook for energy demand and carbon emissions in the near term. The Outlook was largely prepared before the military action by Russia in Ukraine and does not include any analysis of the possible implications of those developments on economic growth or global energy markets.
- In *Energy Outlook 2020*, the impact of the COVID-19 crisis was assumed to lower the level of global GDP by around 2.5% in 2025 and 3.5% in 2050, with these economic impacts falling disproportionately on emerging economies.
- Although considerable uncertainty remains, the widespread deployment of effective vaccines combined with huge fiscal and monetary support means the near-term economic impact of COVID-19 is likely to be less damaging than previously feared, at least in the developed world.
- As a result, the level of global GDP in 2025 in this *Energy Outlook* is around 1% higher than in Outlook 2020, with almost all this upward revision occurring in the developed world, where access to vaccines and government support has been greatest. This stronger profile for GDP boosts energy demand and carbon emissions in the near term.
- In contrast, further out, the level of world GDP is assumed to be a little lower than in the 2020 *Outlook*. This downward revision stems entirely from emerging economies, reflecting in part the long-term economic scarring effects associated with the pandemic.
- As in *Energy Outlook 2020*, the outlook for global GDP attempts to take account of the impact of climate change on economic growth. This includes estimates of both the impact of increasing temperatures on economic activity and the upfront costs of actions to reduce carbon emissions. More details of the approach followed can be found (see pages 100-101). The environmental and economic models underpinning these estimates are highly uncertain and almost certainly incomplete, and future editions of the *Energy Outlook* will update these estimates as the evolution of those models enables us to do so.
- In all three scenarios, global GDP annual growth averages around 2.5% (on a 2015 Purchasing Power Parity basis) over the outlook. Although this pace of growth is considerably slower than its average over the past 20 years, it still implies that the world economy more than doubles by 2050. Emerging economies account for over 80% of this expansion, driven by increasing prosperity and living standards.

Growing government ambition points to increased momentum in tackling climate change

Carbon emissions from energy use and industrial processes



* For comparison purposes, EO20 data has been rebased to match EO22 historical energy and process emissions.
** Updated for COP26 announcements.

There has been a marked strengthening in the past two years in the ambitions of governments around the world to increase the pace and extent to which they reduce carbon emissions. Although the extent to which these greater ambitions will be met is uncertain, they do suggest that there might be stronger momentum towards the world reducing carbon emissions than implied by many 'business-as-usual' type scenarios.

- One notable measure of this increased ambition is that sovereign aims and pledges to reduce CO_2 emissions to *Net Zero* now cover around 90% of the world's carbon emissions, compared with less than 20% in 2019. This has been accompanied in some countries by strengthening aims and targets concerning the pace of decarbonization by 2030.

- The International Energy Agency, in its Announced Pledges Scenario, updated to take account of pledges and commitments made at COP26, estimates that if all announced climate commitments made by governments around the world are met in full and on time, CO_2 emissions from energy and industrial processes would fall by around 50% by 2050 (relative to 2019).

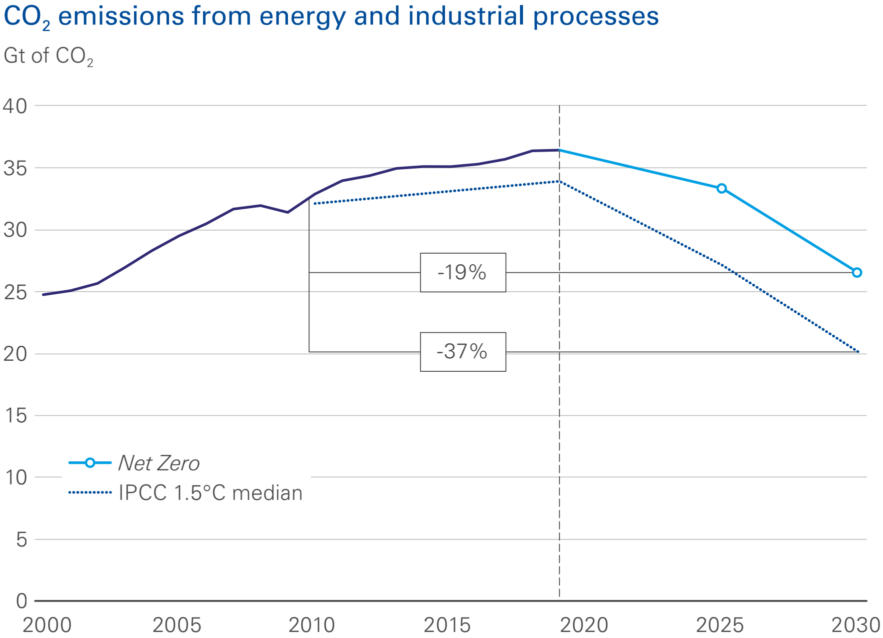
- In comparison, the *Business-as-usual (BAU)* scenario in the *Energy Outlook 2020* – which assumed that government policies, technologies and social preferences continue to evolve in a manner and speed seen over the recent past – pointed to a fall in CO_2 emissions from energy use of only around 10% by 2050.

- The aim of *New Momentum* is to capture the broad trajectory along which the global energy system is currently evolving. In doing so, as well as placing some weight on the pace of progress seen over the recent past, it also places weight on the marked increase in global climate pledges and commitments seen in the past few years and a judgement on the likelihood they will be achieved.

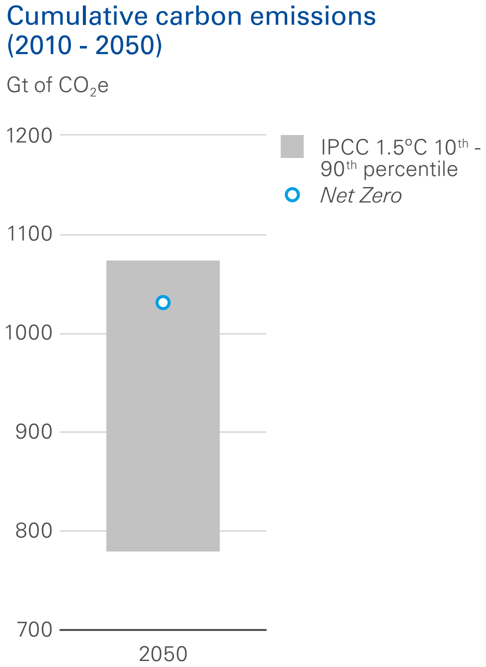
- The relative weights to place on these two factors is uncertain. In *New Momentum*, CO_2e emissions fall by around 20% by 2050 (relative to 2019).

- This scale of decarbonization is significantly less than that implied if all global commitments and pledges are met in full. And it is significantly slower than the pace of decarbonization needed to be consistent with meeting the Paris climate goals. Even so, the speed of decarbonization over the outlook is roughly double that assumed in the 2020 BAU scenario.

Increased focus on speed of global decarbonization to 2030



The IPCC 1.5°C median is based on scenarios with limited or no overshoot



There has been increasing attention over the past few years on achieving a significant fall in global emissions by 2030 to conserve the world's remaining carbon budget.

- Analysis contained in the 2018 IPCC Special Report (SR15) suggested that, under some scenarios, to be consistent with a 1.5°C climate goal, global net anthropogenic CO_2 emissions would need to decline by about 45% by 2030 (relative to 2010 levels).

- This fall in CO_2 emissions in the SR15 analysis included reduced emissions from both the energy and industry sectors and the AFOLU (Agriculture, Forestry and Other Land Use) sector. The fall in CO_2 emissions from 'fossil fuels and industry' was around 37% (relative to 2010). The corresponding fall in CO_2 emissions in *Net Zero* is around 20%.

- The smaller fall in CO_2 emissions assumed in *Net Zero* partly reflects the higher level of CO_2 emissions in 2019 than assumed in the SR15 analysis, together with the assumption that emissions rise over the next year or so as the global economy continues to recover from the pandemic. It also reflects an assessment of the likely lead times associated with financing and implementing the required changes to the global energy system that are necessary to support a rapid decarbonization.

- The pace of decarbonization in *Net Zero* in the second half of this decade is broadly similar to that assumed in the SR15 analysis, albeit from a higher level.

- As explained (see pages 98-99), cumulative CO_2 emissions in *Net Zero* lie in the range of the IPCC 1.5°C scenarios. The slower pace of decarbonization to 2030 in *Net Zero* is partially offset by a faster pace of decline than the median 1.5°C scenario in the second half of the Outlook. Even so, cumulative CO_2 emissions in *Net Zero* lie in the top half of the range.

- To achieve a significant fall in carbon emissions by 2030, the likely rise in emissions over the next year or so, together with the lead times associated with reforming some aspects of the energy sector, highlights the potential importance of carbon dioxide removals (CDRs) (see pages 92-93), including natural climate solutions, in helping to reduce net carbon emissions in the short run while these investments and changes are undertaken.

Core beliefs

Gradual shift in energy demand: declining role for hydrocarbons,
rapid expansion in renewables and electrification

Energy transition underpinned by a range of low-carbon
energy sources and technologies

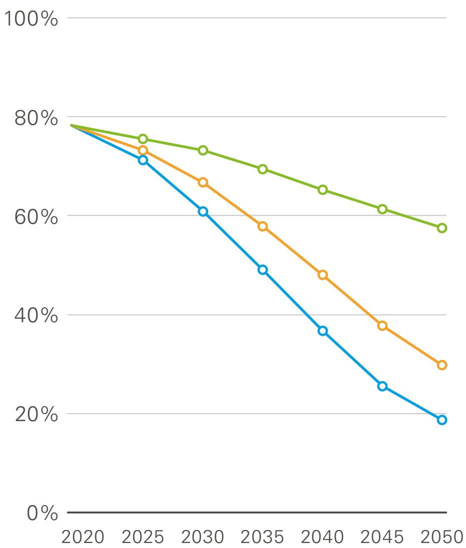
Changing nature of global energy markets:
more diverse energy mix, increased competition and greater customer choice

Delaying action increases the risk of a costly and disorderly transition

Gradual shift in energy demand: declining role for hydrocarbons, rapid expansion in renewables and electrification

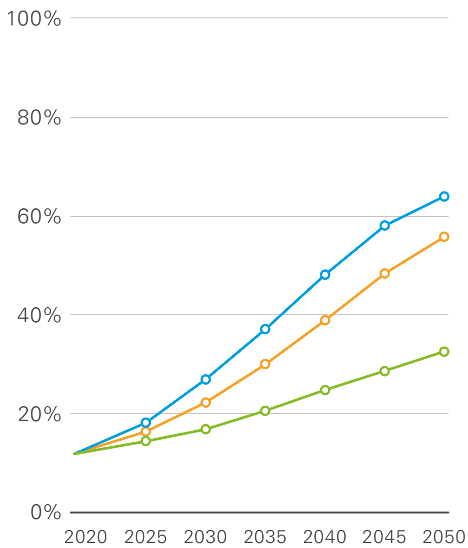
Fossil fuels

Share of primary energy



Renewables*

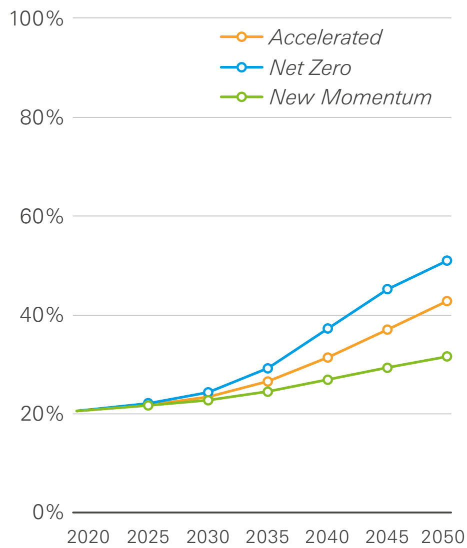
Share of primary energy



* Includes wind, solar, bioenergy and geothermal

Electricity

Share of total final consumption



The scenarios can be used to identify three trends in energy demand which are apparent across a range of different transition pathways: a gradual decline in the role of hydrocarbons; a rapid expansion of renewable energy; and an increasing electrification of the world. The consistency of these trends across all three scenarios helps underpin some of bp's core beliefs about the energy transition.

Consider these three trends in turn.

- The role of hydrocarbons gradually declines as the world transitions to lower carbon energy sources. Fossil fuels in 2019 accounted for around 80% of global primary energy. In the three scenarios, that share declines to between 60% and 20% by 2050.

- Indeed, the total consumption of fossil fuels declines in all three scenarios over the outlook. This would be the first time in modern history that there is a sustained fall in the demand for any fossil fuel.

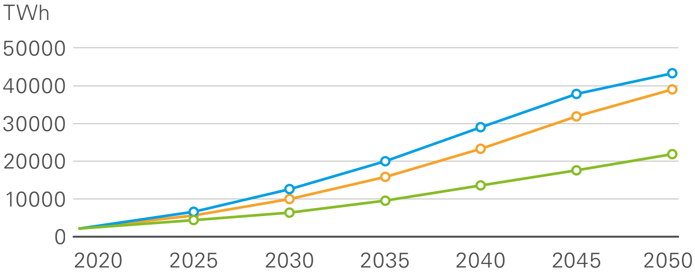
- The declining role for fossil fuels is offset by the rapid expansion of renewable energy (wind and solar power, bioenergy, and geothermal power). The share of renewable energy in global primary energy increases from around 10% in 2019 to between 35% and 65% by 2050 in the three scenarios.

- In all three scenarios, the pace at which renewable energy penetrates the global energy system is quicker than any form of fuel in history.

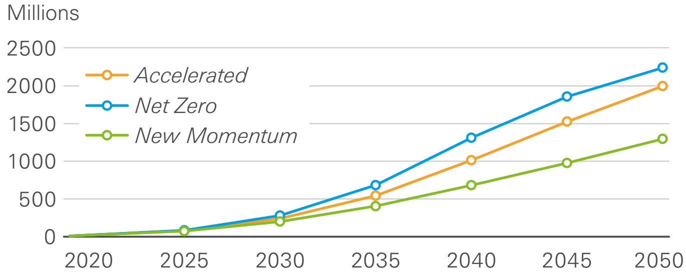
- Third, the increasing importance of renewable energy is supported by the continuing electrification of the energy system. The share of electricity in total final energy consumption increases from around 20% in 2019 to between 30% and 50% by 2050 in the three scenarios.

Energy transition underpinned by a range of low-carbon energy sources and technologies

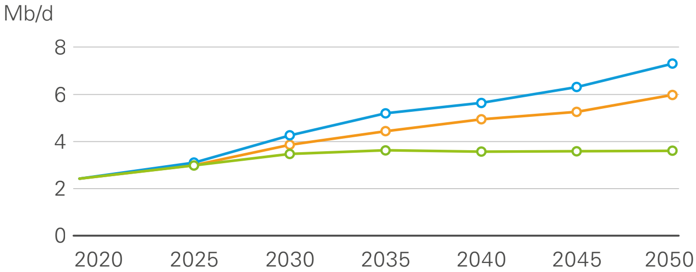
Wind and solar power generation



Electric vehicles

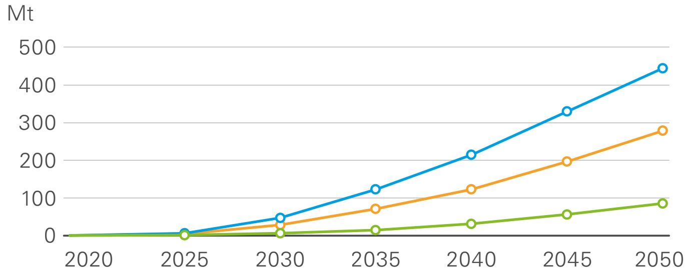


Biofuels



Biofuels includes liquids biofuels and gaseous biofuels (biomethane, expressed in biodiesel equivalent terms)

Low-carbon hydrogen



The transition to a low-carbon energy system in *Accelerated* and *Net Zero* is underpinned by rapid growth in a broad range of low-carbon energy sources and technologies: wind and solar power, electric vehicles, biofuels, and low-carbon hydrogen.

- A central element of the transition pathways in *Accelerated* and *Net Zero* is a deep decarbonization of the global power sector and an increasing electrification of energy end-uses and processes.

- The decarbonization of the power sector is driven by rapid growth in wind and solar power. Wind and solar power generation increases by around 20-fold over the outlook in *Accelerated* and *Net Zero*, increasing to around 40,000-45,000TWh and more than accounting for the entire growth in global power generation (see pages 76-77).

- A key area of increasing electrification is road transportation. The share of electric vehicles (pure battery electric vehicles and plug-in hybrids) in new vehicle sales increases from 2% in 2019 to 25-30% in 2030 and around 90% in 2050 in *Accelerated* and *Net Zero*. In these two scenarios, there are around 2 billion or more electric vehicles in the global vehicle parc by 2050, compared with 7 million in 2019.

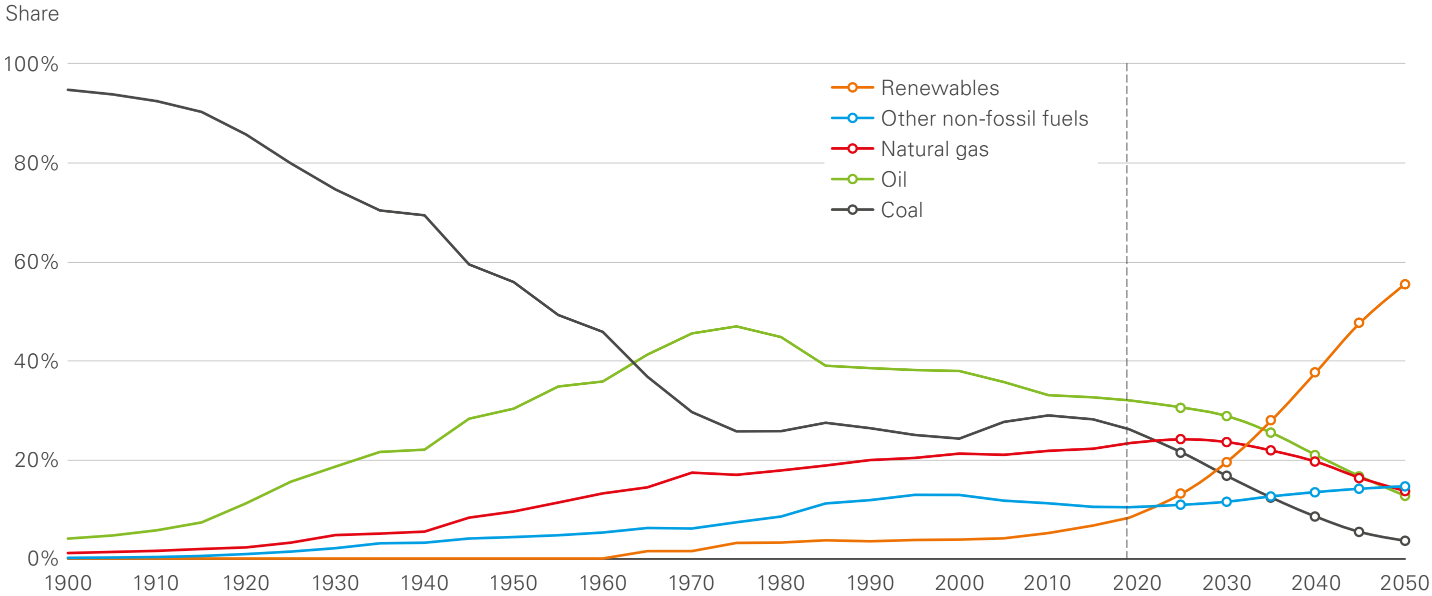
- But some end-uses and processes are difficult or prohibitively costly to electrify. The decarbonization of these hard-to-abate uses and processes can be aided by the use of biofuels and hydrogen.

- The use of biofuels (including biomethane) increases more than 2-fold over the outlook in *Accelerated* and *Net Zero* to 6-7Mb/d by 2050. Biofuels play a particularly important role helping to decarbonize the aviation sector, with bio-based sustainable aviation fuel accounting for around 30% of aviation fuel demand in *Accelerated* by 2050 and 45% in *Net Zero* (see pages 46-47).

- The widespread use of low-carbon (blue and green) hydrogen emerges in the 2030s and 2040s in *Accelerated* and *Net Zero* as it helps to decarbonize parts of industry and transport. Within industry, the use of low-carbon hydrogen is concentrated in areas of heavy industry which rely on high-temperature processes, such as iron and steel, chemicals, and cement. In transportation, hydrogen (and hydrogen-derived fuels) are used as an alternative to fossil fuels in long-distance marine, aviation, and heavy-duty road transportation. The demand for low-carbon hydrogen increases to 280-450 mtpa by 2050 in *Accelerated* and *Net Zero* (see pages 80-82).

Changing nature of global energy markets: more diverse energy mix, increased competition and greater customer choice

Share of primary energy in *Accelerated*



Excludes traditional biomass
Other non-fossil fuels includes hydro and nuclear

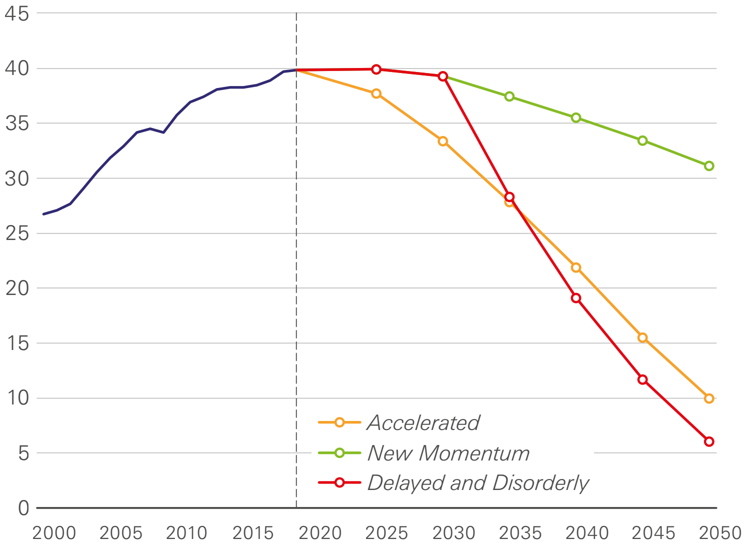
The transition to a low-carbon energy system would be likely to lead to a fundamental reshaping of global energy markets, with a more diversified energy mix, increased levels of competition, and a greater role for customer choice. These changes can be illustrated by the changing structure of energy markets in *Accelerated*; similar features are also apparent in *Net Zero*.

- For much of the past 100 years or so, the energy system has been dominated by a single energy source: coal in the first half of the 20th century and then oil from the 1970s.
- The energy transition envisaged in *Accelerated* leads to a far more diversified energy mix over the next 20-years or so, with renewables and other non-fossil fuels providing a growing share of the world's energy, alongside traditional fossil fuels.
- This greater variety of energy sources together with the growing range of technologies that allow for greater substitution between energy sources and carriers at the point of use – e.g., the growth of electric cars alongside internal combustion engine cars – means the fuel mix is increasingly driven by customer choice rather than the availability of different fuels, with the potential for consumers to increase their demands for integration across different fuels and energy services.
- The increasing diversity of the fuel mix, together with the greater role for customer choice, leads to growing competition between different forms of energy as they compete for market share. Moreover, the declining demand for fossil fuels leads to increasing competition within individual fossil fuels, as producers compete to ensure their energy resources are produced and consumed. This growing competition, both across and within fuels, increases the bargaining power of consumers, with economic rents shifting away from traditional upstream producers towards energy consumers.

Delaying action increases the risk of a costly and disorderly transition

Carbon emissions

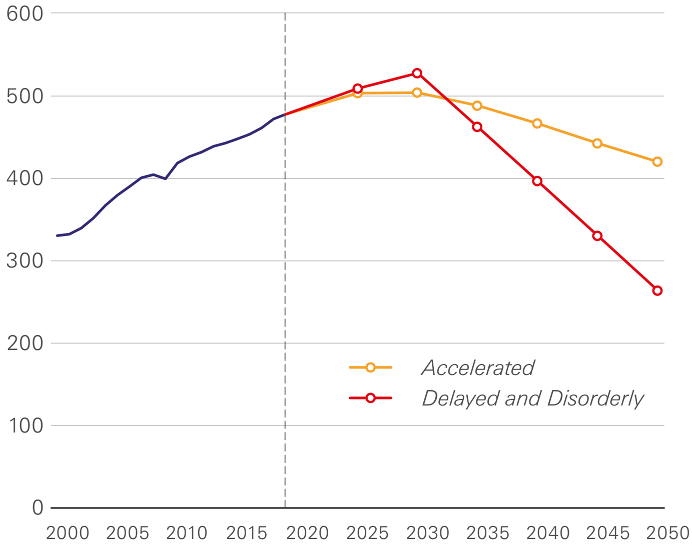
Gt of CO_2e



Carbon emissions include CO_2 emissions from energy use, industrial processes, natural gas flaring, and methane emissions from energy production

Total final consumption

EJ



The nature of the finite carbon budget consistent with achieving the Paris climate goals means that every year in which decisive action to reduce global carbon emissions is delayed, the difficulty of staying within the budget significantly increases. This raises the risk that an extended period of delay could greatly increase the economic and social costs associated with trying to remain within the carbon budget.

- This possibility is explored in an alternative *Delayed and Disorderly* scenario in which the global energy system is assumed to move in line with *New Momentum* until 2030, after which sufficient policies and actions are undertaken to limit cumulative CO_2e emissions over the entire outlook (2020-2050) to that in *Accelerated*.

- *Delayed and Disorderly* is highly stylized – the nature of any delayed transition path will depend on the factors triggering the eventual change and the response of government and society. Even so, it highlights an important feature of the carbon budget that, even if improvements in energy efficiency and switching to low-carbon fuels occur at historically unprecedented rates, achieving the same level of cumulative CO_2e emissions over the next 30 years as in *Accelerated* would likely be possible only if final energy consumed over that period was substantially lower.

- For example, *Delayed and Disorderly* assumes that, although starting 10 years later, both energy efficiency and the carbon intensity of the fuel mix are able to reach the same levels as in *Accelerated* by 2050. Despite that, total final energy consumption by 2050 needs to be around 40% lower than in *Accelerated* to meet the same carbon budget, implying that energy use is significantly rationed and constrained.

- Although not modelled explicitly, the restrictions and controls needed to achieve this lower level of energy consumption are likely to have a significant cost on both economic activity and levels of well-being.

Energy demand

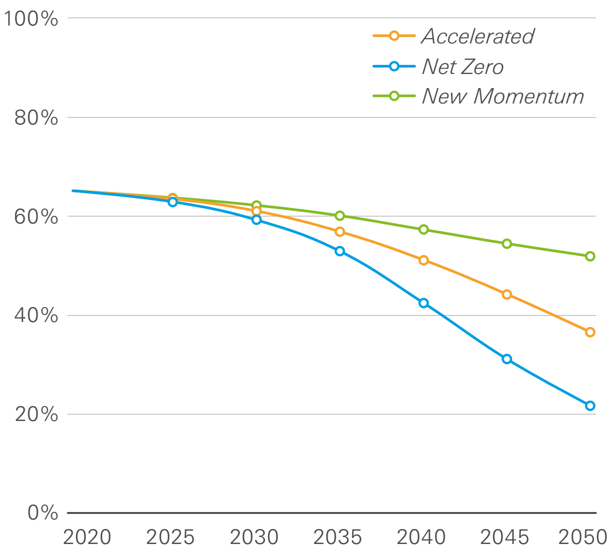
Total final energy consumption decarbonizes as fossil fuels are replaced by electricity and hydrogen

The share of fossil fuels in primary energy falls as renewable energy increases rapidly

Total final energy consumption decarbonizes as fossil fuels are replaced by electricity and hydrogen

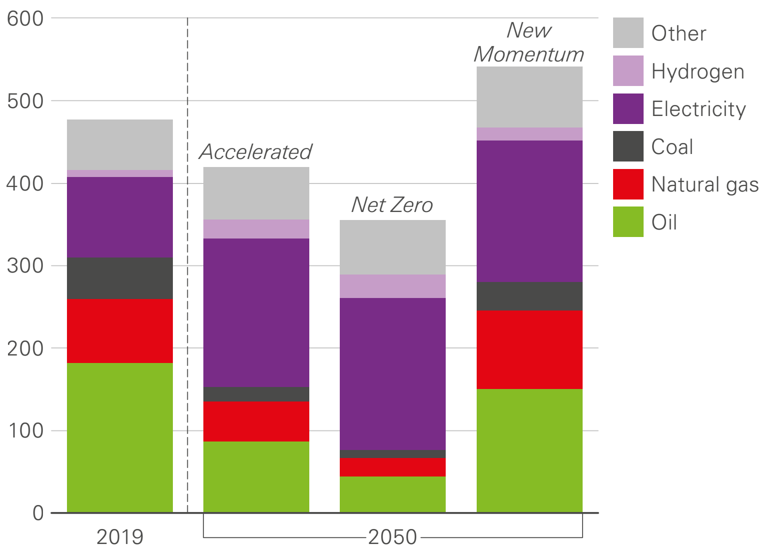
Fossil fuels as a share of final consumption

Share



Fuel composition of final consumption

Energy demand, EJ



Global energy demand measured at the final point of energy use decarbonizes in all three scenarios as the world electrifies and makes increasing use of hydrogen.

- The share of fossil fuels in total final energy consumption (TFC) declines from around 65% in 2019 to 30-50% by 2050 in the three scenarios. Within hydrocarbons, the largest falls occur in the share of coal as the world increasingly shifts towards lower-carbon fuels in industry and buildings, and in the share of oil, driven primarily by falling use of oil in road transport (see pages 46-47).

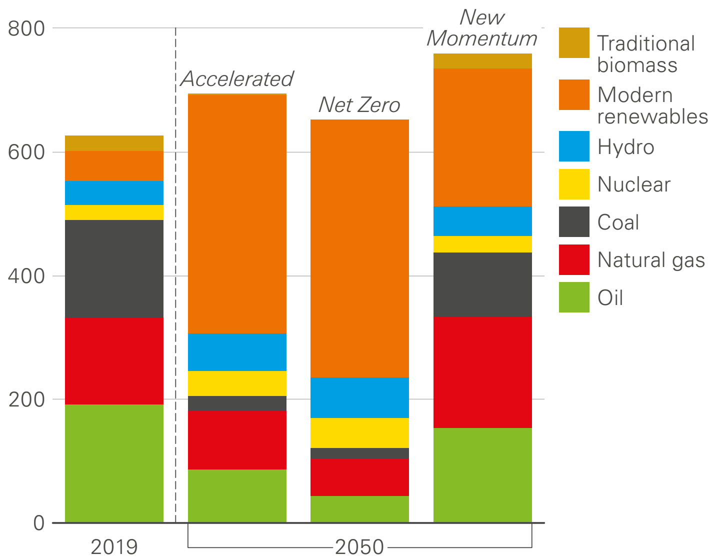
- The role of electricity increases substantially, with electricity consumption increasing by 75-85% over the outlook in all three scenarios. The share of electricity at the final point of use increases from 20% in 2019 to around 30% in *New Momentum* and 45-50% in *Accelerated* and *Net Zero*. The growth in electrification in all three scenarios is met mostly by the rapid growth in wind and solar power (see pages 68-69).

- Low-carbon hydrogen (see pages 80-81) is also increasingly used in *Accelerated* and *Net Zero* helping to decarbonize hard-to-abate industrial processes and transport modes, as well as providing feedstock used in the petrochemical and refining sectors. The share of low-carbon hydrogen in TFC reaches between 6% and 8% by 2050 in *Accelerated* and *Net Zero*, with total hydrogen demand – including that used to produce synthetic fuels and generate power – nearly double this.

The share of fossil fuels in primary energy falls as renewable energy increases rapidly

Primary energy by fuel

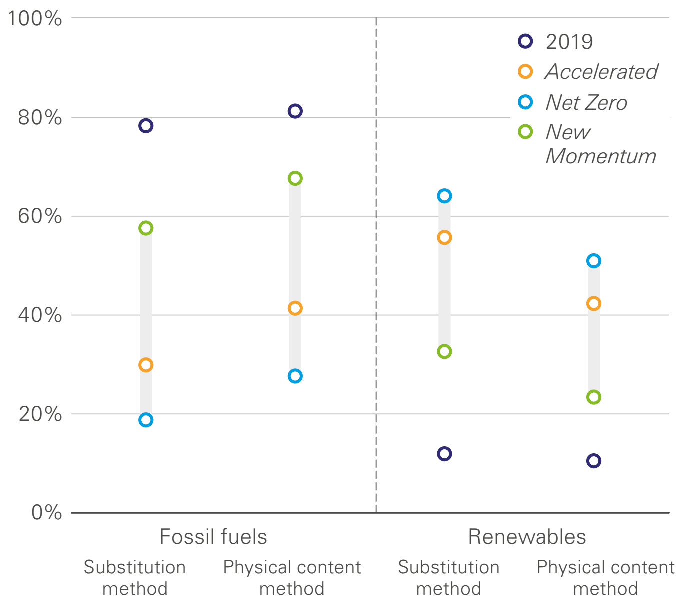
EJ



Modern renewables includes wind, solar, geothermal, biofuels, biomethane and modern biomass

Share of fossil fuels and renewables in primary energy in 2050

Share



A similar trend towards a lower carbon fuel mix is also apparent in primary energy, as the use of fossil fuels declines and renewable energy (wind and solar power, bioenergy and geothermal power) grows rapidly.

- Based on the *substitution method* – which grosses up energy from non-fossil power generation to reflect the equivalent losses associated with converting fossil fuels to electricity (see pages 106-107) – the share of fossil fuels in primary energy falls from close to 80% in 2019 to 30-20% by 2050 in *Accelerated* and *Net Zero*. This fall is driven by the virtual elimination of coal from the global energy system and oil demand falling sharply. Natural gas is more durable, although its share in primary energy also declines in both *Accelerated* and *Net Zero*.

- The declining importance of fossil fuels in global energy is offset by the increasing role played by renewable energy, whose share in primary energy increases from a little over 10% in 2019 to 55-65% by 2050 in *Accelerated* and *Net Zero*.

- These trends towards a lower-carbon fuel mix within primary energy are less pronounced in *New Momentum*. Fossil fuels still account for close to 60% of all primary energy in 2050, with renewables accounting for around a third.

- These broad trends of a declining role for fossil fuels offset by the increasing importance of renewable energy are also apparent if primary energy is calculated using the alternative *physical content* method (see pages 106-107). But since this method does not gross up renewable (and other non-fossil) energy to take account of the conversion losses associated with fossil fuels, the rise in the share of renewables over the outlook is slightly less pronounced, with renewables by 2050 accounting for between 40-50% of primary energy in *Accelerated* and *Net Zero* and around 25% in *New Momentum*.

Oil demand

Oil demand falls over the outlook, driven by declining use in road transportation

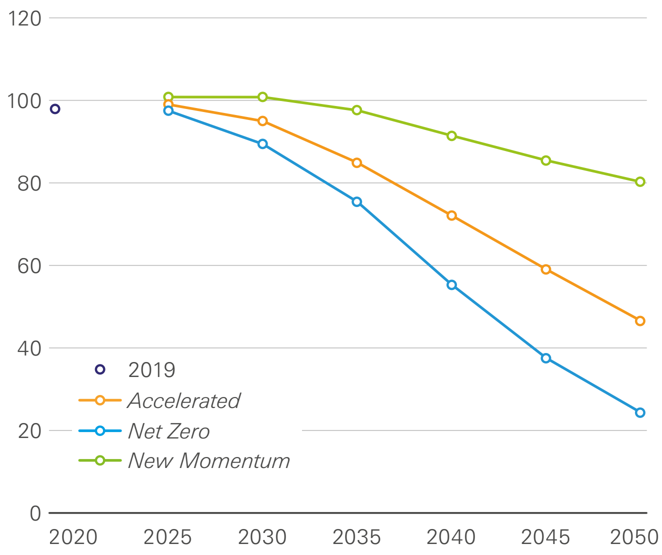
Falling use of oil in transport led by improving efficiency and increasing switch to electrification and other low-carbon fuels

The pattern of oil consumption shifts towards emerging economies and its use as a feedstock

Oil demand falls over the outlook, driven by declining use in road transportation

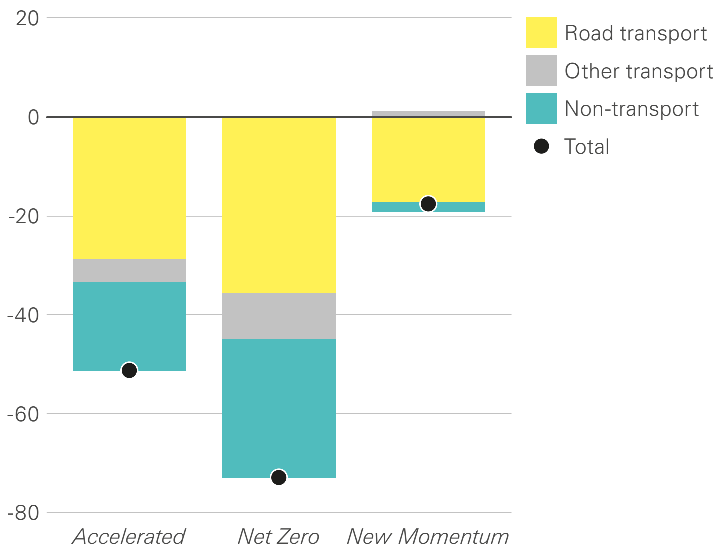
Oil demand

Mb/d



Change in oil demand (2019 - 2050)

Mb/d



Oil demand increases to above its pre-COVID-19 level in all three scenarios, boosted by the stronger-than-expected rebound in economic growth.
Oil consumption peaks in the mid-2020s in *Accelerated* and *Net Zero* and around the turn of the decade in *New Momentum*. Thereafter, oil consumption in *Accelerated* and *Net Zero* falls substantially; the declines in oil demand in *New Momentum* are slower and less marked.

- Oil consumption in *Accelerated* and *Net Zero* falls substantially through the second half of the outlook, reaching around 45Mb/d and 25Mb/d by 2050, respectively. Oil demand in *New Momentum* is stronger, remaining above pre-COVID-19 levels until the mid-2030s before declining gradually, reaching 80Mb/d by 2050.

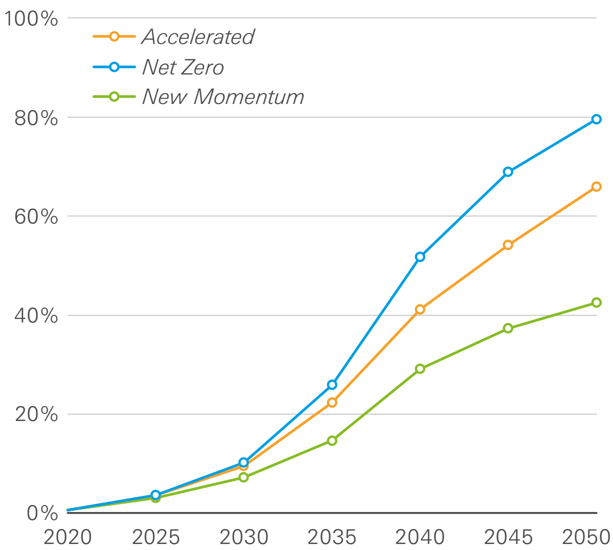
- The declines in oil consumption are dominated by the falling use of oil within road transport as the vehicle fleet becomes more efficient and is increasingly electrified.
The decreasing use of oil in road transport accounts for around half of the fall in global oil consumption in *Accelerated* and *Net Zero* and almost the entire fall in *New Momentum*.

- In all three scenarios, the pace of decline in oil demand accelerates over the course of the outlook as the electrification of road vehicles gathers pace.

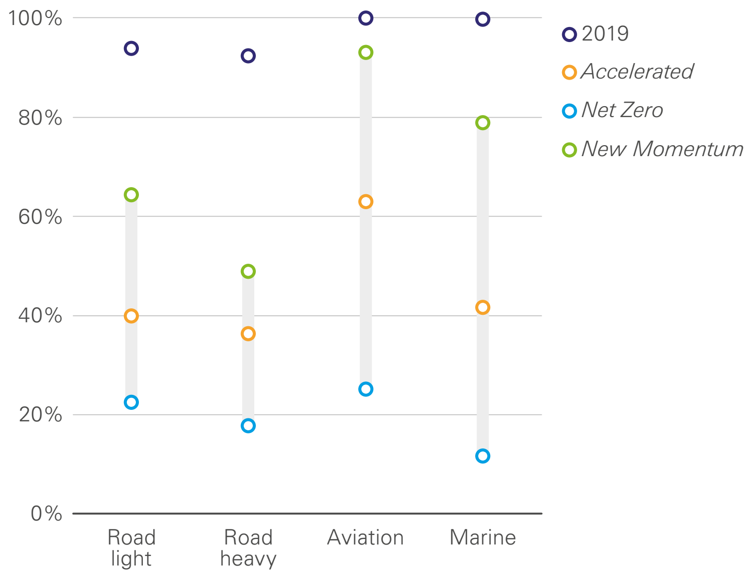
- The falls in oil consumption in *Accelerated* and *Net Zero* over the outlook also reflect a more generalized shift away from oil across other sectors of the economy, including its use in industry and buildings.

Falling use of oil in transport led by improving efficiency and increasing switch to electrification and other low-carbon fuels

Share of car and truck vehicle kilometres electrified



Oil's share of transport sector energy demand in 2050



The role of oil in transport falls in all three scenarios. In road transport, this decline largely reflects a combination of improving vehicle efficiency and increasing electrification. In aviation and marine, the decline in oil is driven by the increasing use of bio- and hydrogen-derived fuels.

- The dominant factor in reducing oil consumption in road transport over the first part of the outlook is the continuing improvement in vehicle efficiency, especially of passenger cars. This reflects the impact of both past improvements in vehicle efficiency as the global car parc turns over and further tightening in vehicle emission standards over the outlook. By 2035, improvements in vehicle efficiency account for 60-70% of the fall in oil used in road transport across the three scenarios.

- The other major factor reducing the use of oil in road transport is the electrification of the vehicle parc. Electric vehicles in *Accelerated* and *Net Zero* account for 65-80% of the vehicle kilometres (VKM) travelled on the road in 2050, compared with less than 1% in 2020. The corresponding share in *New Momentum* by 2050 is around 40%. There is also increasing use of hydrogen in trucking, accounting for around 15-20% of heavy trucking VKMs in *Accelerated* and *Net Zero* by 2050.

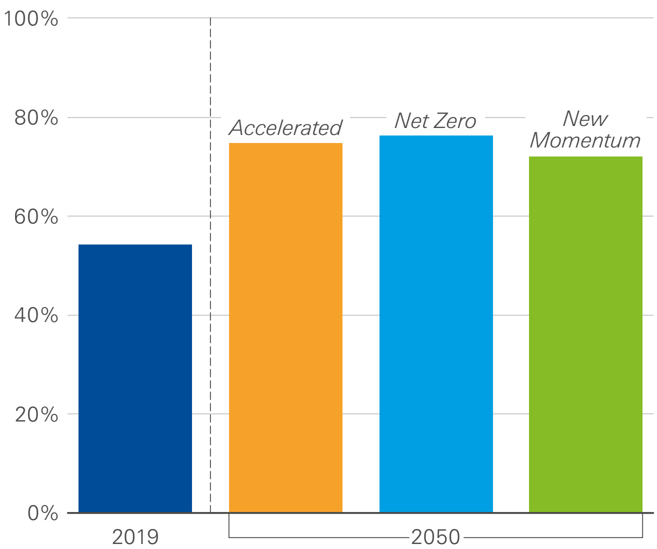
- Oil used in aviation falls by around 25% and 75%, respectively in *Accelerated* and *Net Zero* by 2050, reflecting increasing use of sustainable aviation fuel (SAF) combined with improving fleet efficiency. In *Accelerated*, the majority of the SAF is derived from bioenergy (biojet). In contrast, in *Net Zero*, there is a greater role for H-fuels* (synthetic jet fuel) alongside biojet (see pages 80-81). By 2050, oil accounts for between 65% and 25% of the total energy used in aviation in *Accelerated* and *Net Zero*, compared with over 90% in *New Momentum*.

- In marine, the main alternative to oil is provided by H-fuels (ammonia, methanol and synthetic diesel), which account for between 30% and 55% of total final energy used in marine in *Accelerated* and *Net Zero* by 2050. Bio-derived fuels (biodiesel and renewable diesel) and natural gas also play an increasing role in *Accelerated* and *Net Zero*. In contrast, oil continues to account for close to 80% of the energy used in marine in *New Momentum* in 2050.

*H-fuels are fuels derived from low-carbon hydrogen, including ammonia, methanol, and other synthetic hydrocarbons.

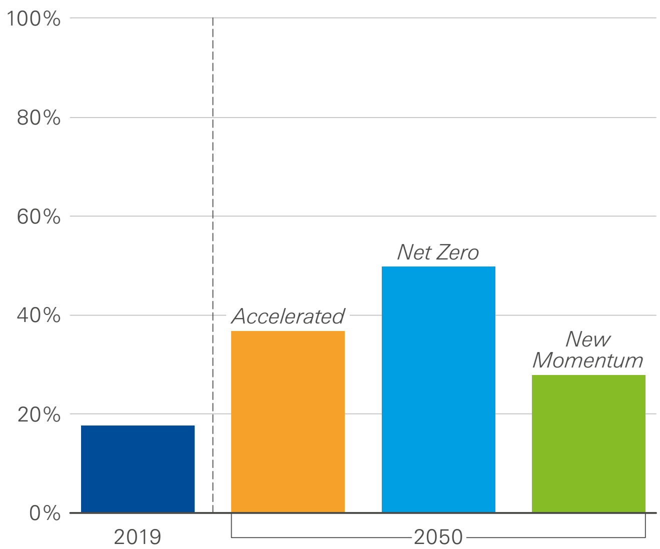
The pattern of oil consumption shifts towards emerging economies and its use as a feedstock

Emerging economies' share of oil demand



Shares are calculated on a volumetric basis

Oil feedstocks as a share of oil demand



The falls in oil demand over the outlook are accompanied by a shift in the centre of gravity of its use, with oil consumption becoming increasingly concentrated within emerging economies, and the use of oil as a feedstock, particularly in the petrochemicals sector, growing in importance.

- Oil demand in emerging economies increases over the first part of the outlook, driven by increasing prosperity and rising living standards, including increasing car ownership and growing access to international travel. Oil consumption in emerging economies remains above its pre-COVID-19 level during the first 10-years or so of the outlook in all three scenarios.
- In contrast, after a brief recovery from its COVID-19-induced dip, oil demand within the developed world resumes its long-term downward trend.
- These contrasting trends mean that, in all three scenarios, emerging economies account for around three-quarters of global oil demand in 2050, compared with a little over half in 2019.
- The use of oil as a feedstock, predominantly for petrochemicals, is one of the most persistent sources of oil demand over the outlook as the consumption of plastics and other petrochemicals derivatives increases, supported by a more than doubling of the world economy.
- However, the pace of growth in the use of oil as a feedstock slows and eventually peaks in all three scenarios as actions, such as the intensity of plastic recycling, increase and the use of some manufactured products, such as single-use plastic packaging, is discouraged. There is also an increasing shift towards bio-based feedstocks as an alternative to oil, especially in *Accelerated* and *Net Zero*.
- Despite these trends, the relative persistence of oil as a feedstock means that its share in overall oil demand increases from less than 20% in 2019 to between 25% and 50% by 2050 across the three scenarios. The level of oil used as a non-combusted feedstock in 2050 ranges from above 20Mb/d in *New Momentum* to close to 10Mb/d in *Net Zero*.

Oil supply

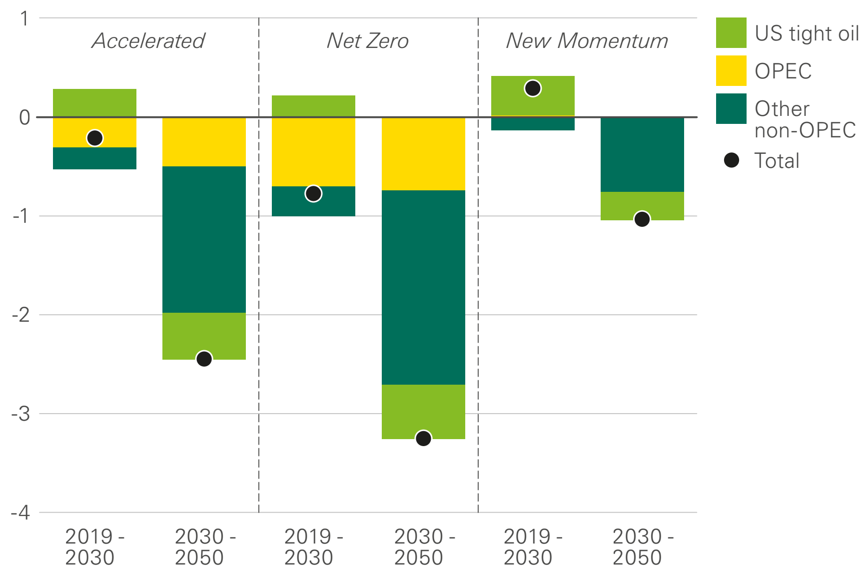
The composition of global oil supplies is dominated by trends in US tight oil and OPEC production

Increasing climate policies incentivize reduction in the carbon intensity of oil

The composition of global oil supplies is dominated by trends in US tight oil and OPEC production

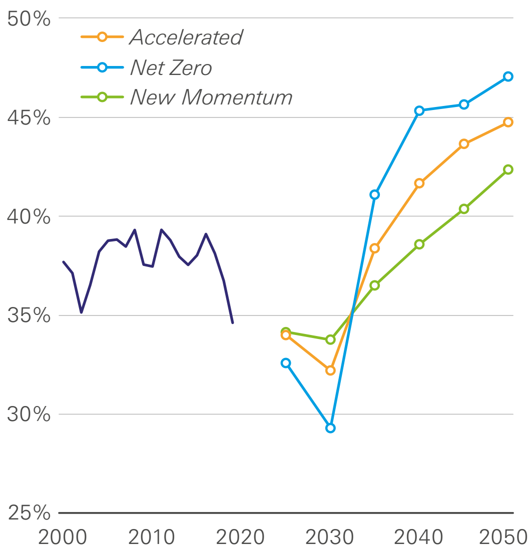
Oil supply growth

Average annual growth, Mb/d



OPEC's market share of global oil supply

Share

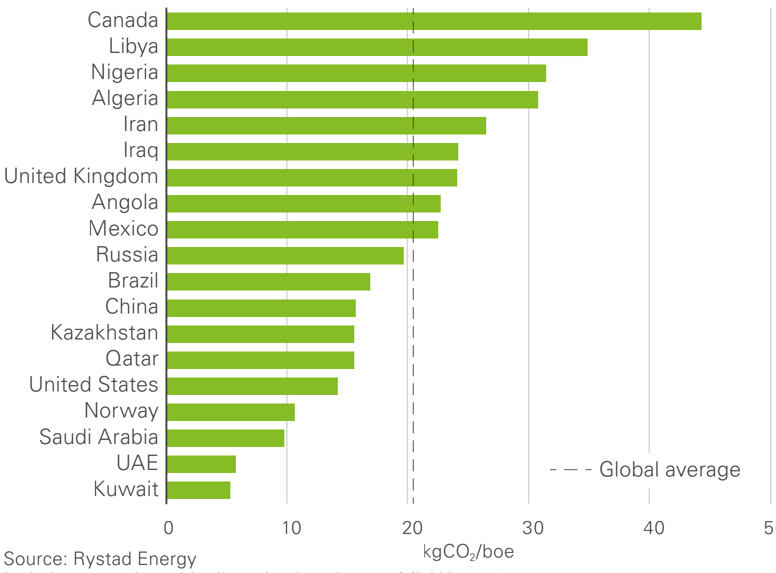


The shifting pattern of global oil supplies over the outlook is driven by contrasting trends in US tight oil and OPEC production. US tight oil recovers over the first part of the outlook, after which it begins to fall and OPEC's market share gradually increases.

- US tight oil – including natural gas liquids (NGLs) – bounces back from the impact of COVID-19, with output peaking above pre-COVID-19 levels at around 15Mb/d during the first decade of the outlook in all three scenarios. Brazilian output also grows over the first 10 years of the outlook. But as US tight formations mature and OPEC adopts a more competitive strategy against a backdrop of accelerating declines in demand, US production (and other sources of non-OPEC output) falls from the late 2020s onwards.
- The short cycle nature of US tight oil production, together with the alignment of the growing use of oil as a feedstock with light crudes and NGLs, helps to mitigate the fall. Even so, US tight oil falls to 5Mb/d or less in *Accelerated* and *Net Zero* by 2050 and to around 10Mb/d in *New Momentum*.
- OPEC's production strategy changes over the course of the outlook. In response to the rebound in US and other non-OPEC supplies, OPEC lowers its production over the first decade or so of the outlook allowing its market share to fall in order to mitigate the downward pressure on prices. The fall in OPEC's market share is most pronounced in *Accelerated* and *Net Zero* given the backdrop of falling oil demand from the mid-2020s.
- As the pace of decline in oil demand increases through the second half of the outlook and the competitiveness of US output wanes, OPEC competes more actively, raising its market share. OPEC's share of global oil production increases to over 40% in *New Momentum* and 45-50% in *Accelerated* and *Net Zero*, which is close to the historical highs reached in the early 1970s.
- The higher cost structure of non-OPEC production means around 70% of the falls in oil production in *Accelerated* and *Net Zero* by 2050 are borne by non-OPEC supplies and all of the fall in *New Momentum*.

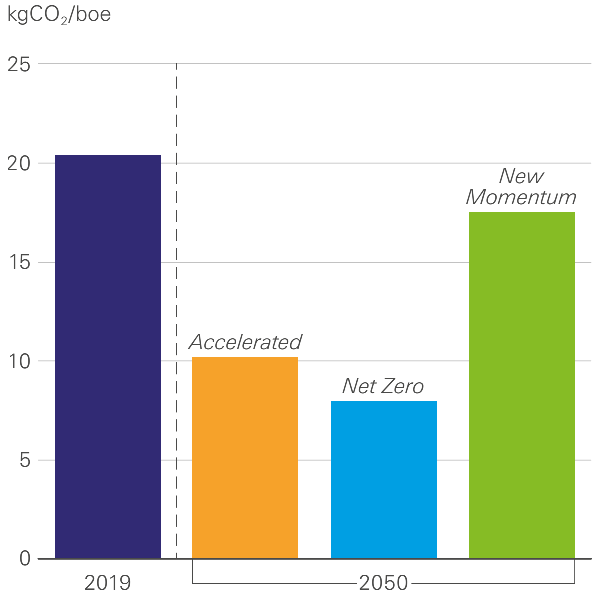
Increasing climate policies incentivize reduction in the carbon intensity of oil

Average carbon intensity of oil production by country, 2019



Source: Rystad Energy
Includes countries with oil production above 1 Mb/d in 2019

Global average carbon intensity of oil production



The variation in carbon intensity of different types of oil production has an increasing bearing on their relative competitiveness as policies on carbon emissions tighten over the outlook. This helps to incentivize a shift towards oil supplies with lower levels of operational carbon intensity as well as encouraging all producers to reduce levels of carbon intensity in their production processes.

- The CO_2 emissions associated with the production of oil account for around 2% of total carbon emissions from energy use in 2019.
- These emissions, measured by the carbon intensity (CI) of oil supplies, vary considerably across (and within) different countries, reflecting differences in the nature and location of the operations.
- The differences in CI affect the relative exposure of different types of production to the tightening in carbon emission policies over the outlook in all three scenarios. These differing levels of exposure act to reduce the average CI of oil supplies by increasing the effective cost of high carbon-intensity oil, improving the competitiveness of supplies with lower levels of CI. In addition, the tightening in climate polices provides an incentive for all oil producers to take steps to reduce the CI of their output, such as by reducing flaring, increasing energy efficiency and electrifying processes.
- As a result, the average CI of global oil production falls by around 15% by 2050 in *New Momentum* and by 50-60% in *Accelerated* and *Net Zero*.
- In a similar manner, tightening policy on carbon emissions also affects the choice of opportunities for investment in new oil production, including between brownfield and greenfield sites, with investment tending towards the most resilient, lowest-carbon resources. For more details on investment needed to support the level of oil and gas production in the three scenarios (see pages 86-87).

Natural gas

Prospects for natural gas demand depend on the speed of the energy transition

Natural gas can help support the transition to a low-carbon energy system

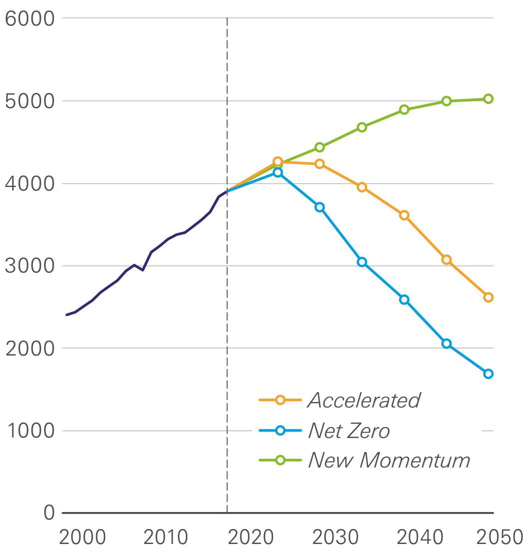
LNG trade increases emerging Asia's access to natural gas, supporting economic growth and a shift to lower-carbon fuels

Natural gas production continues to be dominated by the Middle East, Russia and the US

Prospects for natural gas demand depend on the speed of the energy transition

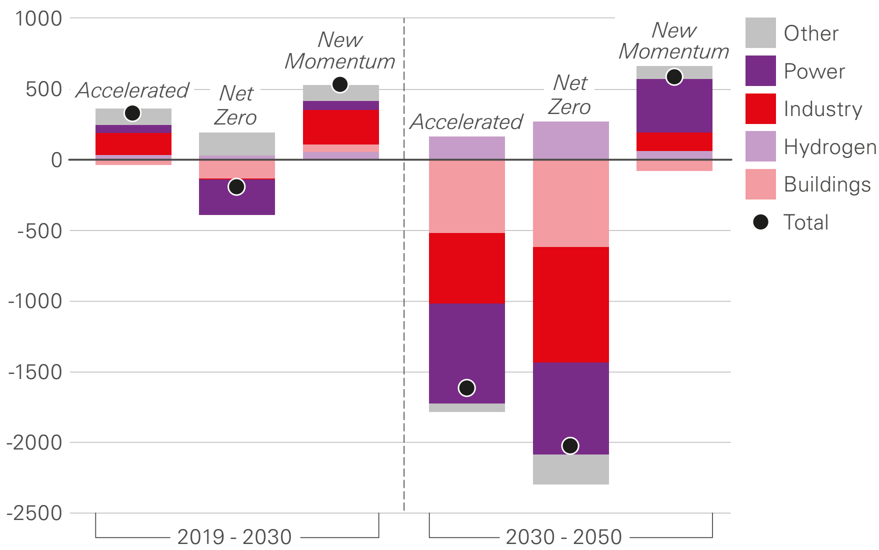
Natural gas demand

Bcm



Natural gas demand by sector

Change, Bcm



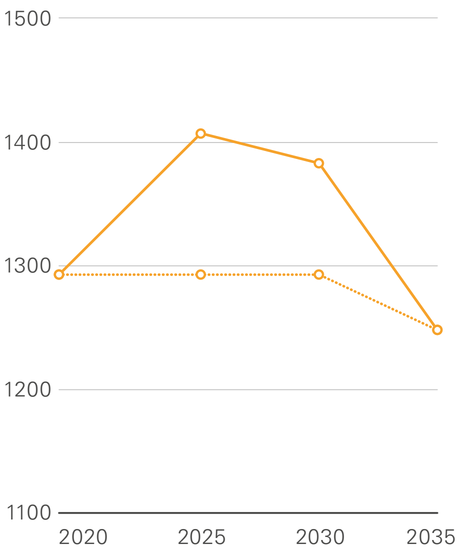
Global gas demand grows initially in all three scenarios, driven by increasing demand in emerging economies. But this growth is subsequently reversed in *Accelerated* and *Net Zero*, with global gas consumption declining by around 35% and 60% by 2050 respectively. In contrast, gas demand in *New Momentum* continues to grow over the entire outlook, expanding by almost 30% of its 2019 level.

- Over the first 10 years or so of the outlook, gas demand increases in both *New Momentum* and *Accelerated*, driven by strong demand in China – underpinned by policies encouraging continued coal-to-gas switching – and in India and other emerging Asia.
- In contrast, demand growth in *Net Zero* is shorter lived, reaching a peak in the mid-2020s before starting to decline. Natural gas demand within emerging Asia grows robustly out to 2030, but this is outweighed by increasing falls in the developed world led by the US and EU.
- From the early 2030s onwards, natural gas demand declines in both *Accelerated* and *Net Zero* as the increasing switch to low-carbon energy sources leads to declining use in the world's major demand centres. In contrast, gas demand in *New Momentum* continues to grow in the 2030s and 2040s, driven by increasing demand in emerging Asia (outside of China) and Africa.
- The growth in global gas demand in the first part of the outlook in *New Momentum* and *Accelerated* is driven by increasing use of natural gas in industry in emerging economies, especially in Asia, as these economies continue to industrialize.
- The growing declines in natural gas demand seen after 2030 in *Accelerated* and *Net Zero* reflect the falling use of gas in industry and buildings, particularly in developed economies, and the increasing penetration of renewables in global power markets. This decline in gas consumption is partially offset by the growing use of natural gas to produce blue hydrogen (see pages 82-83).
- In contrast, global gas consumption continues to grow in *New Momentum* supported in part by natural gas broadly maintaining its share in global power generation as overall power production increases robustly.

Natural gas can help support the transition to a low-carbon energy system India case study

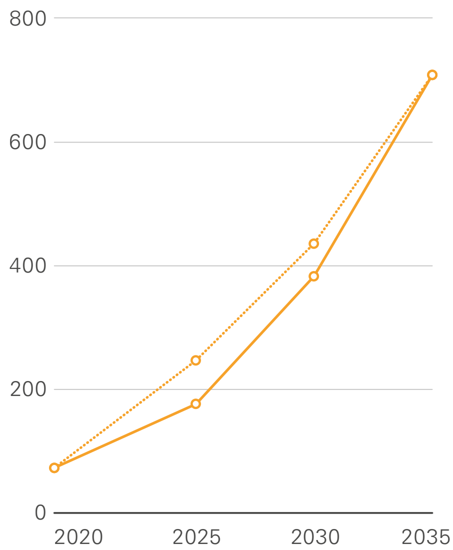
Power generation: coal

Generation, TWh



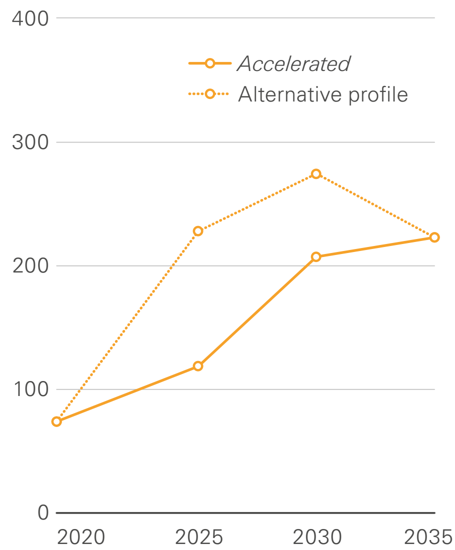
Installed wind and solar capacity

Capacity, GW



Power generation: natural gas

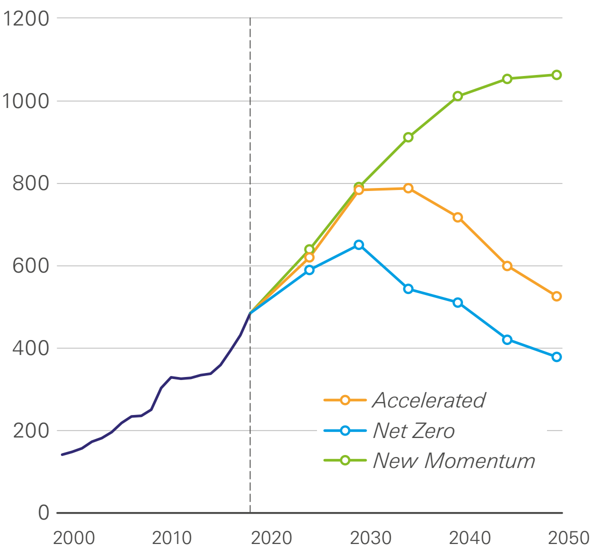
Generation, TWh

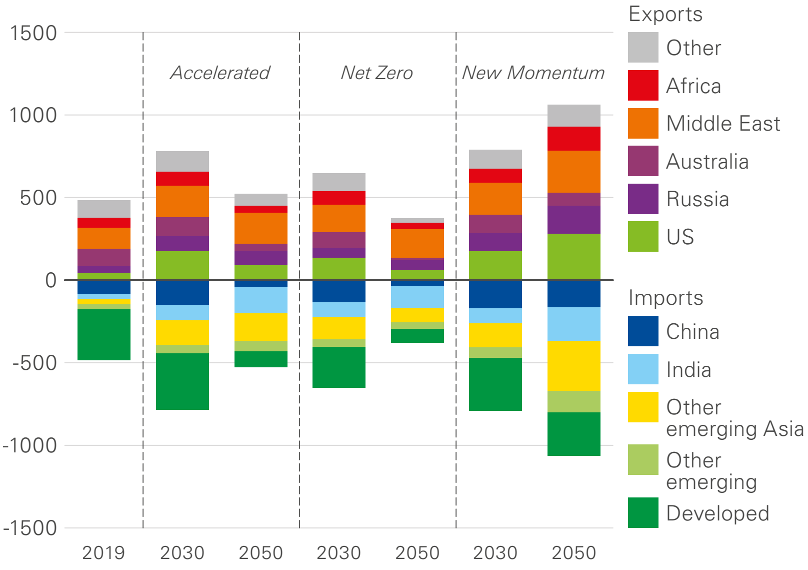


Natural gas can potentially play two important roles as the world transitions to a low-carbon energy system: increasing the speed at which fast-growing emerging economies reduce their dependency on coal, and providing a source of low-carbon energy when combined with carbon capture, use and storage (CCUS).

- The potential role of gas to help quicken the pace at which emerging economies reduce their use of coal can be illustrated by the outlook for the Indian power sector in *Accelerated*.
- In *Accelerated*, Indian wind and solar power expands rapidly in the 2020s, such that installed capacity is around 400GW by 2030 and wind and solar power generation grows almost 6-fold compared to 2019. Over the same period, gas-powered generation roughly triples.
- However, these rapid increases in renewable and natural gas power generation are not sufficient to match the substantial growth in Indian electricity demand. As a result, coal-fired generation, which maintains its cost competitiveness relative to other fossil fuels, increases until the late 2020s and remains above its 2019 level until the mid-2030s.
- In order to avoid any increase in coal-fired generation, one option would be for wind and solar power to increase even more rapidly. But that would require wind and solar capacity to increase by nearly twice the rapid speed already assumed in *Accelerated*, reaching 250GW by the mid-2020s.
- An alternative option would be for gas-powered generation to increase temporarily from the levels assumed in *Accelerated*, such that in the late 2020s it is around three times its level in 2019. Given the current under-utilization of existing gas-fired power capacity in India this would be possible with little or no increase in gas generation capacity.
- Natural gas can also support the transition to a low-carbon energy system by providing a source of low-carbon energy when combined with CCUS. By 2050, around 45% of the natural gas consumed in *Accelerated* and 80% in *Net Zero* is abated using CCUS. Around half of this gas is used directly in industry and power. The remainder is used to produce blue hydrogen, which is subsequently used as a low-carbon energy carrier or feedstock. (See pages 90-91 for more details of the role of CCUS in the energy transition and pages 82-83 for blue hydrogen).

LNG trade increases emerging Asia's access to natural gas, supporting economic growth and a shift to lower-carbon fuels

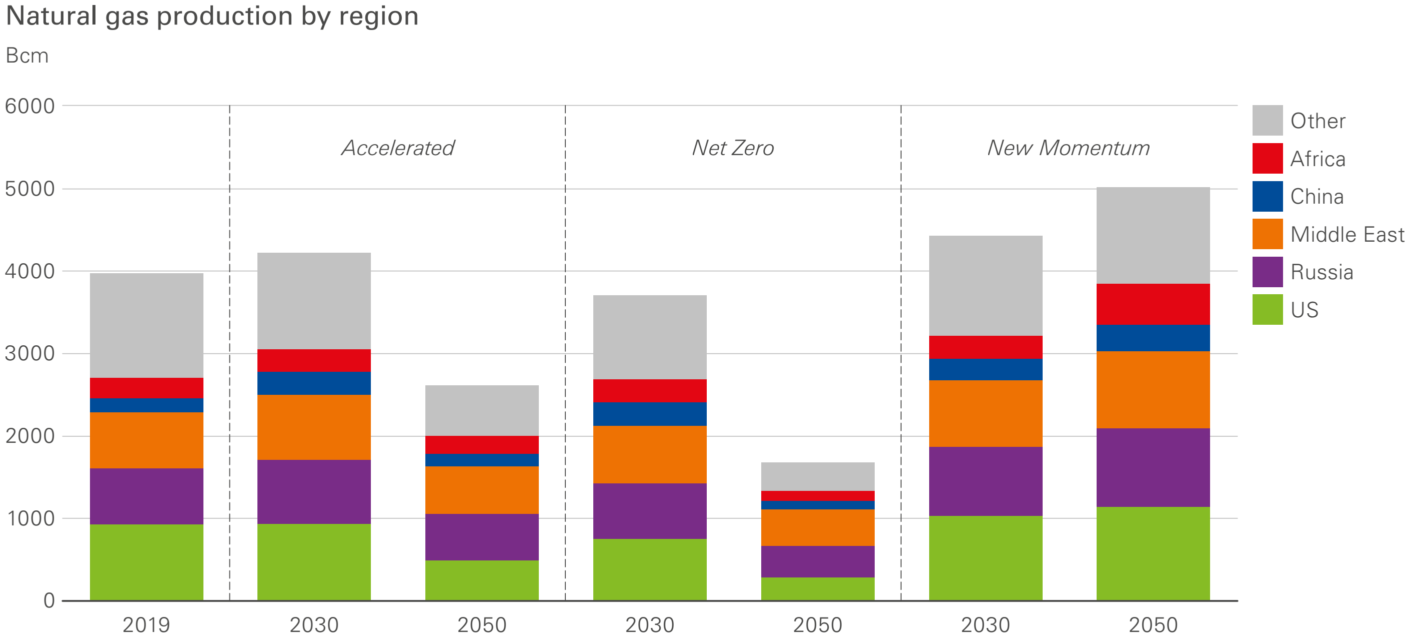




Growing trade in liquefied natural gas (LNG) plays a central role in increasing emerging markets' access to natural gas, helping to support economic growth and a shift to lower-carbon fuels.

- LNG trade grows strongly over the first 10 years of the outlook, increasing by around two-thirds in *New Momentum* and *Accelerated*, and a third in *Net Zero*.
- The vast majority of this growth is driven by increasing gas demand in emerging Asia (China, India and other emerging Asia) as they switch away from coal and, outside of China, continue to industrialize. LNG imports are the main incremental source of this increased use of gas, accounting for 70-75% of the increased gas consumption in emerging Asia out to 2030 across the three scenarios.
- This growth in LNG trade is reversed over the second half of the outlook in *Accelerated* and *Net Zero*, as the use of natural gas – and hence need for LNG imports – declines across much of the world's major LNG demand centres. The level of LNG trade by 2050 is only 10% higher than 2019 levels in *Accelerated* and around 20% lower in *Net Zero*.
- In contrast, LNG imports continue to expand in *New Momentum*, rising to over 1,000 Bcm by the end of the outlook, supported by increasing imports into India and other emerging Asia, and continuing strong imports into Europe.
- The growth in LNG exports over the first part of the outlook is driven by the US, which accounts for over 40% of the increase in LNG exports to 2030 in all three scenarios. Growth in LNG exports is also supported by sizeable increases in supply from the Middle East, Russia and Africa.
- The subsequent fall in LNG trade in the second half of the outlook in *Accelerated* and *Net Zero* is also borne disproportionately by the US, reflecting its higher transport costs to the remaining centres of LNG demand in Asia relative to the Middle East and Eastern Africa.
- In contrast, LNG exports from the US and the Middle East continue to grow in the second half of the outlook in *New Momentum*, reinforcing their role as the main global centres of LNG exports.

Natural gas production continues to be dominated by the Middle East, Russia and the US



The production of natural gas is driven initially by increasing exports of liquified natural gas to meet growing demand in emerging economies. Global gas production falls in the second half of the outlook in *Accelerated* and *Net Zero*, mirroring the declines in domestic demand in the major gas consuming centres.

- Over the first 10 years or so of the outlook, increases in global gas production are led by the Middle East, Russia, and the US (in *New Momentum*), with much of this increased gas production being exported in the form of liquefied natural gas (LNG) (see pages 62 to 63). The growth in LNG is partially offset by falls in pipeline exports as the pattern of demand shifts to regions with less access to gas pipelines.

- The production of natural gas falls in the second half of the outlook in *Accelerated* and *Net Zero* as domestic demand in the world's major gas consuming centres declines, with the brunt of the reductions in gas output concentrated in the US, the Middle East and Russia. By 2050, global gas production is around 35% and 60% lower than its 2019 level in *Accelerated* and *Net Zero*, respectively, with the US, the Middle East and Russia together accounting for around half of those declines.

- In contrast, global gas production in *New Momentum* continues to increase in the 2030s and 2040s, led by significant increases in African supplies feeding the rapidly expanding domestic market for natural gas.

- The base declines in gas production mean that, even in *Net Zero*, significant amounts of new production are required. In *Net Zero*, around 1.5Tcm of new gas supplies are required by 2035; this increases to 2.5-3.0Tcm in *Accelerated* and *New Momentum*. For more details of the implied levels of investment in oil and natural gas (see pages 86-87).

Renewable energy

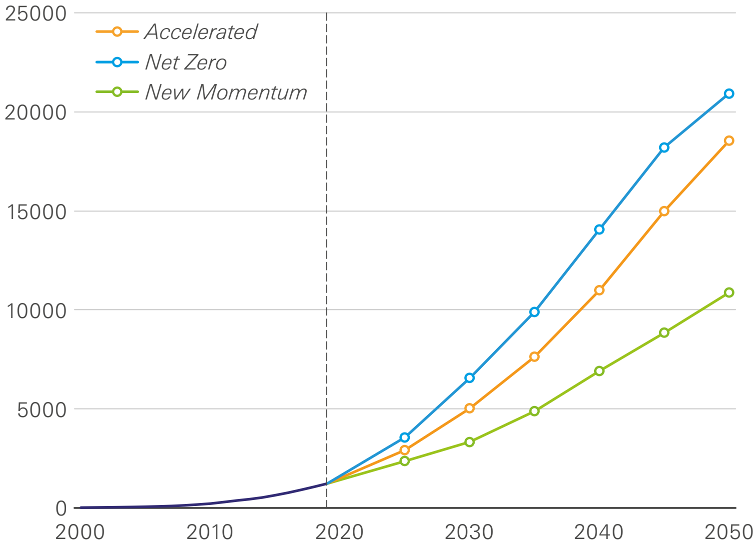
Wind and solar power grow rapidly

Modern bioenergy increases sharply, supporting the transition to a low-carbon energy system

Wind and solar power grow rapidly

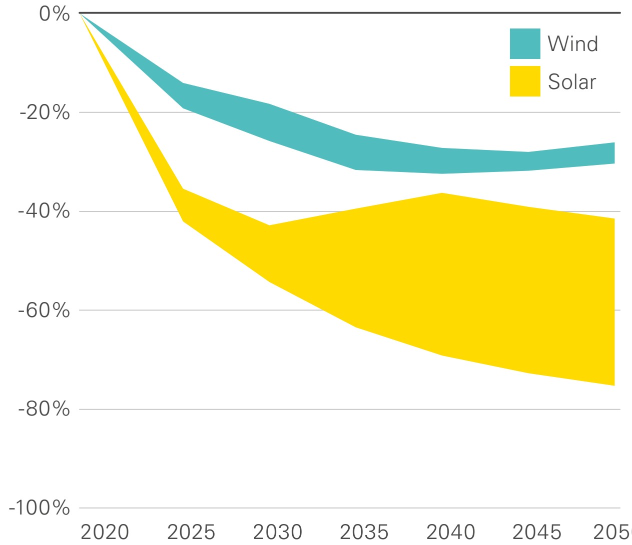
Installed wind and solar capacity

GW



Cost of wind and solar

Change relative to 2019



Cost of wind and solar refers to their global average levelized cost of electricity, including their integration costs

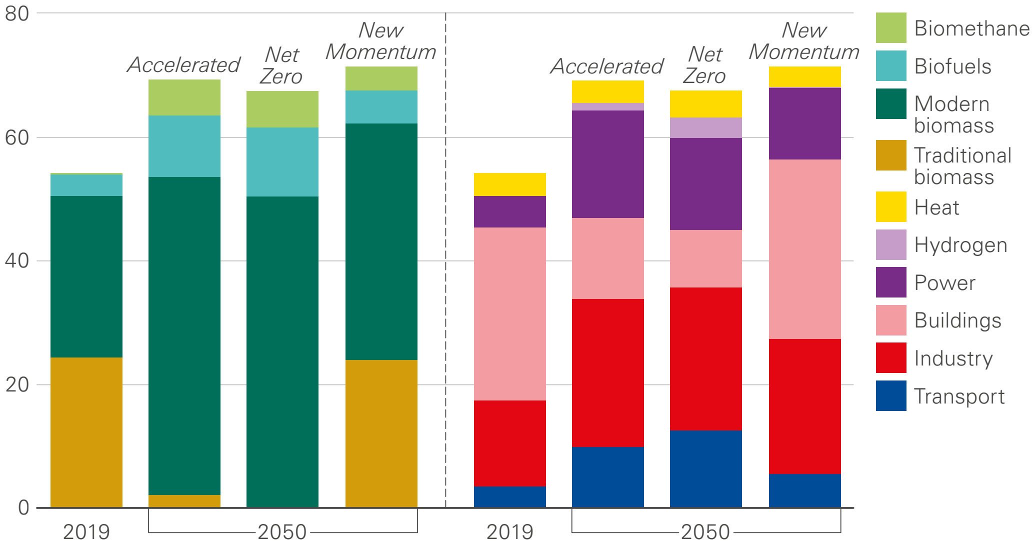
Wind and solar power expand rapidly in all three scenarios. Combined installed wind and solar capacity by 2050 increases more than 15-fold from 2019 levels in *Accelerated* and *Net Zero* and by nine-fold in *New Momentum*.

- The majority of this capacity is used to provide electricity at the final point of use, although by 2050 in *Accelerated* and *Net Zero* around 20-30% is used to produce green hydrogen (see pages 82-83).
- The rapid expansion in wind and solar power is underpinned by continuing falls in their costs, especially over the first 10 years or so of the outlook, as technology and production costs decline with increasing deployment, supported by increasing module efficiency and project scales for solar, and by higher load factors and lower operating costs for wind. The levelized cost of electricity (LCOE) generated from wind and solar power, including integration costs, falls by around 20-25% and 40-55%, respectively, by 2030 across the three scenarios.
- The pace of cost reductions slows and eventually plateaus in the final two decades of the outlook as falling costs of generation are offset by the growing expense of balancing power systems with increasing shares of variable power sources.
- The expansion in installed capacity in the three scenarios requires a significant acceleration of the pace at which new capacity is financed and built. The average rate of increase in installed capacity in *Accelerated* and *Net Zero* is 600-750GW per year in the 2030s and 700-750GW in the 2040s – two or three times faster than the highest rate of increase seen in the past. This rapid acceleration in the installation of wind and solar capacity is dependent on a range of enabling factors scaling at a similar rate, including transmission and distribution capacity, availability of key materials, planning and permitting, and social acceptability.
- The pace of increase in wind and solar capacity slows in the final 10 years or so of the outlook, especially in *Net Zero*, as the power sector nears full decarbonization and the cost of including increasing shares of wind and solar grows.
- Emerging economies account for over three quarters of the increased deployment of wind and solar capacity in *Accelerated* and *Net Zero* by 2050, with China contributing around a quarter of the increase.

Modern bioenergy increases sharply, supporting the transition to a low-carbon energy system

Bioenergy supply and demand

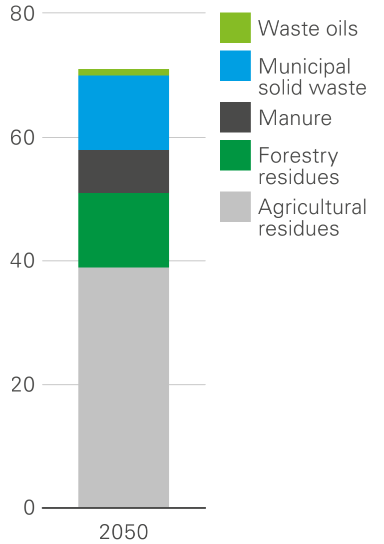
Primary energy, EJ



Modern biomass includes biogas (but excludes biomethane)
Industry includes feedstocks

Sources of modern bioenergy

Primary energy, EJ



The use of modern bioenergy – traded solid biomass, biofuels and biomass-derived gases – grows significantly in all three scenarios as it helps to decarbonize hard-to-abate sectors.

- The growth in modern bioenergy is most pronounced in *Accelerated* and *Net Zero*, increasing to around 70EJ by 2050, more than double its 2019 level. Nearly all this growth in demand stems from emerging economies, aided in part by a virtual eradication of the use of traditional biomass. The consumption of modern bioenergy in *New Momentum* increases to around 50EJ by 2050, with little reduction in the use of traditional biomass.

- The amount of bioenergy used in all three scenarios is judged to be achievable without any increase from the current levels of land devoted exclusively to bioenergy, with the vast majority sourced regionally through residues (from agriculture and forestry, manure and wastes) which are accessible without detrimental effect to their ecosystems.

- The largest source of modern bioenergy is solid biomass, which accounts for around three-quarters of total bioenergy demand in *Accelerated* and *Net Zero* by 2050 and around half in *New Momentum*.

- The increasing use of modern solid biomass is driven in part by its growing role in the power sector, particularly in Asia, as well as in hard-to-abate industrial processes, such as cement, and in buildings.

- The use of biofuels increases to roughly 10EJ by 2050 in *Accelerated* and *Net Zero*, driven by their use in aviation. By 2050, the use of bio-derived SAF (sustainable aviation fuel) accounts for between 55-65% of total biofuels demand in *Accelerated* and *Net Zero*. These scenarios also see increasing use of biofuels in marine and as an alternative to oil-based feedstocks in industry.

- Biomethane (also known as renewable natural gas) grows rapidly from around 0.2EJ in 2019 to around 5EJ in *Accelerated* and *Net Zero* by 2050. The growth in biomethane is broadly based across all sectors of the economy: transport, industry, and buildings.

- By 2050, 4-12EJ of bioenergy in *Accelerated* and *Net Zero* is combined with carbon capture and storage (BECCS) providing a source of negative emissions. Around half of the available BECCS is used in the power sector, with the remainder used in industry, and to produce hydrogen and heat.

Electricity and power systems

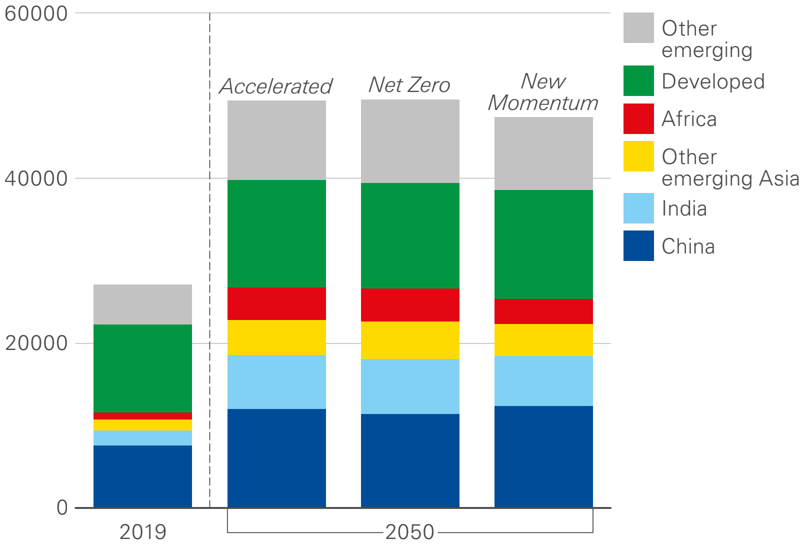
Electricity demand grows strongly as the world increasingly electrifies

Growth in power generation is dominated by wind and solar
as the global power system decarbonizes

Electricity demand grows strongly as the world increasingly electrifies

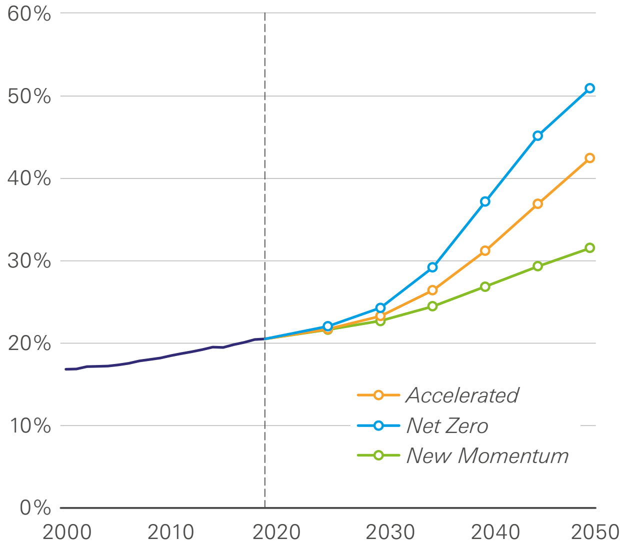
Final consumption of electricity

TWh



Electricity as a share of total final consumption

Share



Electricity demand increases strongly in all three scenarios driven by growing prosperity in emerging economies and increasing electrification of the global energy system. Final electricity demand increases over 80% by 2050 in *Accelerated* and *Net Zero* and by 75% in *New Momentum*.

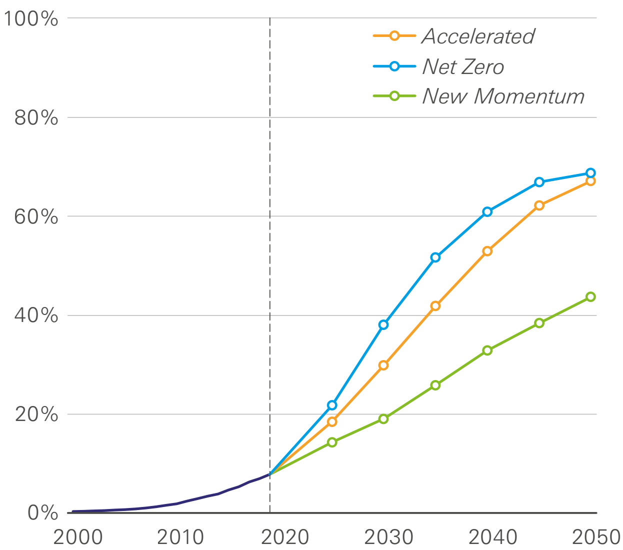
- The vast majority of the growth in electricity consumption in all three scenarios is accounted for by emerging economies, led by emerging Asia (China, India, Other Asia) and Africa, as increasing prosperity and living standards enable a rapid expansion in the use of electricity. This strong growth means that, in all three scenarios, emerging economies account for around three-quarters of global electricity demand by 2050, up from 60% in 2019.

- The trend towards the increasing electrification of energy-using activities and processes is most marked in *Accelerated* and *Net Zero*, with the share of electricity in total final consumption (TFC) increasing from 20% in 2019 to close to 45% in *Accelerated* and over 50% in *Net Zero* by 2050. Despite the slower pace of decarbonization, the share of electricity in TFC in *New Momentum* still increases to around 30% by the end of the outlook.

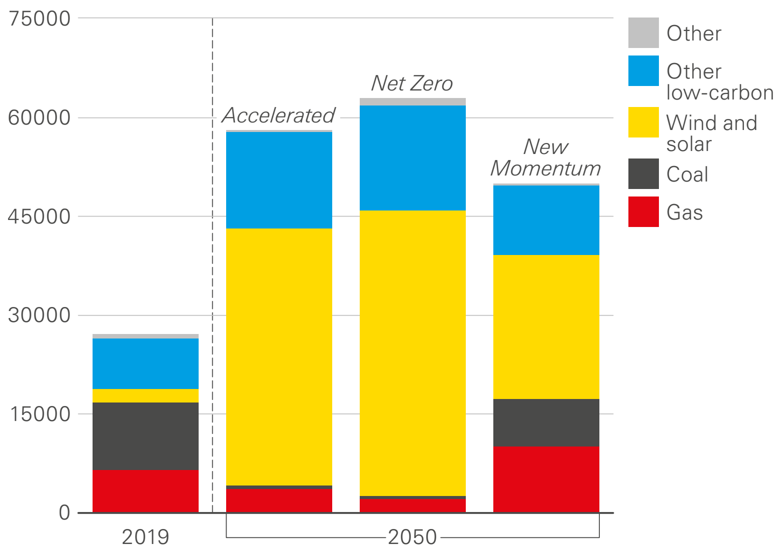
- The increase in electricity demand is broadly-based across all three end-use sectors: industry, transport and buildings. The growth in electricity use in the transport sector is particularly pronounced in *Accelerated* and *Net Zero* as road transportation is increasingly electrified.

Growth in power generation is dominated by wind and solar as the global power system decarbonizes

Wind and solar as a share of total power generation



Electricity generation by fuel



Gas includes natural gas and biomethane
Other low-carbon includes biomass, nuclear, hydro and geothermal

World power systems are increasingly dominated by wind and solar power, which more than account for the entire growth of global power generation in *Accelerated* and *Net Zero*, and around 85% of the increase in *New Momentum*.

- The expansion of wind and solar generation is led by wind power, which accounts for close to 40% of total power generation by 2050 in *Accelerated* and *Net Zero*, with the share of solar power around 30%. Within wind power, offshore wind increases rapidly from a low base, accounting for around 20% of the increase in wind generation by 2050.
- By 2050, wind and solar power account for around 70% of global power generation – and closer to 80% in the most advantaged regions – in *Accelerated* and *Net Zero*. These high wind and solar penetration levels are aided by the falling cost of integrating variable power sources, including from the use of batteries and increasing integration with hydrogen as a source of flexible demand (use of electrolysers) and supply (hydrogen turbines).
- In addition to powering end-use activities, around 15-20% of global electricity generation by 2050 in *Accelerated* and *Net Zero* is used to produce green hydrogen (see pages 82-83).
- The main fuel to lose ground to wind and solar is coal, which is virtually eliminated from global power generation by 2050 in *Accelerated* and *Net Zero*.
- The role of natural gas in global power generation is relatively stable over the first part of the outlook in *Accelerated* and *New Momentum*, supported by its increasing role in the emerging world (see pages 60-61). But the use of natural gas declines sharply in the second half of the outlook in *Accelerated* and *Net Zero* as the expansion of wind and solar power gathers pace.
- Other sources of low-carbon power generation (nuclear, hydro, bioenergy and geothermal) continue to play a significant role, especially in *Accelerated* and *Net Zero*, where they account for around 25% of power generation in 2050. Nuclear power generation increases by 80% by 2050 in *Accelerated* and more than doubles in *Net Zero*, accounting for around 10% of power generation.
- The shift to renewable energy, combined with increasing use of CCUS (see pages 90-91), means CO_2e emissions from power generation in *Accelerated* are almost entirely eliminated by 2050 and are negative in *Net Zero*.

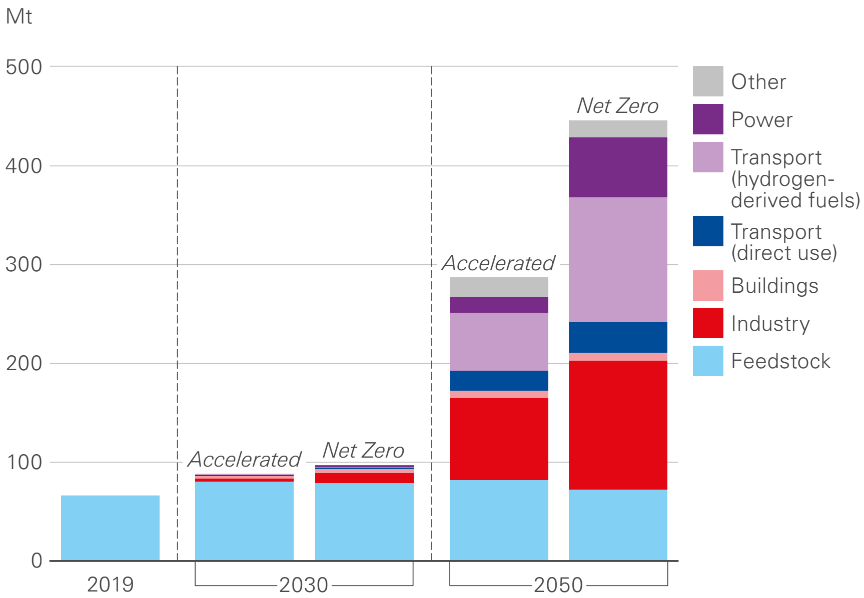
Hydrogen

Demand for low-carbon hydrogen grows as the world transitions to a low-carbon energy system

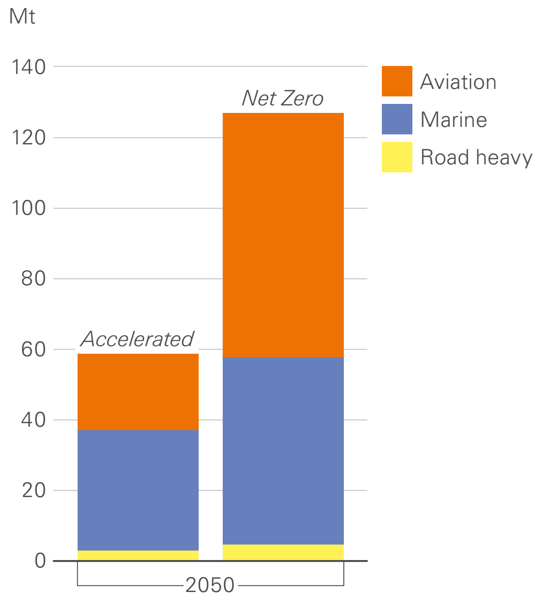
Low-carbon hydrogen is dominated by green and blue hydrogen

Demand for low-carbon hydrogen grows as the world transitions to a low-carbon energy system

Hydrogen demand by sector



Demand for hydrogen-based fuels

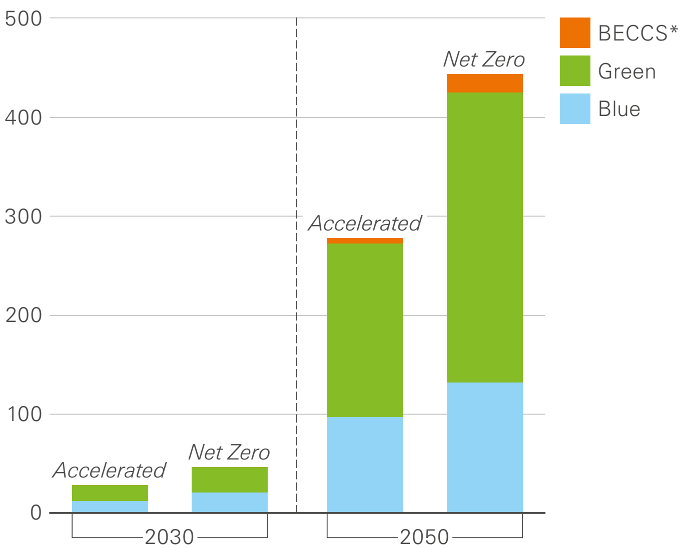


The use of hydrogen grows significantly in *Accelerated* and *Net Zero* as the world transitions to a low-carbon energy system, increasing more than four-fold in *Accelerated* and seven-fold in *Net Zero* by 2050.

- The growth of hydrogen over the first ten years of *Accelerated* and *Net Zero* is relatively modest, driven by the increasing use of low-carbon hydrogen as a feedstock, albeit constrained by the long lead times for low-carbon hydrogen projects to come online at scale.
- The pace of growth accelerates sharply in the 2030s and 2040s as falling costs of production and tightening carbon emission polices allow low-carbon hydrogen to compete against incumbent fuels. In particular, the expanding use of low-carbon hydrogen complements the growing electrification of the energy system in *Accelerated* and *Net Zero*, providing a source of low-carbon energy for activities and processes which are difficult to electrify, especially in industry and transport, as well as being a source of flexibility for power system stability.
- The use of hydrogen in industry is concentrated in parts of heavy industry, such as iron and steel, chemicals, and cement, which rely on high-temperature processes. By 2050, hydrogen accounts for 5-10 % of total final energy used in industry in *Accelerated* and *Net Zero*.
- The greatest use of hydrogen within the transport sector is to help decarbonize long-distance transportation, especially within marine (in the form of ammonia, methanol and synthetic diesel) and aviation (in the form of synthetic jet fuel). The production of these H-fuels account for around 75-80% of the hydrogen used within the transport sector by 2050 in *Accelerated* and *Net Zero*. The remainder is used directly in heavy-duty road transport and, to a much lesser extent, rail. By 2050, H-fuels and hydrogen account for around 5-15% of total final energy used by the transport sector in the two scenarios.
- The relatively high costs of transporting hydrogen means that most of the hydrogen is produced and consumed within regions, although some inter-regional trade develops over the outlook in *Accelerated* and *Net Zero*, with exports from regions with advantaged production, including the Middle East, Russia, South & Central America and Africa, flowing to developed Asia and the EU.

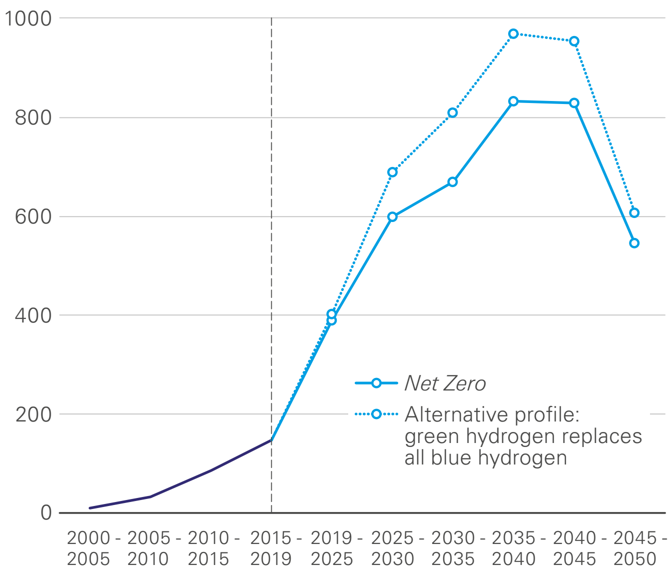
Low-carbon hydrogen is dominated by green and blue hydrogen

Low-carbon hydrogen supply



* BECCS hydrogen from biomass gasification with carbon capture and storage

Average annual increase in wind and solar capacity



Low-carbon hydrogen grows in importance over the outlook in *Accelerated* and *Net Zero*, accounting for virtually all hydrogen production by 2050. Low-carbon hydrogen is dominated by a combination of green hydrogen, made via electrolysis using renewable power, and blue hydrogen, made from natural gas (or coal) with CO_2 capture and stored.

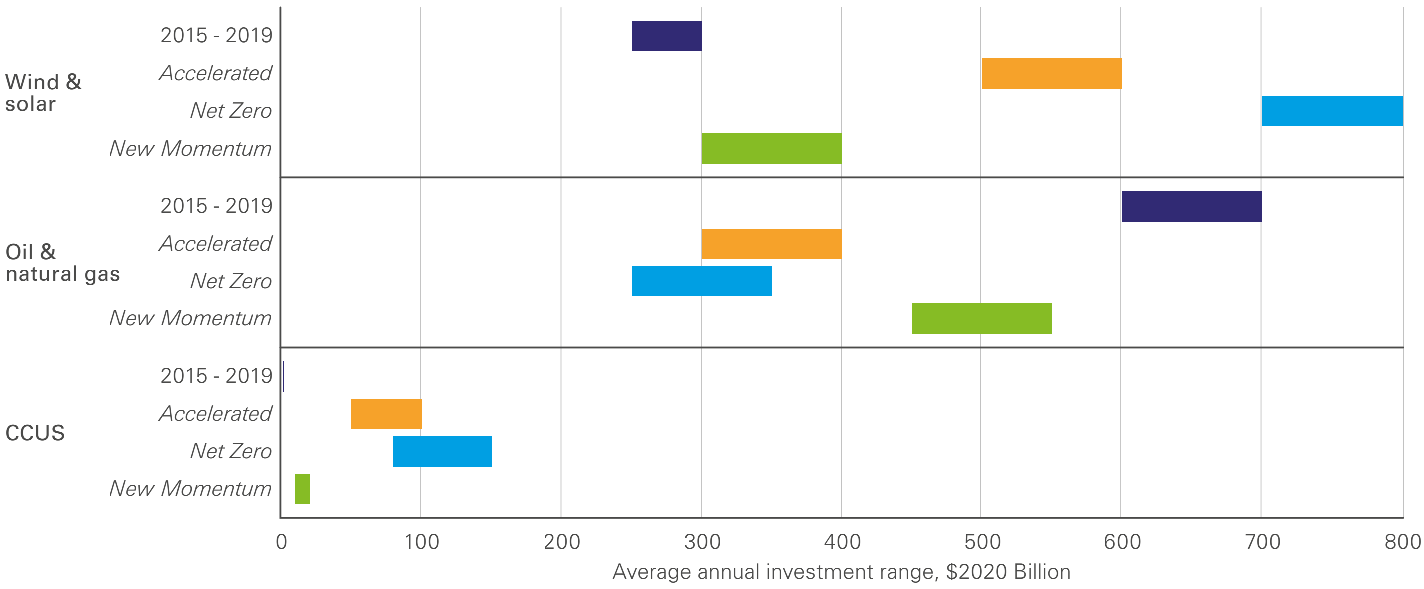
- The growth of low-carbon hydrogen crowds out so-called grey and brown hydrogen, which is produced from natural gas and coal without the use of carbon capture and storage.
- At the beginning of the outlook, the cost of producing blue hydrogen is lower than for green hydrogen in most parts of the world. But this cost advantage is gradually eroded over the outlook as improvements in technology and manufacturing efficiency reduce the price of both wind and solar power and electrolysers.
- In contrast, the more limited scope for gains in technology and manufacturing efficiency in hydrogen production from natural gas (and coal) with CO_2 capture means the cost of blue hydrogen remains relatively flat over the outlook.
- The strong policy support provided to green hydrogen over the initial part of the outlook, combined with the sharp falls in its relative costs, means green hydrogen accounts for an increasing share of low-carbon hydrogen production in *Accelerated* and *Net Zero*. In 2030, green hydrogen accounts for around 55% of low-carbon hydrogen in the two scenarios, with that share increasing to around 65% by 2050. Most of the remaining low-carbon hydrogen is provided by blue hydrogen, although there is also a small amount of hydrogen produced from bioenergy combined with CCS (BECCS) by 2050 in both scenarios.
- In addition to being cost competitive in many parts of the world, the production of blue hydrogen in *Accelerated* and *Net Zero* helps enable the expansion of low-carbon hydrogen without relying solely on renewable power. For example, to substitute green for blue hydrogen in *Net Zero* would require wind and solar capacity to increase by close to 850GW per annum on average in the 2030s and 2040s, compared with a little over 700GW in *Net Zero* and a historical high of around 250GW.

Investment

The energy transition requires significant levels of investment

The energy transition requires significant levels of investment

Average annual investment, history and 2020-2050



The energy pathways envisaged by the three scenarios require substantial levels of investment across a wide range of energy value chains. The implied levels of investment in wind and solar power capacity accelerate markedly from recent levels. Despite declining levels of demand, continuing investment in upstream oil and gas is also required.

- Estimates of the investment paths implied by different scenarios are uncertain since they depend on a number of factors affecting the cost of energy investments over the next 30 years, including the cost of key materials, technology trends and the cost and availability of capital. The assumptions underlying the implied investment requirements are discussed (see pages 102-103). Investments are in real $2020 prices.

- The central role that wind and solar power play in the provision of increasingly low-carbon electricity in *Accelerated* and *Net Zero* imply a material acceleration in investment in new capacity. Despite the falling cost of wind and solar capacity, the average annual investment consistent with these two scenarios over the outlook is $500-$800 billion. This is two to three times greater than recent investment levels, with around 65-70% of that implied investment occurring in emerging economies. This significant increase in the pace of investment in wind and solar power would need to be supported by corresponding investment increases in critical enabling technologies and infrastructure, including transmission and distribution capacity.

- Although the demand for oil and gas falls in all three scenarios, natural decline in existing production implies that continuing investment in new upstream oil and gas is required in all three scenarios, including *Net Zero*. However, the implied rates of investment, especially in *Accelerated* and *Net Zero*, are much lower than past levels and significantly less than the required investment in wind and solar capacity.

- The average annual investment in upstream oil and gas over the next 10 years consistent with the three scenarios is around $375-$500 billion, compared with around $415 billion in 2020*.

- The investment levels implied by the expansion of carbon capture, use and storage (CCUS) facilities in the three scenarios (including the cost of capture, transport and storage) is relatively small compared to that required by either wind and solar capacity or upstream oil and gas. However, it is much greater than recent historical levels, suggesting that a significant scaling-up in financing would be required to support the build out.

*Upstream oil and gas investment includes capital expenditures on wells construction, facilities and exploration.

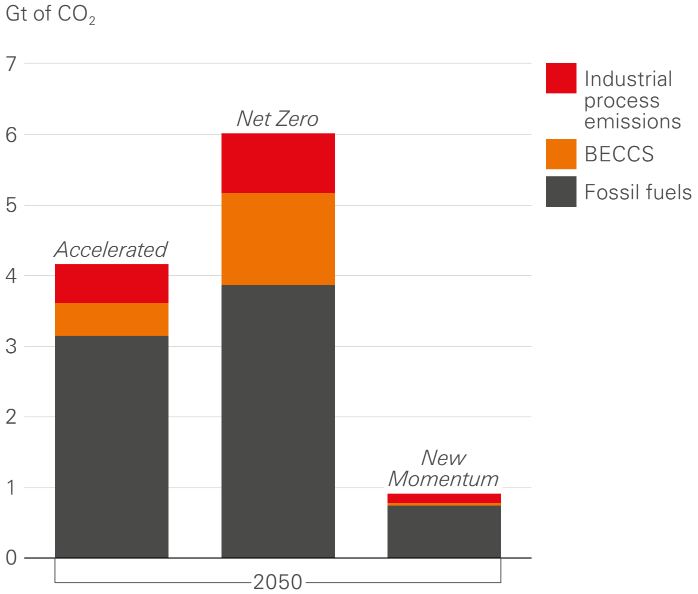
Carbon mitigation and removals

CCUS plays a vital role in the transition to a low-carbon energy system

Carbon dioxide removals may play a key role in achieving the Paris climate goals

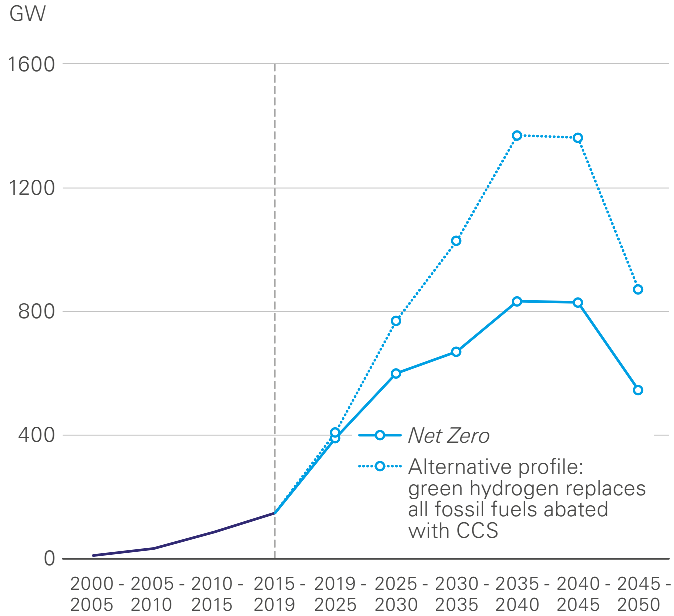
CCUS plays a vital role in the transition to a low-carbon energy system

Carbon capture use and storage in 2050 by emissions source



BECCS: Bioenergy with carbon capture storage

Average annual increase in wind and solar capacity

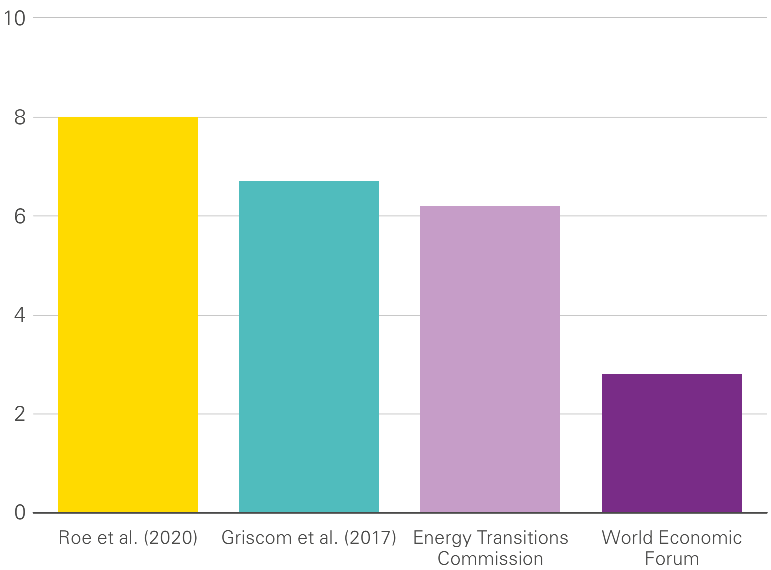


Carbon capture, use and storage (CCUS) plays a central role in supporting the transition to a low-carbon energy system. CCUS deployment reaches around 4-6GtCO_2 by 2050 in *Accelerated* and *Net Zero*, compared with around 1 Gt CO_2 in *New Momentum*.

- The stronger growth of CCUS in *Accelerated* and *Net Zero* is supported by tightening carbon emission policies, as well as by increasing recognition from policymakers and society of the important role CCUS can play in enabling an efficient transition to a low-carbon energy system. Even so, the pace of deployment is slowed by several other factors, including the need for extensive appraisal and permitting of prospective storage sites, and the long lead times associated with developing storage sites and their related transport infrastructure.
- In *Accelerated* and *Net Zero* around 25-35% of the CCUS operating in 2050 is used either to capture and store emissions which inherently arise from industrial processes, such as from the production of cement, or as a form of carbon dioxide removal (CDR) in conjunction with the use of bioenergy (BECCS) (see pages 92-93). The ability to use other technologies or processes to perform these two functions – avoid industrial process emissions and provide a source of engineered CDR – is relatively limited.
- The remaining CCUS is used to capture emissions from fossil fuels. CCUS is used to both abate emissions from natural gas and coal combustion in the industrial and power sectors and to produce blue hydrogen (see pages 82-83). Within that, around 65-70% of CCUS by 2050 is used with natural gas and the remainder with coal.
- In principle, it is possible to reduce the need for CCUS used with fossil fuels by consuming greater quantities of other low-carbon energy sources such as green hydrogen. But this would require an even faster expansion of renewable energy than assumed in *Accelerated* and *Net Zero*.
- For example, to replace all the abated fossil fuels used in *Net Zero* with green hydrogen produced by wind and solar power would require an average annual increase in wind and solar capacity of around 1.2TW in the 2030s and 2040s, roughly 60% greater than assumed in *Net Zero* and around five times faster than the highest annual increase on record.

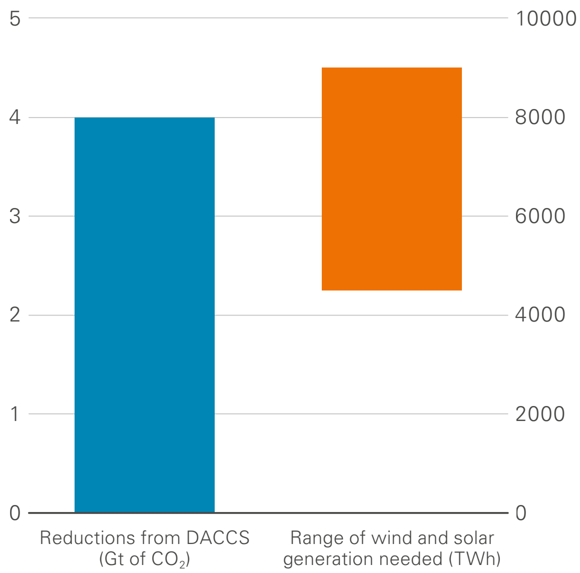
Carbon dioxide removals may play a key role in achieving the Paris climate goals

Estimates of potential natural climate solutions removals



See Annex for more details

Illustrative example: range of additional energy required to remove 4 Gt of CO_2 via direct air carbon capture with storage (DACCS)



The scenarios in the *Energy Outlook* focus largely on emissions emanating from the production and use of energy. In that context, they include bioenergy combined with CCUS, but do not explicitly model other forms of carbon dioxide removal which operate outside of the energy sector.

- For the world to remain within a limited carbon budget and achieve the Paris climate goals, a range of other carbon dioxide removals (CDRs) may be needed, including natural climate solutions (NCS) and direct air carbon capture with storage (DACCS).

Natural Climate Solutions (NCS)

- NCS refers to actions that conserve, restore or manage forests, wetlands, grasslands and agricultural lands in such a way as to increase carbon storage or avoid greenhouse gas emissions.
- In doing so, NCS can either *'reduce'* carbon emissions or *'remove'* CO_2 already in the atmosphere. Both types of NCS (*reduce and remove*) have the potential to play an important role, but towards 2050 attention is likely to focus increasingly on removals since they directly reduce the concentration of CO_2 in the atmosphere.
- There is considerable uncertainty as to the potential scale of NCS. Focussing on cost-effective removal measures, several external estimates imply a potential range of 6-8 $GtCO_2$ per annum, although some estimates are lower.

Direct Air Carbon Capture

- Direct air carbon capture is a process of capturing CO_2 directly from ambient air to form a concentrated stream of CO_2, which can then either be utilised, e.g. for the production of H-fuels, or stored to act as a form of CDR.
- DACCS has a number of attractions. It has the potential to be scaled materially. Its flexibility means it can be located in the most advantaged regions. And it provides greater certainty as to the permanence and additionality of the carbon removed.
- But DACCS also faces some challenges. The low concentrations of CO_2 in ambient air requires large quantities of air to be processed. The current cost of DACCS is high relative to other forms of CDR. And it is relatively energy intensive. For example, to achieve 4 $GtCO_2$ of carbon removal using DACCS would require somewhere in the region of 4,500-9,000 TWh of renewable power generation, roughly equivalent to around 10-20% of the total wind and solar power generation in *Net Zero* in 2050.

Annex

Data tables

		Level in 2050*			Change 2019-2050 (p.a.)			Share of primary energy in 2050		
	2019	*Accelerated*	*Net Zero*	*New Momentum*	*Accelerated*	*Net Zero*	*New Momentum*	*Accelerated*	*Net Zero*	*New Momentum*
Primary energy by fuel										
Total	627	692	653	760	0.3%	0.1%	0.6%	100%	100%	100%
Oil	193	87	44	154	-2.5%	-4.6%	-0.7%	13%	7%	20%
Natural gas	140	94	61	181	-1.3%	-2.7%	0.8%	14%	9%	24%
Coal	158	25	17	103	-5.8%	-6.9%	-1.4%	4%	3%	13%
Nuclear	25	40	49	27	1.6%	2.2%	0.3%	6%	7%	4%
Hydro	38	61	65	48	1.6%	1.8%	0.8%	9%	10%	6%
Renewables (incl. bioenergy)	74	384	418	247	5.5%	5.7%	4.0%	56%	64%	33%
Primary energy by fuel (native units)										
Oil (Mb/d)	98	47	24	81	-2.4%	-4.4%	-0.6%			
Natural gas (Bcm)	3900	2614	1681	5020	-1.3%	-2.7%	0.8%			
Primary energy by region										
Developed	234	172	167	196	-1.0%	-1.1%	-0.6%	25%	26%	26%
United States	97	73	71	83	-0.9%	-1.0%	-0.5%	10%	11%	11%
European Union	65	48	47	52	-1.0%	-1.1%	-0.7%	7%	7%	7%
Emerging	393	519	486	565	0.9%	0.7%	1.2%	75%	74%	74%
China	147	156	144	166	0.2%	-0.1%	0.4%	22%	22%	22%
India	42	91	88	96	2.5%	2.5%	2.7%	13%	14%	13%
Middle East	37	48	45	50	0.8%	0.6%	0.9%	7%	7%	7%
Russia	30	32	29	34	0.1%	-0.1%	0.4%	5%	5%	4%
Brazil	16	17	15	20	0.3%	-0.1%	0.8%	2%	2%	3%

		Level in 2050*			Change 2019-2050 (p.a.)			Share of final consumption in 2050		
	2019	*Accelerated*	*Net Zero*	*New Momentum*	*Accelerated*	*Net Zero*	*New Momentum*	*Accelerated*	*Net Zero*	*New Momentum*
Total final consumption by sector										
Total	477	420	351	542	-0.4%	-1.0%	0.4%	100%	100%	100%
Transport	119	103	91	120	-0.5%	-0.8%	0.0%	25%	26%	22%
Industry	188	163	136	217	-0.5%	-1.0%	0.5%	39%	39%	40%
Feedstocks	38	39	30	49	0.1%	-0.7%	0.8%	9%	8%	9%
Buildings	132	114	94	157	-0.5%	-1.1%	0.6%	27%	27%	29%
Energy carriers (generation)										
Electricity ('000 TWh)	27	58	63	50	2.5%	2.8%	2.0%	50%	65%	33%
Hydrogen (Mt)	66	287	446	146	4.8%	6.3%	2.6%	8%	15%	3%
Production										
Oil (Mb/d)	98	46	24	80	-2.4%	-4.4%	-0.6%			
Natural gas (Bcm)	3976	2617	1681	5020	-1.3%	-2.7%	0.8%			
Coal (EJ)	168	25	16	99	-6.0%	-7.2%	-1.7%			
Emissions										
Carbon emissions (Gt of CO_2e)	39.8	9.9	2.4	31.1	-4.4%	-8.7%	-0.8%			
Carbon capture use & storage (Gt)	0.0	4.2	6.0	0.9	56%	58%	48%			
Macro										
GDP (trillion US$ PPP)	127	283	283	283	2.6%	2.6%	2.6%			
Energy intensity (MJ / US$ of GDP)	3.7	1.5	1.2	1.9	-2.9%	-3.5%	-2.1%			

** EJ unless otherwise stated*

Construction of IPCC scenario sample ranges

The world's scientific community has developed a number of "integrated assessment models" (IAMs) that attempt to represent interactions between human systems (the economy, energy, agriculture) and climate. They are "simplified, stylized, numerical approaches to represent enormously complex physical and social systems" (Clarke 2014). These models have been used to generate many scenarios, exploring possible long-run trajectories for greenhouse gas emissions and climate change under a wide range of assumptions.

The Intergovernmental Panel on Climate Change (IPCC) carries out regular surveys of this scenario modelling as part of its assessment work. The most recent survey was carried out in support of the IPCC Special Report on Global Warming of 1.5°C (SR15). A total of 414 scenarios from 13 different modelling frameworks were compiled and made available via an online portal hosted at the International Institute for Applied Systems Analysis (IIASA).

Some of the scenarios are now quite dated and, in some cases, scenario results are already significantly out of line with recent historical data and so were excluded from our analysis. From the remaining model runs, 112 scenarios were judged to be consistent with the Paris climate change agreement of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. These scenarios were further divided into two subsets: "well below 2°C" (69 scenarios); and "1.5°C with no or low overshoot" (43 scenarios).

These two subsets were further refined by excluding, first, scenarios in which historical year 2010 emissions from energy and industrial sources deviate more than 5% from the mean of the scenario sample and, second, scenarios with implied (shadow) pre-2020 average global carbon prices higher than $30 per ton CO_2 ($2010) which were viewed as being overly optimistic about the state of climate policy by 2020. For the remaining scenarios in each of these two subsets, the ranges of outcomes for key variables are described in terms of medians and percentile distributions (See Scenario selection methodology bp.com) for a more detailed explanation). To allow for direct comparisons with the *Energy Outlook* scenarios, methane emissions from energy supply are added to emissions from energy and industrial processes. For those scenarios that do not report methane emissions we used the corresponding subset average.

It is important to note that the scenario dataset represents a collection of scenarios that were available at the time of the IPCC survey, and which were produced for a variety of purposes. "It is not a random sampling of future possibilities of how the world economy should decarbonize" (Gambhir et al, 2019). That means that the distributions of IPCC scenarios cannot be interpreted as reliable indicators of likelihood of what might actually happen. Rather, the distributions simply describe the characteristics of the scenarios contained in the IPCC report.

In addition to this selection of scenarios, chart (see page 14) shows the emissions path for a representative scenario based on the information available in Table 2.4 in the IPCC report *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*. This path is constructed using the median level of CO_2 from fossil fuels and industry (net) in 2030 and the average decline of emissions in 2010-2030 and 2020-2030 for 42 scenarios consistent with 1.5°C with no or limited overshooting.

Sources

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Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V.Vilariño, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Economic impact of climate change

The GDP profiles used in the *Energy Outlook* come from Oxford Economics (OE). These long-term forecasts incorporate estimates of the economic impact of climate change. These estimates draw on the latest research in the scientific literature and follow a similar methodology to that used in *Energy Outlook 2020*.

OE updated and extended the models developed by Burke, Hsiang and Miguel (2015), which use the IPCC Representative Concentration Pathways (RCP) scenarios to assess the impact of temperature changes on GDP. Like Burke et al., OE's updated results find evidence of a non-linear relationship between productivity and temperature, in which per capita income growth rises to an average (population weighted) temperature of just under 15°C (Burke et al's initial assessment was 13°C). This temperature curve suggests that 'cold country' income growth increases with annual temperatures. However, at annual temperatures above 15°C, per capita income growth is increasingly adversely affected by higher temperatures.

The OE forecasts are broadly in line with the RCP 6.0 scenario and assume average global temperatures will reach 2°C above pre-industrial levels by 2050. The results suggest that in 2050 global GDP is around 3% lower than in a counterfactual scenario where the temperature change remained at the current level. The regional impacts are distributed according to the evolution of their temperatures relative to the concave function estimated by OE. These estimates are hugely uncertain and incomplete; they do not, for example, explicitly include impact from migration or extensive coastal flooding.

The mitigation costs of actions to decarbonize the energy system are also uncertain, with significant variations across different external estimates. Most estimates, however, suggest that the upfront costs increase with the stringency of the mitigation effort, suggesting that they are likely to be bigger in *Accelerated* and *Net Zero* than in *New Momentum*. Estimates published by the IPCC (AR5 – Chapter 6) suggest that for scenarios consistent with keeping global temperature increases to well below 2°C, median estimates of mitigation costs range between 2-6% of global consumption by 2050.

Given the huge range of uncertainty surrounding estimates of the economic impact of both climate changes and mitigation, and the fact that all three of the main scenarios include both types of costs to a greater or lesser extent, the GDP profiles used in the *Outlook* are based on the illustrative assumption that these effects reduce GDP in 2050 by around 3% in all three scenarios, relative to the counterfactual in which temperatures are held constant at recent average levels.

Sources

Burke, M., Hsiang, S. & Miguel, E. Global non-linear effect of temperature on economic production. Nature 527, 235–239 (2015)

The global aggregate mitigation cost estimates in terms of GDP losses are taken from IPCC AR5 – Chapter 6

Investment methodology

Oil and gas upstream

Implied levels of oil and gas investment are derived from the production levels in each scenario. Upstream oil and natural gas capital expenditure includes well capex (costs related to well construction, well completion, well simulation, steel costs and materials), facility capex (costs to develop, install, maintain, and modify surface installations and infrastructure) and exploration capex (costs incurred to find and prove hydrocarbons). It excludes operating costs and midstream capex such as capex associated with developing LNG liquefaction capacity.

Asset level production profiles are aggregated by geography, supply segment (onshore, offshore, shale and oil sands), supply type (crude, condensates, NGLs, natural gas) and developmental stage, i.e., classified by whether the asset is currently producing, under development, or non-producing and unsanctioned. As production from producing and sanctioned assets declines, incremental production from infill drilling and new, unsanctioned assets is called on to meet the oil and gas demand shortfalls. The investment required to bring this volume online is then added to any capital costs associated with maintaining producing and sanctioned projects.

The average 2022-2050 decline rate for assets currently producing and under development is around 5.0% p.a. for oil and 5.5% p.a. for gas but varies widely by segment and hydrocarbon type. All estimates are derived from asset-level assessments from Rystad Energy.

Wind and solar

Wind and solar energy investment requirements are based on the capital expenditure costs associated with the deployment profiles of each technology in each scenario.

Wind and solar deployment profiles include both renewable power capacity for end-use and for green hydrogen production. The deployment profiles also consider the potential impact of curtailment.

Capital expenditure costs are assigned to each scenario based on their historical values and estimated future evolution. They are differentiated by technology, region and scenario using a combination of internal bp estimates and external benchmarking. The capital expenditure figures do not include the incremental wider system integration costs associated with wind and solar deployment.

Carbon capture use and storage

Power sector post-combustion capture costs are based on internal bp estimates drawn from a wide range of sources. Capture costs for industry, heat and hydrogen are based on the 2019 US National Petroleum Council Report *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage.*

Transportation and storage costs were based on internal expert judgment by primary storage archetype for each region and assessment of either pipeline or shipping costs.

Carbon emissions definitions and sources

Unless otherwise stated, carbon emissions refer to CO_2 emissions from energy use (ie the production and use of energy in the three final end-use sectors: industry, transport and buildings), most non-energy related industrial processes, and natural gas flaring, plus methane emissions associated with the production, transmission and distribution of fossil fuels, expressed in CO_2 equivalent terms.

CO_2 emissions from industrial processes refer only to non-energy emissions from cement production. CO_2 emissions associated with the production of hydrogen feedstock for ammonia and methanol are included under hydrogen sector emissions.

As in the bp Statistical Review, historical data for natural gas flaring data is taken from VIIRS Nightfire (VNF) data and produced by the Earth Observation Group (EOG), Payne Institute for Public Policy, Colorado School of Mines. The profiles for natural gas flaring in the scenarios assume that flaring moves in line with wellhead upstream output.

Historical data on methane emissions associated with the production, transportation and distribution of fossil fuels are sourced from IEA estimates of greenhouse gas emissions. The profiles for future methane emissions assumed in the scenarios are based on fossil fuel production and take account of recent policy initiatives such as the Global Methane Pledge. The net change in methane emissions is the aggregation of future changes to fossil fuel production and methane intensity.

There is a wide range of uncertainty with respect to both current estimates of methane emissions and the global warming potential of methane emissions. To ensure alignment with financial and government reporting standards, the methane to CO_2e factor used in the scenarios is a 100-year Global Warming Potential (GWP) of 25, recommended by the IPCC in AR4.

Sources

Andrew, R.M., 2019. *Global CO_2 emissions from cement production, 1928–2018*. Earth System Science Data 11, 1675–1710, (updated dataset July 2021)

IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).

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IEA (2021), Greenhouse Gas Emissions from Energy Data Explorer, IEA, Paris

IPCC Fourth Assessment Report: Climate Change 2007.

IEA (2021), Methane Tracker 2021, IEA, Paris

Sustainability Reporting Guidance for the Oil and Gas Industry, 4th Edition, 2020. IPIECA/API/IOGP.

Other data definitions and sources

Data

Data definitions are based on the bp Statistical Review of World Energy, unless otherwise noted. Data used for comparisons, including scenarios from the Intergovernmental Panel on Climate Change (IPCC), unless otherwise noted are rebased to be consistent with the bp Statistical Review.

Primary energy, unless otherwise noted, comprises commercially traded fuels and traditional biomass. In this Outlook, primary energy is derived in two ways:

- the substitution method - which grosses up energy derived from non-fossil power by the equivalent amount of fossil fuel required to generate the same volume of electricity in a thermal power station. The grossing assumption is time varying, with the simplified assumption that efficiency will increase linearly from 40% today to 45% by 2050
- the physical content method – which uses the output of non-fossil power generation directly.

Figures and charts of primary energy are estimated using the substitution method, unless otherwise stated.

Gross Domestic Product (GDP) is expressed in terms of real Purchasing Power Parity (PPP) at 2015 prices.

Sectors

Transport includes energy used in heavy road, light road, marine, rail and aviation. Electric vehicles include all four wheeled vehicles capable of plug-in electric charging. Industry includes energy used in commodity and goods manufacturing, construction, mining, the energy industry including pipeline transport, and for transformation processes outside of power, heat and hydrogen generation. Feedstocks includes non-combusted fuel that is used as a feedstock to create materials such as petrochemicals, lubricant and bitumen. Buildings includes energy used in residential and commercial buildings, agriculture, forestry, and fishing.

Regions

Developed is approximated as North America plus Europe plus Developed Asia. Developed Asia includes OECD Asia plus other high income Asian countries and regions. Emerging refers to all other countries and regions not in Developed. China refers to the Chinese Mainland. Other Emerging Asia includes all countries and regions in Asia excluding mainland China, India and Developed Asia.

Fuels, energy carriers, carbon and materials

Oil, unless otherwise noted, includes crude (including shale oil and oil sands), natural gas liquids (NGLs), gas-to-liquids (GTLs), coal-to-liquids (CTLs), condensates, and refinery gains. H-fuels are all fuels derived from low-carbon hydrogen, including ammonia, methanol, and other synthetic hydrocarbons

Renewables, unless otherwise noted, includes wind, solar, geothermal, biomass, biomethane, and biofuels and exclude large-scale hydro. Non-fossils include renewables, nuclear and hydro. Traditional biomass refers to solid biomass (typically not traded) used with basic technologies e.g. for cooking.

Hydrogen demand includes its direct consumption in transport, industry, buildings, power and heat, as well as feedstock demand for the production of H-fuels and for conventional refining and petrochemical feedstock demand.

Low-carbon hydrogen includes green hydrogen, biomass with CCUS, gas with CCUS, and coal with CCUS. CCUS options include CO2 capture rates of 93-98% over the Outlook. The global average methane emissions rate for the gas or coal consumed to produce blue hydrogen is between 1.4-0.7% over the Outlook.

Sources

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Roe et al. (2020), Land-based measures to mitigate climate change: Potential and feasibility by country

Griscom et al. (2017), Natural climate solutions

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World Economic Forum (2021), Nature and Net Zero

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