Achieving Net Zero Electricity Sectors in G7 Members

International Energy Agency

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Abstract

Achieving Net Zero Electricity Sectors in G7 Members is a new report by the International Energy Agency that provides a roadmap to driving down CO_2 emissions from electricity generation to net zero by 2035, building on analysis in *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

The new report was requested by the United Kingdom, under its G7 Presidency, and followed the G7 leaders' commitment in June 2021 to reach "an overwhelmingly decarbonised" power system in the 2030s and net zero emissions across their economies no later than 2050. It is designed to inform policy makers, industry, investors and citizens in advance of the COP26 Climate Change Conference in Glasgow that begins at the end of October 2021.

Starting from recent progress and the current state of play of electricity in the G7, the report analyses the steps needed to achieve net zero emissions from electricity, and considers the wider implications for energy security, employment and affordability. It identifies key milestones, emerging challenges and opportunities for innovation.

The report also underscores how G7 members can foster innovation through international collaboration and, as first movers, lower the cost of technologies for other countries while maintaining electricity security and placing people at the centre of clean energy transitions.

Foreword

Momentum is building for countries and companies around the world to strengthen their energy and climate commitments, and an increasing number have set targets to reach net zero emissions by mid-century or soon after. The urgency of tackling greenhouse gas emissions was reaffirmed by the recent report by the Intergovernmental Panel on Climate Change (IPCC) – Climate Change 2021: the Physical Science Basis – which asserted that the effects of climate change could come faster and be more intense than previously envisaged.

The 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change in November 2021 in Glasgow will be a crucial opportunity to strengthen global ambitions and action on climate, building on the foundations of the 2015 Paris Agreement. It comes at the start of a critical decade for achieving climate goals: significant progress by 2030 is essential if the goals agreed in Paris in 2015 are to be met.

The International Energy Agency (IEA) has been supporting the United Kingdom government's COP26 Presidency, including co-hosting the IEA-COP26 Net Zero Summit with COP26 President-Designate Alok Sharma in March 2021. This Summit took stock of the growing commitments from governments and corporations to reach Paris Agreement goals and focused on the actions necessary to start turning those net zero goals into reality.

The IEA report Net Zero by 2050: A Roadmap for the Global Energy Sector, released in May 2021, provides a pathway to net zero emissions by 2050, which involves advanced economies collectively reaching net zero emissions from electricity by 2035 and the rest of the world doing so by 2040. The report clearly marks out the gap between pledges and specific implementation plans. Net zero pledges to date cover 60-70% of global CO_2 emissions. However, less than one-quarter of announced net zero pledges are fixed in domestic legislation, and many pledges have not yet been backed up by specific measures or policies to deliver them in full and on time. The report also makes clear that, even if implemented in full, the net zero pledges made up to the time of publication are not sufficient to achieve the goals of the Paris Agreement.

Following the G7 Climate and Environment Ministers' Meeting in May 2021, the United Kingdom Presidency of the G7 requested a follow-up report on a pathway to electricity sectors with net zero emissions in the G7 by 2035. Building on the Net Zero by 2050 Roadmap, this report provides a roadmap to achieving net zero emissions electricity in the G7, highlighting key milestones, emerging challenges and opportunities for innovation. Considering country specific circumstances, the G7 could lead the way by shifting rapidly away from unabated coal towards low-emissions sources while maintaining electricity security. At the same time, the G7 needs to keep people at the centre of energy transitions and show the way for economies around the world, adding momentum to global efforts to reach net zero emissions by 2050.

Acknowledgements, contributors and credits

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Edmund Hosker carried editorial responsibility. Rebekah Folsom was the copy-editor.

Valuable comments and feedback were provided by other senior management and colleagues within the IEA, in particular, Mechthild Wörsdörfer, Keisuke Sadamori, César Alejandro Hernández, Paolo Frankl, Peter Fraser, Timur Gül, and Aad Van Bohemen. Thanks also go to the IEA Communications and Digital Office (CDO) for their help in producing the publication, especially to Astrid Dumond, Clara Vallois, Tanya Dyhin and Therese Walsh.

The study was commissioned by the United Kingdom governments' Presidency of the G7 and benefitted from collaboration with colleagues from the UK Department of Business, Energy and Industrial Strategy, in particular Ariana Agapiou, Ciara O'Sullivan and Pelin Zorlu.

The findings also draw on strategic insights and guidance received during an IEA high-level workshop on the G7 net zero power commitment to action co-hosted by IEA and UK on 17 September 2021.

The IEA would like to thank the following experts who provided essential inputs, review and encouragement (by G7 member alphabetical order): Isabel Murray and Gareth Savage (Department of Natural Resources, Canada); Michael Hackethal and Joanna Ruszkowska (Federal Ministry of Economics and Technology, Germany); Francesco Ferioli, Miguel Gil Tertre and Fabian Kreuzer, (European Commission); Philippe Geiger (Ministry of Ecological Transition, France); Nicola Bazzani, Michele De Nigris, and Isabella Moscato (Ministry of Foreign Affairs, Ricerca sul Sistema Energetico [RSE], Ministry of Economic Development, Italy); Hidechika Koizumi (Ministry of Economy, Trade and Industry, Japan); Tom Bastin (Department for Business, Energy & Industrial Strategy, United Kingdom); Michael Apicelli, Russell Conklin and Celeste Marshall (Department of Energy, United States).

Executive summary

The G7 has an opportunity to lead the global energy markets towards net zero emissions by 2050. In June 2021, the G7 Leaders committed to "net zero no later than 2050" and to "lead a technology-driven transition to net zero, supported by relevant policies". These commitments demonstrate political leadership and come at a critical time, ahead of the 26th Conference of the Parties of the United Nations Framework Convention on Climate Change. G7 members – Canada, France, Germany, Italy, Japan, the United Kingdom, the United States plus the European Union – in 2020 accounted for nearly 40% of the global economy, 30% of global energy demand and 25% of global energy-related CO_2 emissions. Implementing the policies, proving the technologies and taking the steps necessary to achieve net zero emissions in a secure and affordable way in the G7 are critical to accelerating people-centred transitions around the world.

Decarbonising electricity is central to reaching net zero emissions, as it addresses the highest emitting sector today and enables the decarbonisation of other sectors. This roadmap for G7 electricity sectors identifies key milestones, emerging challenges, opportunities for innovation and principles of action to achieve net zero by 2035. It builds on the IEA report *Net Zero by 2050: A Roadmap for the Global Energy Sector* and is aligned with the June 2021 G7 commitment to "an overwhelmingly decarbonised power system in the 2030s". The G7 roadmap follows the IEA Net Zero Emissions by 2050 Scenario (NZE) global pathway that is consistent with limiting the global average temperature rise to 1.5 °C, although it is not the only pathway to this objective. It was developed within the comprehensive energy modelling frameworks of the World Energy Outlook and Energy Technology Perspectives report, incorporating the latest energy data and the state of technology, and expands on policy settings around the world.

Clean energy transitions in the G7 are underway

The electricity sector accounts for one-third of G7 energy-related emissions today, well below the peak share of nearly 40% in 2007, as electricity sector emissions are on a decline with coal giving way to cleaner sources. The main drivers of these reductions in recent years were cheap natural gas in several markets and strong growth for renewables. In 2020, natural gas and renewables were the primary sources of electricity in the G7, each providing about 30% of the total, followed by nuclear power and coal at close to 20% each.

Momentum is building as governments in the G7 are re-shaping the electricity policy landscape with net zero in their sights. All G7 members have made a commitment to reach net zero emissions, underpinned in each case by a range of policy measures and targets that aim to phase out or reduce unabated coal-fired power while increasing the use of renewables, hydrogen, ammonia and carbon capture technologies, among other things. Over USD 500 billion in government funds have been collectively committed by G7 members to clean energy to boost sustainable recoveries from the Covid-19 pandemic, almost 20% of which is for the electricity sector. G7 members have also pioneered carbon pricing mechanisms and continue to apply these to support the decarbonisation of electricity.

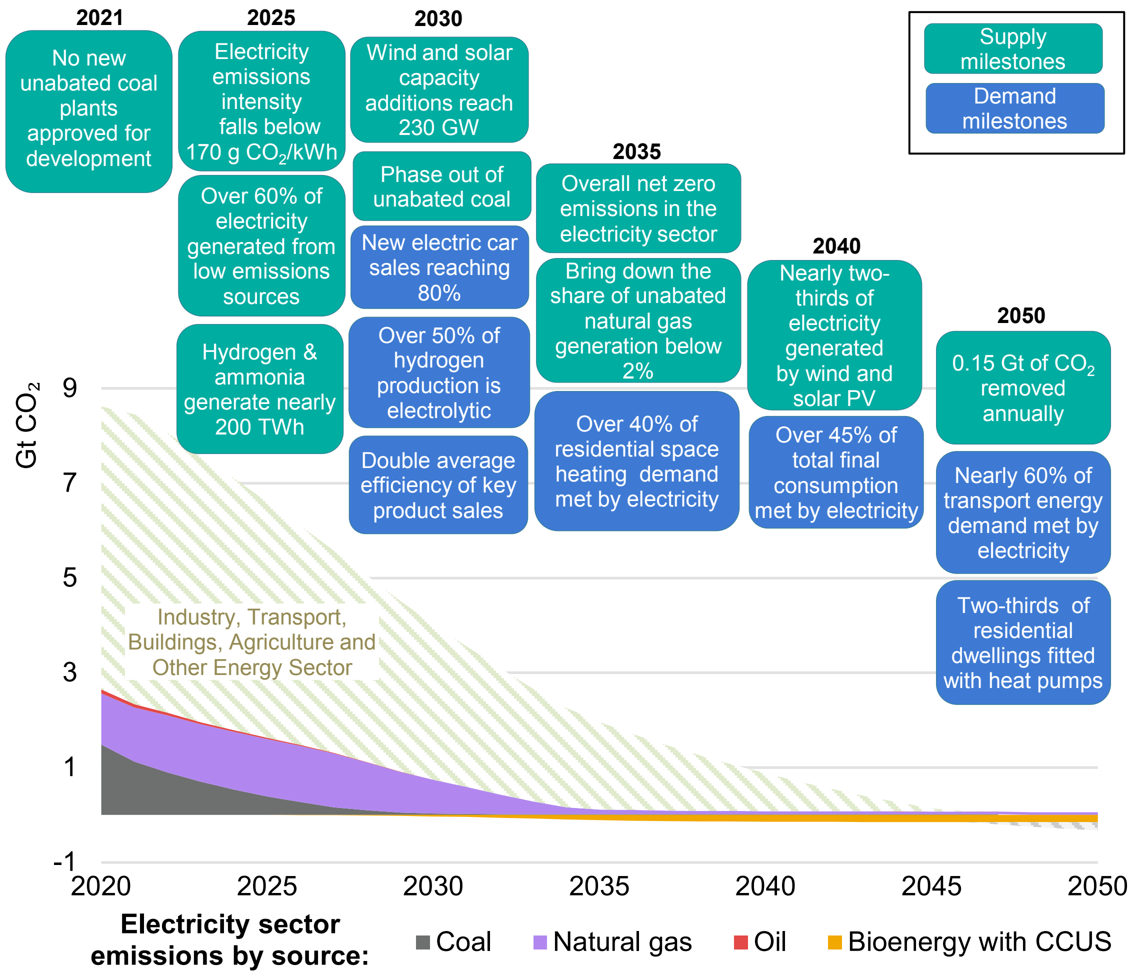
G7 action must accelerate to reach key milestones on the path to net zero electricity by 2035

Scaling up low-carbon technologies is the central pillar to achieve net zero, with wind and solar PV capacity additions scaling up from about 75 GW in 2020 to 230 GW by 2030. On the path to net zero electricity, renewables reach 60% of electricity supply by 2030 in the G7, compared with 48% under current policies. This requires effective government action to remove barriers and design and implement predictable and consistent policies, markets and regulatory frameworks. Nuclear power, low-carbon hydrogen and ammonia, and plants equipped with carbon capture add further to the low-emissions electricity supply.

The expansion of low-carbon electricity goes hand-in-hand with phasing out unabated coal. This means no approvals for new unabated coal plants from 2021, retrofitting existing plants to co-fire biomass or low-carbon ammonia or add carbon capture equipment, and retiring any plants that are not retrofitted in this way. It is also critical to drive down the share of unabated natural gas-fired generation in the G7 to just a few percentage points by 2035 compared with nearly 25% under current policies.

Rapid electrification of end-uses is also needed to achieve net zero emissions by 2050, with energy efficiency moderating electricity demand growth. In the G7, electricity demand rises by one-quarter in 2030 and over 80% in 2050 compared with the 2020 demand level, pushing the share of electricity in final energy demand from 22% in 2020 to 30% in 2030 and 56% in 2050. Electrification of the passenger car fleet and hydrogen production have the biggest impact, and heat pumps come to dominate the provision of heating in buildings. Growing economic activity adds to demand to 2050, but is more than offset by efficiency savings, with the efficiency of key products sold doubling between today and 2030 in the NZE, in line with targets from the Super-Efficient Equipment and Appliance Deployment initiative.

G7 energy-related emissions and electricity sector milestones in the Net Zero Emissions by 2050 Scenario, 2020-2050



Net zero emissions from electricity in the G7 is part of the broader pathway set out in the IEA *Net Zero by 2050: a Roadmap for the Global Energy Sector* that establishes over 400 sector-specific and technology-specific milestones. The global electricity sector transitions from the highest emitting sector today to achieve net zero by 2040, enabling other sectors to cut emissions via electrification. Global milestones for 2030 include renewables capacity more than tripling to over 10 000 GW, electric vehicles passing 60% of new car sales, low-carbon hydrogen production scaling up to 150 million tonnes, and all new buildings are zero-carbon ready. In industry, all electric motors are best in class by 2035 and 90% of heavy industry production uses low-emissions technologies by 2050.

People-centred transitions can create new opportunities

Investments in electricity generation within the G7 triple in the coming decade in the NZE, and then stabilise at about twice the current level in the 2030s and 2040s. Over 60% of this investment goes into wind and solar PV in 2030. Investments in networks double by 2030 and decline thereafter. Investments on this scale are far beyond those projected under current policies and need to be underpinned by measures to ensure timely project approvals and coordinate electricity system investments across the value chain.

The decarbonisation of electricity in the NZE creates many employment opportunities, including 2.6 million jobs in the G7 within the electricity sector in the next decade, although 0.3 million jobs are lost at fossil fuel power plants by 2030 plus reduced upstream jobs in fuel supply. In the NZE, job creation across the entire energy industry greatly outweighs job losses in fossil fuel sectors, however, the local impacts can be pronounced. G7 members will need to carefully deploy transition mechanisms and funding to ensure that affected workers and communities are not left behind. The IEA Global Commission for People-Centred Clean Energy Transitions is delivering recommendations to COP26 regarding how to design these transitions to ensure equity and inclusion, and to ensure climate progress can endure political cycles.

The affordability of energy is crucial to ensuring a just and people-centred transition; in the long term in the NZE, households spend a lower share of their disposable income on energy in the G7. While total energy spending across the G7 increases by 0.3% annually between now and 2050, its share of GDP declines from around 7% today to just over 4% in 2050. Household spending on electricity increases, but this is more than offset by a decline in household spending on coal, natural gas and oil products, and total household energy spending in the G7 declines by one-third by 2050. Taking account of additional investments in efficiency, total energy spending per household in G7 countries is about USD 200 less in 2050 in the NZE on average than today. Governments must ensure that all households are able to access these gains, including through tariff designs, by facilitating energy efficiency and, where applicable, supporting the transition to clean options that are more expensive.

Electricity security takes centre stage

New challenges emerge as the share of electricity in total energy demand rises along with the share of wind and solar PV, leading to a tripling of hour-to-hour flexibility requirements in the G7 from 2020 to 2050. The share of wind and solar in electricity generation rises in the G7 from 14% in 2020 to over 40% in 2030 and to two-thirds in 2050. Moving well beyond experience to date, the G7 has an opportunity to demonstrate that electricity systems with 100% renewables — during specific periods of the year and in certain locations — can be secure and affordable. At the same time, the primary sources of flexibility shift from unabated coal and natural gas to demand response and battery storage in the long term, with hydropower as an important source throughout. Robust electricity grids are essential to support transitions and take advantage of all sources of flexibility. The G7 can lead the way in developing technological solutions that address emerging challenges, including the need for seasonal storage, alongside appropriate market structures and system operation practices.

The challenges to electricity and wider energy security in the NZE require a whole systems approach. This extends beyond narrow operational issues to encompass systems resilience in the face of threats such as climate change, natural disasters, power failures and cyberattacks. To accomplish this, G7 members will need to work collectively to share best practices and put cyber and climate resilience at the heart of their energy security policies. The NZE sees a notable reduction in dependency on net energy imports over time for importing countries in the G7, which is a positive from an energy security perspective, but new concerns arise, notably with respect to supply chains for the critical minerals needed for clean energy technologies.

Innovation is essential to reach net zero electricity

Innovation delivers about 30% of G7 electricity sector emissions reductions in the NZE to 2050 by bringing additional technologies to market. Mature technologies like hydropower and light-water nuclear reactors contribute only about 15% of reductions, while about 55% of reductions come from the deployment of technologies currently in either the steady scale-up or early adoption phases. Onshore wind and crystalline silicon PV cells are being scaled up currently while coal with carbon capture, large-scale heat pumps, demand response and battery storage are examples from the early adoption phase. The remaining 30% of G7 electricity sector emissions reductions are delivered by technologies still in the demonstration or prototype phase today. These include floating offshore wind, carbon capture technologies for natural gas or biomass, and hydrogen and ammonia. Without strong international cooperation that includes the G7, the transition to net zero emissions could be delayed by decades. Initial deployment of key technologies could be delayed by 5-10 years in advanced economies and by 10-15 years in emerging market and developing economies.

Innovation can be accelerated through international cooperation, building on existing initiatives, especially in the form of knowledge sharing and coordination of development and demonstration efforts. Such cooperation could bring technologies to market more quickly, for example coordinating multiple demonstration projects in parallel, unlocking emissions reductions and opening new markets. As it has done for nuclear power, solar PV, onshore wind and fixed-bottom offshore wind, the G7 could lead development of floating offshore wind, and also hydrogen and ammonia use in power plants.

Digitalisation would also gain from international cooperation regarding best practices, unlocking benefits such as enhanced demand-side flexibility and approaches to cyber security. Policymakers can help level the playing field for all sources of flexibility, facilitate consumer engagement, develop standards and protocols for data exchanges, and coordinate planning to ensure that investments made in grids and other infrastructure help to unlock the benefits of digitalisation.

The G7 is a key enabler for global net zero emissions

As advanced economies, the G7 must respond to global calls for major economies to go faster, as being a first mover will create spill-over benefits that support other countries' energy transitions. G7 Leaders have shown political leadership through their commitment to reach net zero emissions no later than 2050. Clear roadmaps to cut emissions in sectors like electricity, industry and transport will be critical to drive innovation and cost reductions for key technologies. Implementation of these roadmaps will also expand policy and technology experience, providing benefits to G7 members through new technology opportunities, new jobs created and in making energy more sustainable and affordable. Other countries also benefit from reduced technology costs, reduced uncertainties and expanded operational experience, notably integrating high shares of variable renewables while addressing cyber and climate resilience risks. The IEA is ready to support the G7 to successfully set an example that would set the stage for other countries to scale up their ambitions to reach net zero.

Introduction

Reaching net zero emissions by 2050 requires large-scale action at a historically unprecedented speed. Central to reaching net zero is the decarbonisation of electricity, which will play a critical role in the decarbonisation of sectors such as transport, heating and industry.

The G7 brings together some of the world's largest advanced economies collectively accounting for about 40% of global GDP and 25% of energy-related CO_2 emissions. G7 members have a history of catalysing innovation, developing new technologies and commercialising them by introducing supportive policies within a stable economic environment. G7 leadership on electricity decarbonisation would bring its members benefits through the creation of new expertise, technologies and jobs. It would bring wider benefits too: sharing lessons learned could help reduce uncertainties and accelerate transitions in other countries that can incorporate G7 innovation, policies and regulations into their own circumstances, helping drive down the cost of low-emissions technologies and make energy transitions more affordable.

The report identifies key areas and provides recommendations that could help accelerate the reduction of emissions from electricity in G7 members. The report starts by setting the global context, building on the recent report *Net Zero by 2050: A Roadmap for the Global Energy Sector.* It continues by looking at the current state of electricity in the G7, and then moves on to analyse the steps that need to be taken by the G7 to achieve net zero emissions from electricity. The report then looks at the wider implications of achieving this, focusing particularly upon energy security and employment, before concluding with a set of milestones and principles for action.

Global pathway to net zero emissions by 2050

Summary and policy recommendations

- The IEA Net Zero Emissions by 2050 Scenario (NZE) targets a pathway consistent with limiting the global average temperature rise to 1.5 °C. The scenario focuses on the energy sector, which is responsible for around three-quarters of global CO_2 emissions today. It describes one of the possible pathways to reach net zero emissions by 2050 without any offsets outside of the energy sector, applies a comprehensive energy modelling framework and builds on the latest energy data, state of technology and policy settings around the world.
- The IEA *Net Zero by 2050: a Roadmap for the Global Energy Sector* lays out over 400 sector-specific and technology-specific milestones, which see the global electricity sector transitioning from the most-emitting sector today to reach net zero by 2040, enabling emissions reductions in other sectors through electrification. Milestones for 2030 include electric vehicles passing 60% of new car sales, the scaling up to 150 million tonnes of low-carbon hydrogen production, and all new buildings being zero-carbon ready. In industry, all electric motors are best in class by 2035 and 90% of heavy industry production uses low-emissions technologies by 2050. Overall, the energy efficiency of key products is set to double over the next decade.
- Investment in the energy system steps up in the NZE, more than doubling by 2030 to nearly USD 5 trillion, and the electricity sector attracts more investment than any other sector. Annual average investment in clean power and electricity networks more than triples by 2030, fuelled by growth in electricity demand and by dramatic growth in wind and solar PV generation. By 2030, 14 million new jobs are created globally in clean energy (a net gain of 9 million jobs in the global energy sector), and a further 16 million in clean energy end-uses. Some fossil fuel-related jobs disappear, however, and inclusive policies are needed to support re-skilling and diversification in fossil fuel dependent communities.
- Innovation and international cooperation have important parts to play in reaching net zero. While the technologies needed to achieve the emissions reductions targets by 2030 in the NZE are widely available, over half of the reductions in 2050 come from technologies not yet available on the market. International cooperation is essential to bring new technologies to commercial

maturity and to unlock the financing needed to speed up the global diffusion and adoption of those technologies. Without the cooperation assumed in the NZE, the deployment of key technologies could be delayed by decades, and with it the achievement of net zero emissions.

- Transitions to net zero electricity call for a rapid scaling up of renewables and other low-emissions technologies to displace unabated fossil fuels. Global renewables capacity more than triples to over 10 000 GW by 2030, with annual additions of wind and solar PV exceeding 1 000 GW in that year alone. Wind and solar PV rise from 10% of generation in 2020 to 40% by 2030 and 70% by 2050. Global unabated coal-fired generation drops by two-thirds by 2030 and is fully phased out by 2040 in the NZE. Carbon capture technologies, hydrogen and ammonia help to reduce emissions from remaining coal and natural gas-fired power plants. Hydro and nuclear power maintain an important role in generation and contribute to rising system flexibility needs, complementing the growth of battery storage and demand-side response.

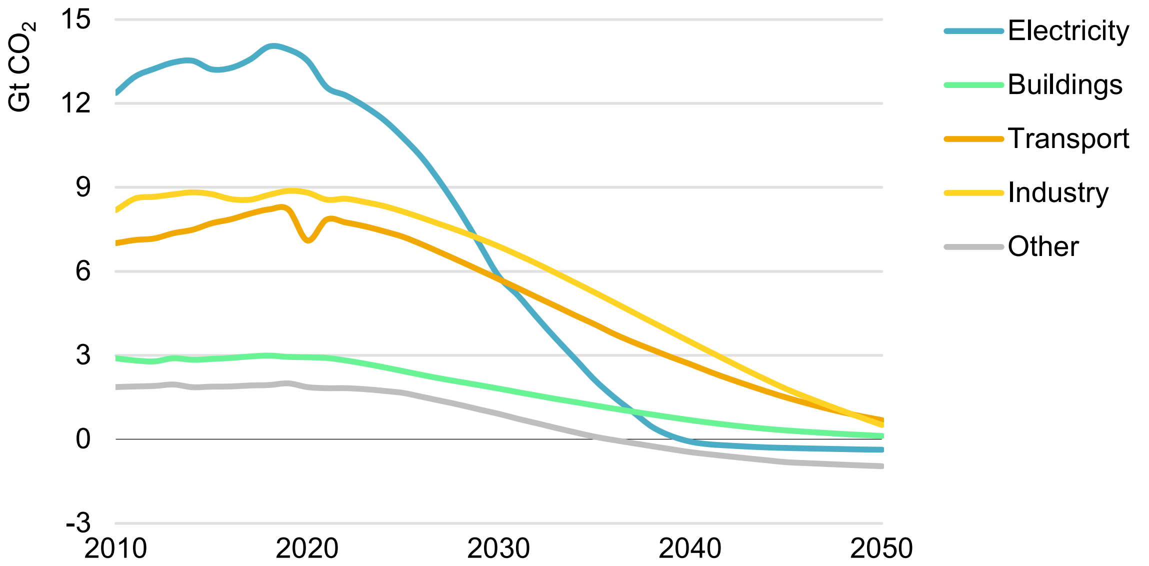
Transformation of the global energy system

Reducing global CO_2 emissions to net zero by 2050 is consistent with limiting the long-term increase in average global temperatures to 1.5 C. The energy sector is responsible for around three-quarters of global CO_2 emissions and is therefore critical to goals to achieve this objective. The recently published IEA report "Net Zero by 2050" charts a narrow but achievable pathway to net zero global energy-related and industrial process CO_2 emissions by 2050.

The path set out in this report is based on a scenario developed by the IEA to achieve net zero emissions globally by 2050 (the NZE scenario). It is not the only possible way forward. However, it is a cost-effective pathway, formulated using the IEA's World Energy Model, and it takes account of the latest energy data, the state of energy technologies, technology preferences, policy settings and resource limitations, such as land use. The NZE achieves net zero energy-related and industrial process emissions by 2050 without any offsetting emissions from outside the energy sector, placing it amongst the most ambitious energy decarbonisation scenarios seen thus far.

In the NZE, all sectors contribute to the pathway to net zero emissions by 2050, although some sectors see more rapid progress than others. The electricity sector is the largest source of global energy-related CO_2 emissions today, and several cost-effective mitigation options are available. In the NZE, net zero emissions from electricity are achieved before all other sectors except the other fuel transformation sector (see below). Its emissions are reduced by almost 60% by 2030 compared to today's level and reach net zero by 2040.

Energy-related CO_2 emissions by sector in the Net Zero Emissions by 2050 Scenario, 2010-2050



Industry is the second largest emitting sector today. While some emission reduction technologies are already available commercially, significant technical challenges need to be overcome to achieve deep cuts in emissions from the production of cement, iron and steel, and the NZE sees continued emissions well above zero through 2050. In transport, the passenger vehicle fleet has already begun to move away from internal combustion engines, but it will be more difficult for heavy-duty vehicles, ships and planes to shift to electricity or hydrogen and ammonia. Buildings represent a diverse set of structures, some with lifetimes that can extend beyond a century. The NZE envisages a progressive transition to energy sources with low or no emissions and high levels of energy efficiency achieved through retrofits of existing buildings and high energy efficiency standards for new ones. In the NZE, both the transport and industry sectors undergo a slower transition than the buildings sector does.

The 'other' sector includes fuel transformation, such as hydrogen and biofuels production. This sector reaches net zero by the mid-2030s in the NZE, due to the deployment of bioenergy carbon-capture and storage (BECCS) in biofuels production and direct air capture and storage (DACS), which give rise to negative emissions. By 2050, carbon removal from BECCS and DACS offsets residual emissions of around 1.9 Gt, largely in the in the transport and industry sectors.

The NZE pathway requires immediate and massive deployment of all currently available clean energy technologies, with particular emphasis on electricity generation, energy efficiency and electrification. This helps to avoid further lock-in of emissions-intensive assets. It also ensures that emissions reduce fast enough to stay within the remaining emissions budget for 1.5 °C.

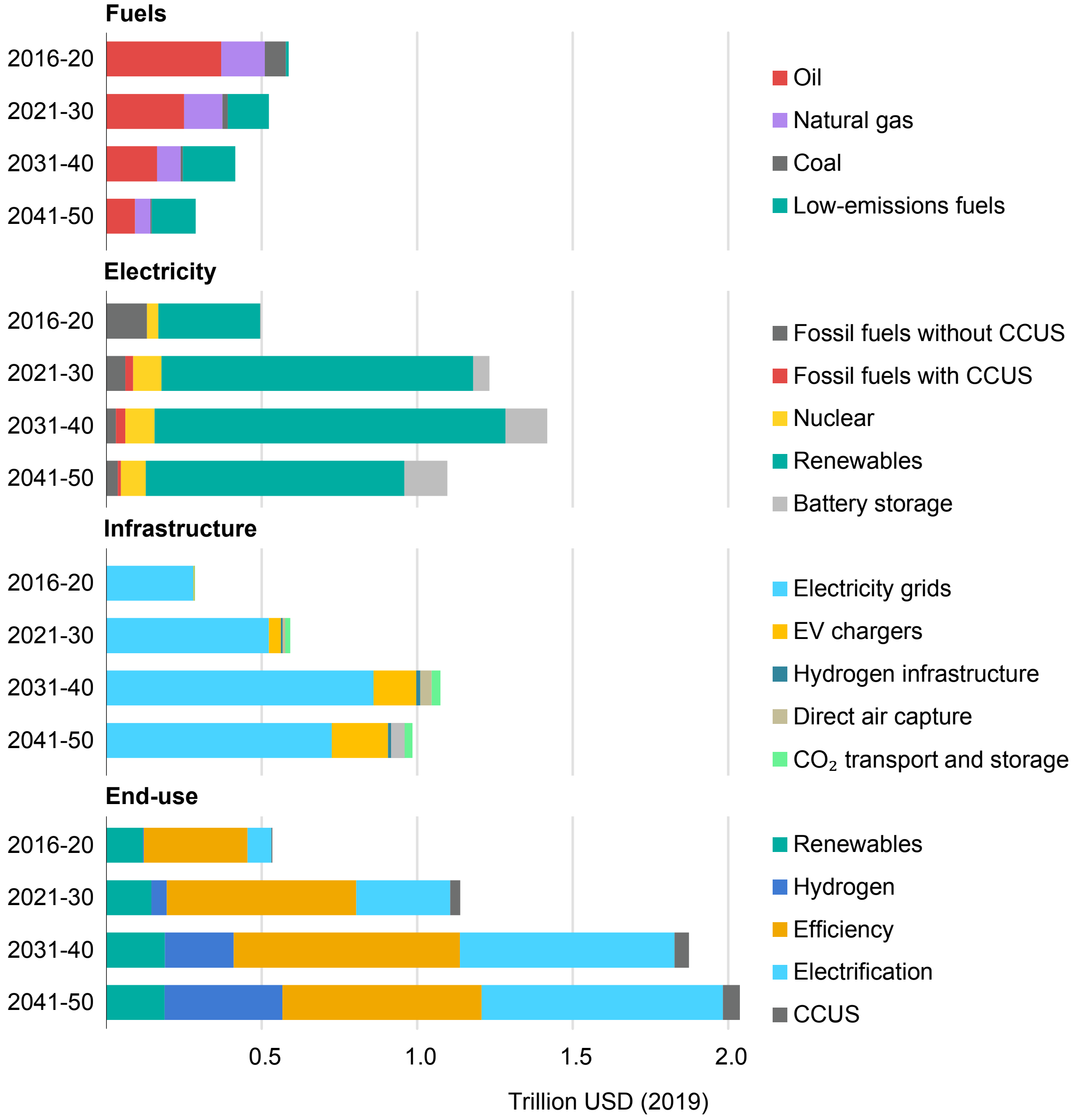
Continuing through to 2050, growing deployment of these currently available technologies contributes to a rapid reduction in the energy intensity of the economy. Total energy supply[1] in the NZE falls by 8% between 2020 and 2050, even as the economy grows by almost 150%. Substantially strengthened energy efficiency policies across all sectors are significant to decoupling energy demand from economic activity, while growing electrification of end-uses not only displaces fossil fuels but also leads to efficiency gains in cases where it is more efficient to use electricity rather than the prevailing fossil fuel-based technologies.

The NZE also requires a huge leap in energy innovation to reach its 2050 objective. Around half the emissions reductions to reach net zero emissions by 2050 come from technologies not currently in the market, and these new technologies become increasingly important after 2030. Electrolyser capacity to produce hydrogen needs to reach 850 GW by 2030, which is nearly eight times more than the capacity in the pipeline today. Advanced battery designs to electrify heavy-duty trucks, short distance ships and short flights are currently in the prototype stage today and need to make rapid progress. Carbon removal technologies such as DAC and BECCS, which help offset residual emissions, also need to scale up significantly. In the NZE, innovation for these clean energy technologies accelerates at an unprecedented pace over the next three decades.

The development and deployment of existing and new technologies results in a transformation in the composition of energy supply in the NZE. From slightly more than 10% today, the share of renewables in total energy supply rises to two-thirds by 2050. The share of fossil fuels declines from four-fifths today to slightly more than one-fifth of total energy supply by 2050.

[1] The terms total primary energy supply (TPES) or total primary energy demand (TPED) have been renamed as total energy supply (TES) in accordance with the International Recommendations for Energy Statistics.

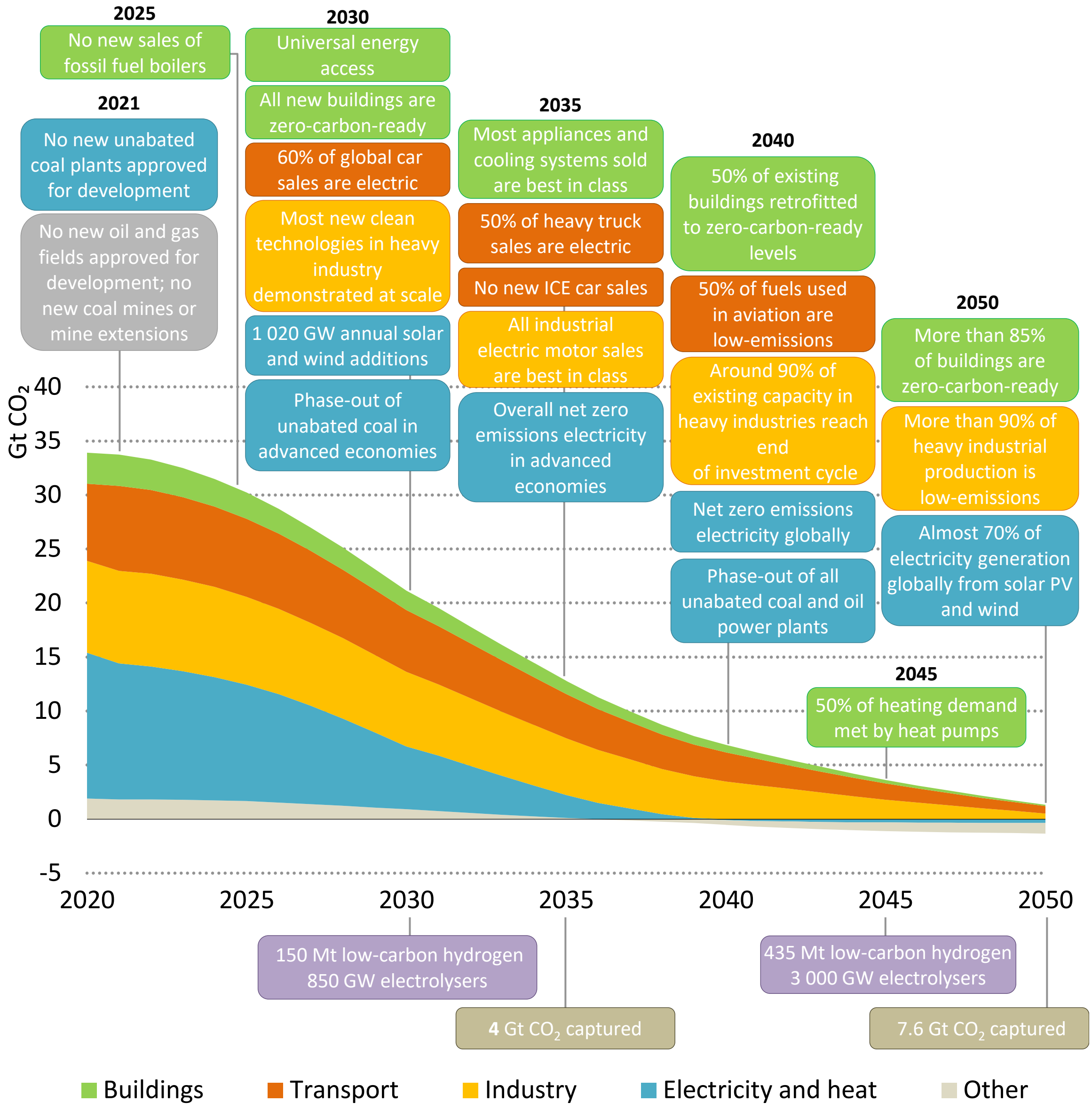
Energy sector investment in the Net Zero Emissions by 2050 Scenario



Investment in the energy system grows significantly in the NZE, and its composition shifts towards low-emissions technologies and energy efficiency. Total energy sector investment increases from about USD 2 trillion today to almost USD 5 trillion by 2030. The electricity sector is the primary driver of this investment surge. By 2030, about USD 1.3 trillion is invested in renewables, surpassing the USD 1.2 trillion peak investment in fossil fuels in 2014. Investment in clean power and electricity networks more than triples by 2030, reflecting growth in variable renewables and rising electricity demand. After 2035, total investment in the energy sector in the NZE peaks and starts to decline. This is because the electricity sector has been largely decarbonised by this point. Investment efforts then shift towards end-uses, which absorb more than USD 2 trillion of capital by the 2040s.

The changes to technology and investment radically alter the energy workforce, which numbers around 40 million today. The NZE sees the creation of around 14 million new jobs in electricity and low-carbon fuels sectors. However, around 5 million jobs are lost in fossil fuels, over half of these in the coal mining sector, and others in oil and gas, particularly in upstream exploration. It will be vital to minimise the hardships associated with these disruptions, for example, by providing retraining to those who lose their jobs, and by encouraging and incentivising locating new clean energy facilities in areas heavily affected by job losses whenever possible.

Key global energy milestones in the Net Zero Emissions by 2050 Scenario



Long-term policy frameworks that track implementation against short-term and mid-term milestones are important to build clarity and confidence for the private sector, which will provide the largest share of the investment required in the NZE. The IEA's NZE scenario details more than 400 milestones that span energy technology innovation and deployment, energy supply and consumption and policy implementation. Key milestones include the deployment of 150 million tonnes of low-emissions hydrogen by 2030, the capture of around 4 Gt of emissions by 2035, and a rise in the percentage of new truck sales accounted for by electric vehicles to 50% by 2035.

Achieving global net zero emissions by 2050 requires a substantial increase in international cooperation in a wide array of fields. Greater coordination of technology innovation efforts, including technology demonstration, is essential to bring key technologies like hydrogen in industry, advanced biofuels, and carbon capture, utilisation and storage (CCUS) to commercial maturity. Financing and technology assistance is similarly essential to speed up the diffusion of new technologies outwards from the initial inventors and adopters. Without the co-operation assumed in the NZE, the initial deployment of key technologies could be delayed by 5-10 years in advanced economies and by 10-15 years in emerging market and developing economies. This could result in both decades of delay to the transition to net zero emissions and in significantly higher cumulative emissions.

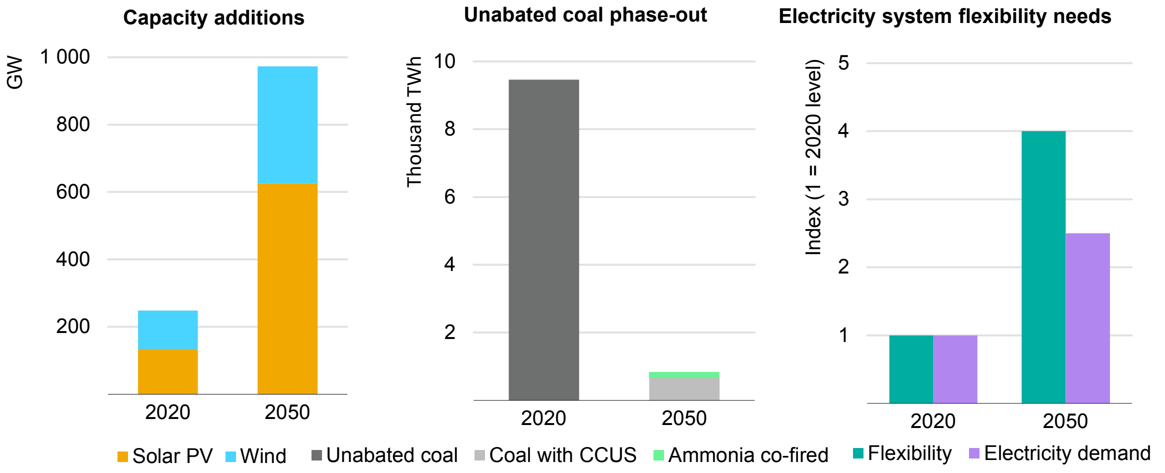
Getting to global net zero electricity

Electricity leads the transition to net zero energy in the NZE. Emissions decline from about 12.3 Gt today to 5.1 Gt by 2030, an average rate of decline of more than 700 Mt per year. By 2035, advanced economies in aggregate achieve net zero emissions from electricity, and all other countries do so by 2040. Global emissions from the electricity sector then become negative in the 2040s with the deployment of BECCS. By 2050, the electricity sector is responsible for net carbon dioxide removal of around 370 Mt CO_2.

Accelerated deployment of low-emissions sources of electricity drive the decline in electricity sector CO_2 emissions. Wind and solar PV lead the way due to low technology costs, policy support and widespread availability. Wind and solar PV capacity additions grow more than fourfold from today's level, surpassing 1 000 GW by 2030. This matches the scale-up from achievements made by the wind and solar industries during the last decade, although the last decade's expansion occurred from a lower base. Total renewables capacity passes 10 000 GW by 2030, more than triple the 2020 level, complemented by over 500 GW of nuclear power and around 80 GW of fossil-fuelled power plants equipped with carbon capture.

By 2030, wind and solar reach 40% of total world electricity generation, approaching the highest national penetrations of wind and solar achieved anywhere in 2020. By 2050, wind and solar account for around 70% of total generation, and total installed capacity reaches around 23 TW, almost triple total global installed power capacity from all sources today.

Key drivers of electricity sector transitions in the Net Zero Emissions by 2050 Scenario



Unabated coal-fired generation declines rapidly on the path to net zero emissions by 2050. In the NZE, no new unabated coal-fired plants are approved from 2021. By 2030, total unabated coal-fired generation is reduced by around 70% from the level in 2020 and the oldest, subcritical plants are fully phased out, with 870 GW coming offline by that date. By 2040, unabated coal-fired generation falls to zero.

Existing coal-fired power plants can contribute to clean energy transitions if they are retrofitted with carbon capture technologies or converted to co-fire with low-carbon ammonia. In the NZE, the deployment of coal-fired CCUS is proportionally small relative to the size of the total global coal fleet today, with just over 50 GW of capacity fitted with CCUS in 2030. Although this is a substantial increase from today's level, it represents only 4% of the installed coal-fired capacity in 2030. The use of ammonia in some coal-fired power plants, first through co-firing in modest ratios and eventually through conversion to 100% ammonia, enables those plants to continue supporting grid stability and reliability while reducing emissions. By 2050, coal accounts for less than 1% of total generation, and all remaining coal-fired capacity is fitted with CCUS.

Hydro and nuclear power, both mature low-emissions technologies, expand in the NZE, and each broadly maintains its current share of generation. Hydropower output nearly doubles from 2020 to 2050, broadly in line with overall electricity demand growth, providing system benefits as a flexible, low-emissions source of dispatchable capacity. Achieving this growth requires speeding up hydro expansion, including pumped hydro facilities, to significantly above the recent rate of capacity additions. Nuclear power also roughly doubles by 2050, with capacity additions in countries that remain open to the technology, and lifetime extensions for existing reactors, particularly in advanced economies.

Hydrogen and ammonia make inroads in the electricity sector as well as in other sectors. Total electricity generation from hydrogen reaches almost 1 600 TWh by 2050, which is only slightly less than wind today. While electricity generation from hydrogen and ammonia represent less than 3% of total electricity generation in 2050, that figure is higher in some regions with lower renewables availability. Hydrogen and ammonia also provide important low-emissions sources of firm capacity in an electricity system dominated by variable renewables, and their contribution to electricity system flexibility in 2050 is almost six times larger than their contribution to total generation.

Rising shares of variable renewables in electricity generation means that system flexibility must grow rapidly in order to maintain electricity security. While electricity generation grows to more than twice its current level by 2050, the demand for electricity system flexibility increases fourfold.[2] The sources of flexibility are also transformed in the NZE. Conventional fossil fuel based plants currently provide about two-thirds of electricity system flexibility services, with hydro providing almost all of the rest. In the NZE, the share of hydro and fossil fuel plants in flexibility services falls to less than a third by 2050, and there is a significant ramp up in flexibility services from other sources, notably batteries, demand response, dispatchable renewables like bioenergy and concentrating solar power (CSP), advanced nuclear plants including small modular reactors, and hydrogen and ammonia.

[2] Electricity system flexibility is quantified here based on hour-to-hour ramping needs, which is only one aspect of flexibility that also includes actions on much shorter time scales to maintain frequency and other ancillary services.

Transformation of the electricity sector in G7 members

Summary and policy recommendations

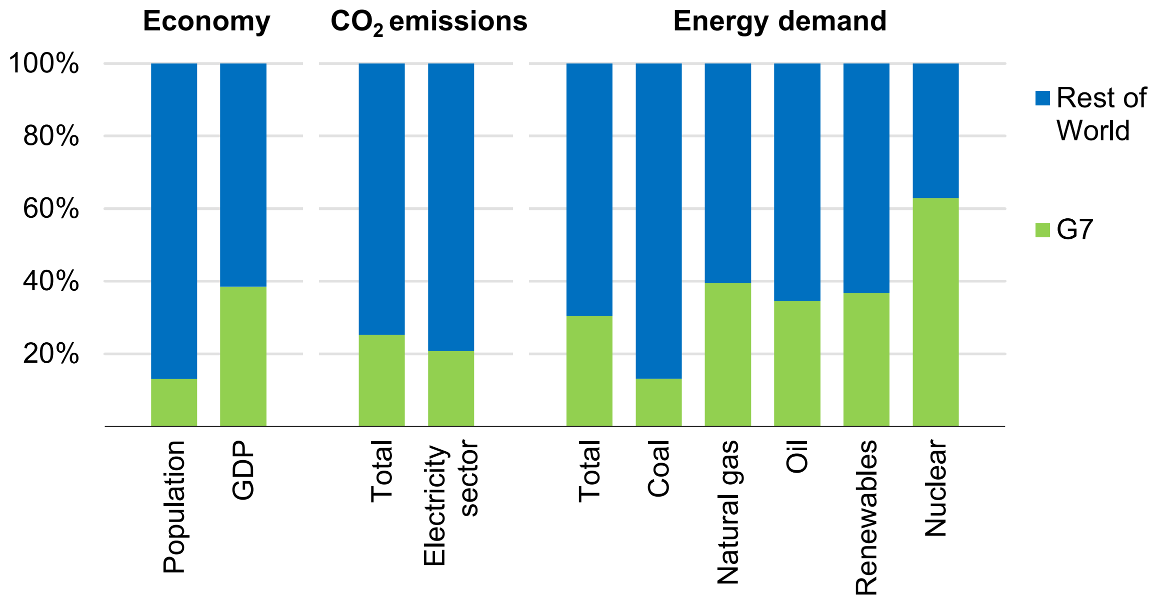
- G7 members – Canada, France, Germany, Italy, Japan, the United Kingdom, the United States plus the European Union – accounted in 2020 for about 40% of the global economy, 30% of global energy demand and 25% of global energy-related CO_2 emissions, including 2.7 Gt from their electricity sectors. Coal once dominated the electricity mix in the G7, but its use peaked years ago for G7 members, together with total electricity sector CO_2 emissions. The primary causes of these reductions in recent years were cheap natural gas in several markets and strong growth for renewables. In 2020, natural gas and renewables are the primary sources of electricity in the G7, with about 30% each of the total, followed by nuclear power and coal with close to 20% each.
- All G7 members have committed to reach net zero emissions, underpinned by a range of policy measures and targets that aim to phase out or reduce unabated coal-fired power while increasing the use of renewables, hydrogen and ammonia and carbon capture technologies, among other things. Over USD 500 billion of government funds have been committed by G7 members collectively to clean energy to boost sustainable recoveries from the Covid-19 pandemic, about 17% of which is for the electricity sector. G7 members have also pioneered carbon pricing mechanisms and continue to apply these to support the decarbonisation of electricity.
- G7 electricity demand rises over 80% in the NZE to over 14 600 TWh in 2050, marking a sharp break from the last decade of stagnation. Rapid electrification of mobility, heat and industrial processes increases demand by over 7 500 TWh to 2050, pushing the share of electricity in final energy demand from 22% today to around 55% in 2050. Electrification of the passenger car fleet and hydrogen production have the biggest impact, and heat pumps come to dominate the provision of heating in buildings. Growing economic activity adds another 6 500 TWh to demand to 2050, but is more than offset by efficiency savings, with the efficiency of key products sold doubling between today and 2030 in the NZE, in line with the targets of the Super-Efficient Appliance Deployment initiative.
- The G7 has an opportunity to lead energy transitions by collectively achieving net zero electricity emissions by 2035. Phasing out unabated coal by 2030 is the central pillar, which means no approvals for new unabated coal plants from 2021, retrofitting existing plants to co-fire biomass or low-carbon ammonia or add carbon capture equipment, and retiring any plants that are not retrofitted. Driving down the share of unabated natural gas-fired generation in the G7 to just 2% by

2035 is also critical (compared with nearly 25% in the IEA's Stated Policies Scenario in the World Energy Outlook 2021. On the path to net zero electricity, renewables reach 60% of electricity supply by 2030 in the G7 (compared with 48% under the Stated Policies Scenario, with wind and solar PV capacity additions rising from about 75 GW in 2020 to 230 GW by 2030. Nuclear power, low-carbon hydrogen and ammonia, and plants equipped with carbon capture add to the low-emissions electricity supply to varying degrees.

- The rapid growth of renewables provides an opportunity for the G7 to take the lead in demonstrating that electricity systems with 100% renewables during specific periods of the year can be secure and affordable. From 2020 to 2050, hour-to-hour flexibility needs to roughly triple in the G7 on the path to net zero, due to higher shares of variable renewables and changing demand patterns. The composition of flexibility sources also shifts dramatically from unabated coal and natural gas today to demand response and battery storage in the long term, with hydropower an important source throughout. Robust electricity grids are essential to support transitions and benefit from all sources of flexibility to maintain electricity security.
- The G7 also can lead by example in accelerating the pace of innovation. Mature technologies like hydropower and light-water nuclear reactors contribute only about 15% of electricity sector emissions reductions in the G7 by 2050. In the NZE, over 55% of reductions come from deploying technologies that are currently in either the steady scale-up phase (for example, onshore wind and crystalline silicon PV cells) or the early adoption phase (for example, solar thermal, coal with carbon capture, large-scale heat pumps, ultra-high voltage transmission, demand response and battery storage). Technologies that today are still in the demonstration or prototype phase (for example, floating offshore wind, carbon capture technologies for natural gas or biomass, and hydrogen and ammonia) become increasingly important over time, and they contribute up to 30% of overall electricity sector reductions by 2050.
- International cooperation within the G7 and with other countries is important, especially in the form of knowledge sharing and the coordination of development and demonstration efforts. Such cooperation could bring technologies to market more quickly, unlocking emissions reductions and opening new markets. As it has done for nuclear power, solar PV, onshore wind and fixed-bottom offshore wind, the G7 could lead the development of floating offshore wind, and also of hydrogen and ammonia use in power plants. Digitalisation would also benefit from international cooperation, not least to scale up available demand-side flexibility and to address cyber security issues. Policymakers can help level the playing field for all sources of flexibility, facilitate consumer engagement, develop standards and protocols for data exchanges, and coordinate planning to ensure investments made in grids and other infrastructure help to unlock the benefits of digitalisation.

The members of the G7 – Canada, France, Germany, Italy, Japan, the United Kingdom and the United States, together with the European Union – represent some of the world's most advanced economies. In 2020, the G7 accounted for nearly 40% of the global economy, around 30% of global energy demand and 25% of global energy-related CO_2 emissions. G7 electricity generation produced 2.7 Gt CO_2 of emissions in 2020, over 20% of the global total from electricity. G7 members are responsible for a significant portion of global demand for and production of fossil fuels, including some major exporters and importers, but they are also leaders in the development and deployment of renewable energy, energy efficiency and, in many cases, of nuclear power too.

G7 share of key global economic and energy indicators, 2020

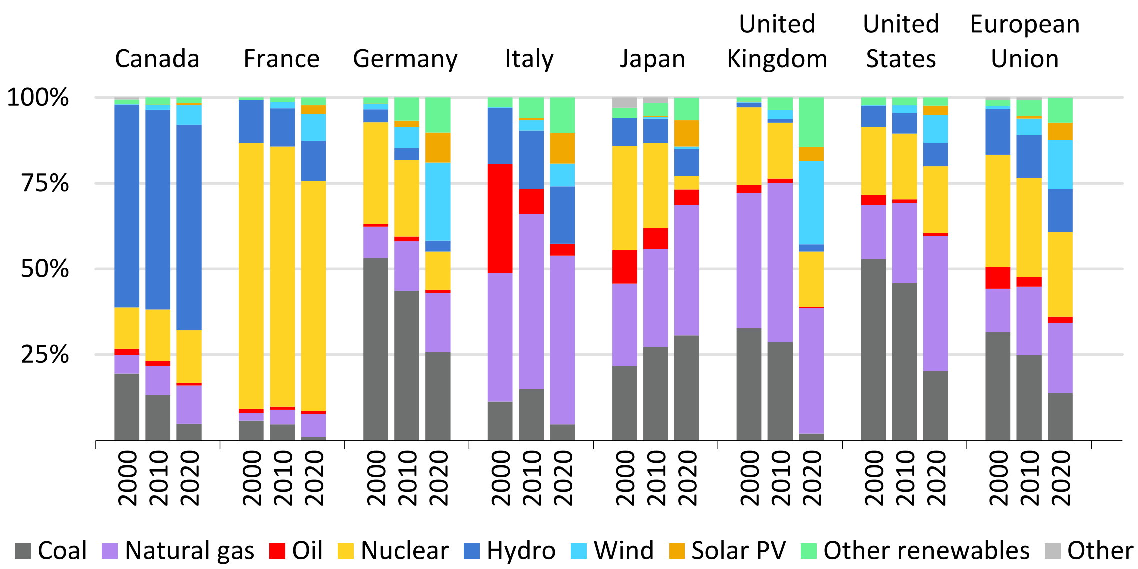


Electricity supply in the G7 has been in transition over the past two decades. Renewables deployment has been on the rise, with wind and solar PV becoming established across the G7 through continued policy support and falling technology costs. In terms of global installed combined wind and solar PV capacity, the United States was second (to China), Germany third, Japan fifth, the United Kingdom seventh, Italy eighth, France tenth and Canada fourteenth as of 2020[1]. Recent growth has added to long-established hydropower facilities, most notably in Canada's electricity mix. G7 members have also long been the leaders in nuclear power, and many plan to continue its use for decades to come. However, the

[1] The European Union in total would be second after China.

accident at Fukushima Daiichi in Japan in 2011 had direct impacts to nuclear operations and on the consideration of nuclear's long-term future, including on decisions to phase out nuclear power in Germany by 2022 and to reduce the share of nuclear to 50% in France by 2035. Natural gas-fired generation has risen since the year 2000, with the availability of cheap natural gas increasing dramatically in the United States in particular. Cheap gas, coupled with carbon pricing in some markets and other environmental policies, has contributed to a gradual reduction in coal-fired generation in most of the G7.

Share of electricity generation by G7 and source, 2000, 2010 and 2020

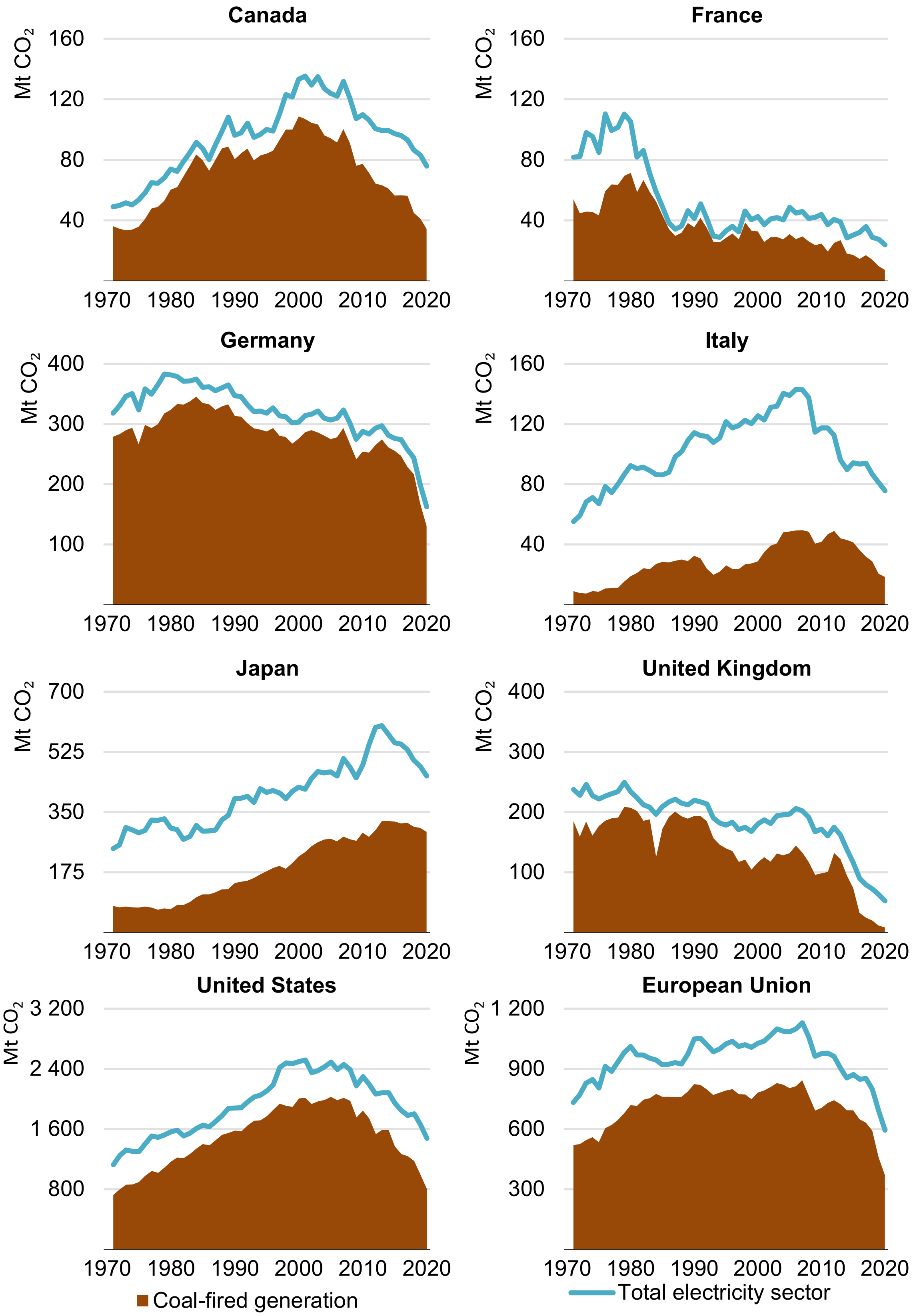


Coal once dominated the electricity mix in the G7 with its use peaking at 13 EJ in 2005, providing 38% of generation in that year. Coal-fired generation CO_2 emissions peaked in France in 1976, Germany in 1984 and the United Kingdom in 1987, where nuclear expansion played a key role. The switch to natural gas-fired generation was central to coal peaking in Canada in 2001, the European Union in 2007, and the United States in 2005. Italy tapped wind and solar PV as well as natural gas to help reach its coal peak in 2012. In Japan, coal use peaked in 2013, rising alongside other fuels to replace sharply reduced nuclear power output following the events of 2011 before starting to decline.

Total electricity sector CO_2 emissions peaked in the G7 in 2007 ahead of the global financial crisis and were 40% below the 2020 level. Electricity sector emissions peaked in France, Germany and the United Kingdom before 1980, in Canada, the United States, Italy and the European Union in the 2000s, and in Japan in 2013.

Electricity sector CO_2 emissions reductions were strongly linked with declining coal-fired generation, but also reflected the introduction of policies such the as the Carbon Price Support in Great Britain and stricter emissions regulations such as the Industrial Emissions Directive in the European Union. All G7 members now have plans in place to phase out or reduce unabated coal use in electricity and to end new direct government support for international unabated coal power generation.

Historical CO_2 emissions from coal-fired generation and the electricity sector in the G7



Current policy landscape in the G7

All G7 members have made net zero emissions commitments over the last two years which are now enshrined in law or are going through a legislative process. These individual commitments build on the collective commitment of the Paris Agreement in 2015 and acknowledge the growing scientific consensus on the urgent need to address global climate change. At the G7 Climate and Environment Ministers' Meeting in May 2021, the G7 also committed to "take concrete steps towards an absolute end to new direct government support for unabated international thermal coal power generation by the end of 2021" and to "work to abate related emissions towards overwhelmingly decarbonised power systems in the 2030s".

An overview of key policies in the G7 shows a range of electricity-related targets and measures that put G7 members on a path towards net zero electricity emissions by 2050 while also maintaining the security and affordability of electricity. In addition to renewable energy, nuclear power and carbon capture technologies are set to play a role in achieving net zero electricity. Some G7 members have also identified policy targets for hydrogen and ammonia co-firing to help reduce emissions from electricity generation.

At least USD 13.5 trillion has been committed to date in G7 government fiscal packages over the next decade, including USD 1.3 trillion from the EU, according to the IEA's Sustainable Recovery Tracker. This includes USD 510 billion for clean energy measures, of which about 17% has been set aside for power generation and improvements in electricity networks. On average, about USD 8.8 billion per year will be spent by G7 members plus the EU on the electricity sector over the next decade.

G7 members have also pioneered the development and implementation of carbon pricing mechanisms and applied them to the electricity sector. Carbon prices in the G7 in 2020 ranged from USD 2.60 per tonne of CO_2 (tCO_2) to USD 52 per tCO_2 where they were being used, though higher prices of as much as USD 135 per tCO_2 by 2030 are expected in some markets. The European Union Emissions Trading Scheme (EU ETS) was established in 2005 and was the first international emissions trading system. France, Germany and Italy participate in the EU ETS. The United Kingdom has instituted a national ETS in place of its participation in the EU ETS, and has a top-up tax on power plants of roughly USD 25 per tCO_2. In the United States, sub-national cap-and-trade programmes for CO_2 emissions were first established in 2005 and now include 11 states under the Regional Greenhouse Gas Initiative plus California's Cap-and-Trade programme. Canada has a federal carbon price and Quebec was the first province to establish a carbon price in 2007, while the first city-level ETS in Asia was set up in Tokyo in 2010. Discussions are now taking place about tightening the emissions cap in the EU under the 'Europe Fit for 55' package released in July 2021 and about the proposed Clean Electricity Standard in the United States Congress.

Key emission reduction targets and selected energy-related recovery plans in the G7

Member	Emissions reduction targets	Electricity emissions targets	Selected energy-related recovery plans
Canada	Net zero emissions by 2050 (in law) 40-45% GHG reductions below 2005 levels by 2030 (NDC)	90% non-emitting electricity generation by 2030	Nearly CAD 18 billion for green recovery
France	Net zero emissions by 2050 (in law) 40% GHG reductions by 2030 from 1990 levels (NDC)*	Virtually carbon-free electricity sector by 2050	EUR 7 billion for green infrastructure and mobility EUR 5.3 billion for green energy technologies
Germany	Net zero emissions by 2045 (in law) 65% GHG emissions reduction by 2030 from 1990 levels (NDC)*	108 million Mt cap for power plant emissions by 2030	EUR 9 billion for hydrogen
Italy	Net zero emissions by 2050 (in policy document) 55% GHG emissions reduction by 2030 from 1990 levels (NDC)*	(none)	EUR 5.9 billion for renewables EUR 4.1 billion for electricity networks EUR 3.2 billion for hydrogen
Japan	Net zero emissions by 2050 46% GHG emissions reduction by 2030 from 2013 levels**	(none)	JPY 73.6 trillion new stimulus package, including JPY 2 trillion for green technologies
United Kingdom	Net zero emissions by 2050 (in law) At least 68% reduction in GHG emissions by 2030 (NDC), and 78% by 2035 (in law), compared to 1990 levels	(none)	GBP 12 billion stimulus package
United States	Net zero emissions by 2050 (proposed) 50-52% GHG emissions reduction below 2005 levels by 2030 (NDC)	100% carbon pollution-free electricity by 2035 (NDC)	USD 1.2 trillion infrastructure plan
European Union	Net zero emissions by 2050 (in law) 55% in GHG emissions reduction by 2030 from 1990 levels (NDC)	(none)	EUR 2 billion to scale up the use of renewable energy EUR 0.7 billion for sustainable transport

Notes: *The EU has a target of at least 55% in GHG emissions reduction by 2030 compared to 1990 levels. **This has been announced at the Leaders' Summit on Climate on 22 April 2021. NDCs = Nationally Determined Contributions.

Selected electricity sector policies in G7 members

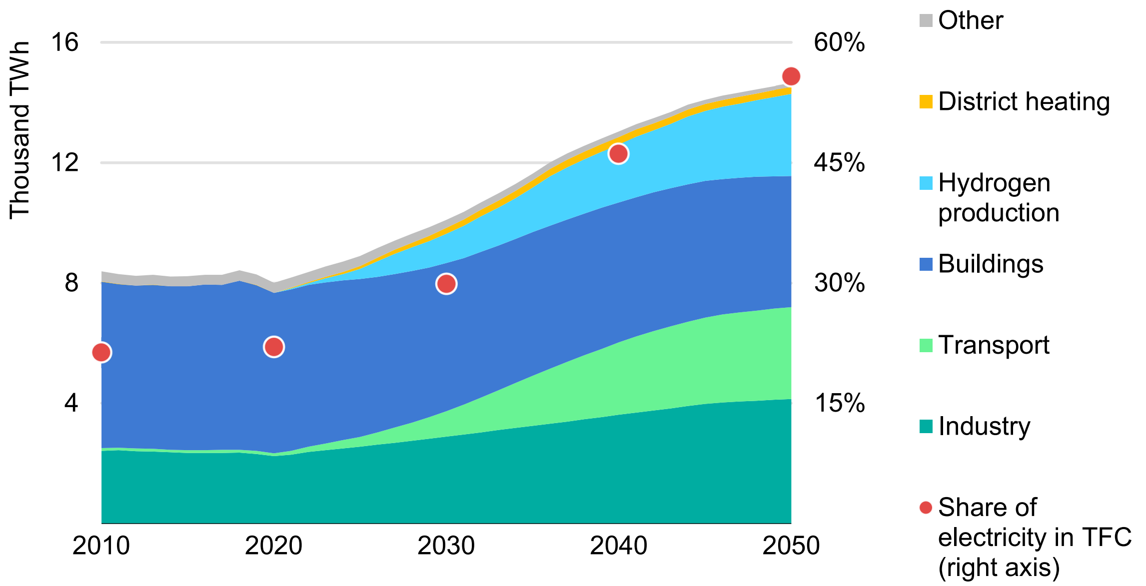
Member	Renewables	Nuclear power	Unabated fossil fuels	Hydrogen, ammonia and CO_2 capture technologies
Canada	Policy targets by province	SMR Action Plan including provinces working to deploy first commercial SMR by 2030	Phase out conventional coal-fired plants by 2030	Proposed Investment Tax Credit for CCUS Federal and state funding for Boundary Dam Carbon Capture project
France	40% renewables share of generation by 2030	Reduce nuclear share of generation to 50% by 2035	Phase out coal-fired plants by 2022	6.5 GW electrolyser capacity by 2030
Germany	65% renewables share of electricity consumption by 2030	Phase out nuclear power plants by 2022	Phase out coal-fired plants by 2038	5 GW electrolyser capacity by 2030 and another 5 GW by 2040
Italy	55% renewables share of generation by 2030 50 GW solar PV capacity by 2030	(none)	Phase out coal-fired plants by 2025	5 GW electrolyser capacity by 2030
Japan*	36-38% renewables share of generation by 2030	20-22% nuclear share of generation by 2030	Reduce coal share of generation to 19% and natural gas share to 20% by 2030	1% hydrogen and ammonia generation by 2030
United Kingdom	40 GW offshore wind capacity by 2030 of which 1 GW to be floating offshore wind	At least one large-scale nuclear project with FID status by 2024	Phase out unabated coal-fired plants by 2024	5 GW low-carbon hydrogen production capacity by 2030 Support at least one CCUS power project deployed by 2030
United States	30 GW offshore wind capacity by 2030 Reduce costs of solar by 60% to USD 0.02/kWh by 2030	Tax credits (state-level and national production credits)	(none)	Expanded tax credits and R&D programme for CCUS Reduce cost of clean hydrogen by 80% to USD 1/kg in one decade
European Union	40% renewables share of gross final consumption by 2030 (proposed) 60 GW offshore wind capacity by 2030, 300 GW by 2050	(none)	End EIB financing for all unabated fossil fuel projects by end-2021	6 GW electrolyser capacity by 2024, 40 GW by 2030 Produce 1 million tonnes of renewable hydrogen by 2024, 10 million tonnes by 2030

Notes: SMR = Small Modular Reactors; CCUS = Carbon capture utilisation and storage; EIB = European Investment Bank; FID = Final Investment Decision. *Based on draft 6th Strategic Energy Plan (not official as of August 2021).

Electricity demand

Electricity demand in the G7 has remained broadly constant between 8 200 TWh and 8 400 TWh over the last decade before dropping to 8 000 TWh in 2020. The effects of growing electrification have yet to be seen at scale, and energy efficiency improvements have thus far largely offset the impacts of increasing economic activity and digitalisation. Rapid electrification of mobility, heating and industry in the NZE tilts the balance toward demand growth, adding over 7 000 TWh to G7 demand by 2050, in addition to an increase of almost 7 000 TWh from expanding economic activity, including the rapid growth of hydrogen production. Although efficiency improvements offset about 7 300 TWh of this growth, demand exceeds 14 600 TWh by 2050, an increase of almost 80% on today's levels.

G7 electricity demand by sector and share of electricity in final energy consumption in the Net Zero Emissions by 2050 Scenario, 2010-2050



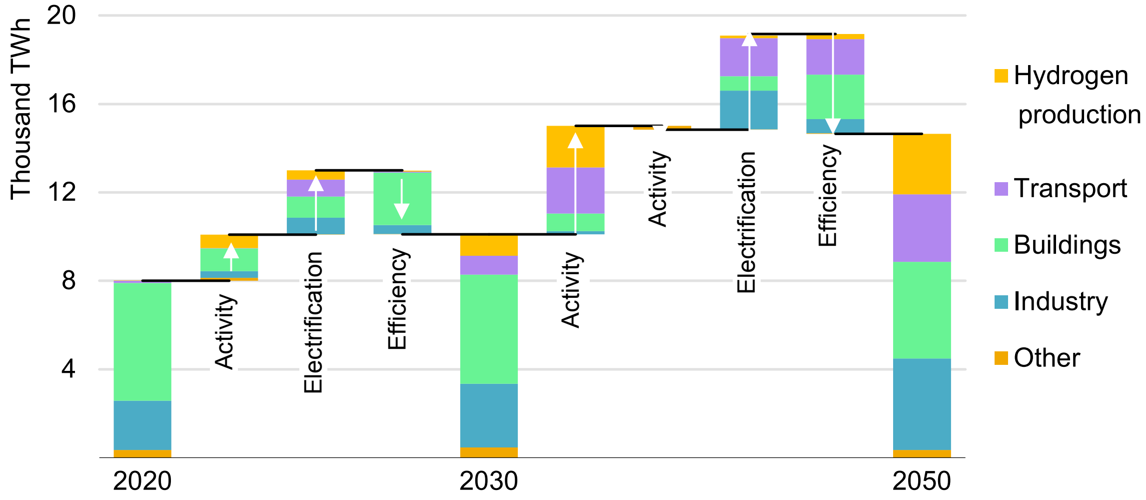
Notes: Other includes electricity demand from the agriculture sector and energy transformation sectors excluding district heat and hydrogen production; TFC = total final consumption.

Between 2010 and 2019, electricity demand fell in four of the seven G7 member states and the European Union. Across the G7, demand declined by 1% by 2019 and then fell a further 3% in 2020 because of the Covid-19 pandemic and related economic impacts. Declines in demand pre-Covid-19 largely reflect energy efficiency improvements: efficiency savings over the past two decades have reduced electricity demand by around 20% across advanced economies, efficiency improvements in industry and appliances have especially impacted the G7. Stagnant electricity demand also reflected instances of electricity-to-gas switching induced by low natural gas prices, particularly in the United States. The impact of electrification of end-uses previously powered by other fuels has meanwhile been marginal so far. As a result, per capita electricity demand across the G7 fell almost 10% from 8 600 kWh in 2010 to less than 7 900 kWh in 2020, while the average electricity demand intensity of GDP declined by 15% over the same period. This mirrors trends in G7 final energy demand, with final demand per capita also falling 10% from 2010 to 2020, and the GDP energy intensity dropping 15%.

Electrification

The growing electrification of energy end-uses in the NZE raises G7 electricity demand in 2030 by almost 3 000 TWh compared with the 2020 level, and in 2050 by over 7 000 TWh. This increase is 1 900 TWh higher in 2030 and 5 000 TWh higher in 2050 than in the IEA's Stated Policies Scenario. The biggest contributors to this growth are transport and the electrification of industrial processes. The impact of electrification is also particularly marked in buildings, where electricity meets over 70% of energy demand by 2050. By 2050, the share of electricity in final G7 energy demand rises to 55%, compared to only 22% today. Annual electricity demand per capita is expected to approach 10 000 kWh by 2030 and exceed 14 000 kWh by 2050.

G7 electricity demand by sector and change in demand by measure in the Net Zero Emissions by 2050 Scenario, 2020-2050



Note: Other includes electricity demand from the agriculture sector and energy transformation sectors, excluding hydrogen production, other own use and transmission and distribution losses.

Transport

Electric vehicles account for less than 1% of the passenger car stock in the G7 today, yet almost 5% of new car sales are electric models. In the NZE, the electrification of passenger cars accelerates, and electric vehicles represent almost 80% of new car sales by 2030. With no new internal combustion engine car sales by 2035 in the NZE, electric cars account for 90% of the G7 car stock by 2050, and fuel cell vehicles for most of the remainder. This leads to an additional 140 million electric cars by 2030 and a further 270 million by 2050. These increase electricity demand by 350 TWh in 2030 and a further 700 TWh in 2050, accounting for 16% of total demand growth through 2050. Electrification of passenger cars alone drives a 1 000 kWh increase in per capita electricity demand in 2050.

Long-distance heavy trucks are more difficult to electrify than passenger cars or other light duty vehicles. Technology improvements and investment in charging infrastructure nonetheless mean that 45% of the heavy trucks sold in the NZE are electric by 2030. By 2030, electricity demand for trucks in the G7 exceeds 180 TWh, and this increases to 850 TWh by 2050. By 2050, two-thirds of G7 road transport is electrified, accounting for almost 2 600 TWh of electricity demand, or more than double the total combined electricity demand of Germany, France and Italy today. Railways also see significant change: they are almost fully electrified or converted to hydrogen by 2050, with the share of demand met by electricity growing from one-quarter in 2020 to 90% in 2050.

Industry

Electricity increases its share of G7 industry energy demand in the NZE from 22% today to 50% by 2050. High temperature heat needs complicate the electrification of industry energy demand, while competitiveness concerns leave little room for industrial actors to absorb the additional costs of investing in low-emissions technologies currently under development. Nonetheless, there are many opportunities for industrial electrification, and the G7 leads the way in the NZE.

Heavy industry accounts for almost three-quarters of industrial energy demand in the G7 today, and electricity demand from heavy industry sectors rises to over 2 100 TWh by 2050. This is double today's level of demand and results in electricity meeting over half of total industrial energy demand. Electricity already provides 55% of energy needs for aluminium production in the G7, and this rises to 85% by 2050 as auxiliary process heat is electrified or decarbonised with hydrogen or biogases. Greater recycling rates and increased use of electric arc furnaces also allow electricity to meet over 70% of iron and steel energy demand by 2050, up from less than 20% today. The NZE assumes significant research and development (R&D) spending and government support for pilot plants and processes, which ensures that electric technologies are ready when current industrial plants are refurbished or replaced.

Low temperature heat needs are increasingly electrified in the NZE, with electricity meeting 20% of heat needs below 200°C by 2030 and more than 50% by 2050. The NZE sees improvements in heat pump performance at higher temperatures that follow increased R&D spending over the coming decade. These allow heat pumps to also make inroads into higher temperature heat needs by 2050. The electrification of process heat increases industry electricity demand to 160 TWh by 2030 and 420 TWh by 2050.

Hydrogen moves to the centre of the energy system in the NZE. Most hydrogen production in the G7 today is produced in-situ using fossil fuels without carbon capture. There is a rapid shift in the NZE to low-emissions options, by the end of the decade, electrolysis accounts for more than half of hydrogen produced (60 Mt in 2030 rising to almost 160 Mt in 2050), and fossil fuels with CCUS for the remainder. This shift requires nearly 600 GW of merchant electrolyser capacity in 2050, which increases G7 electricity demand by 2 700 TWh. Half of the hydrogen produced is used for transport in 2050, 30% for electricity generation, and the remainder in industry and buildings.

Building heating

Fossil fuels meet 70% of the demand for heat in buildings across the G7 today. In the NZE, bans on sales of new fossil fuel boilers are introduced globally in 2025, and the share of fossil fuels in building heating falls below 1% by 2050. Boilers continue to be sold only where fuel supply is fully decarbonised via hydrogen, biomethane or other low-carbon alternatives. Electrification is, however, the most suitable decarbonisation option in most contexts. Using electricity in place of fossil fuels for space heating, water heating and cooking requires a rapid switch to the most efficient electric technologies, including heat pumps for space and water heating and induction cooktops. Electrification of building heat in the NZE increases electricity's share of heating energy demand from 15% today to 36% by 2050.

The stock of heat pumps in residential and services buildings increases to 110 million units by 2030 and approaches 170 million by 2050. By 2050, electric heat pumps and heaters account for two-thirds of heating in residential buildings in the G7. Heat pumps can be three to four times more efficient than non-electric alternatives, and this mitigates the impact of electrification on electricity demand. Concurrent improvements in building envelope energy performance further reduce energy demand for heating, while also improving heat pump performance. As a result, electricity demand for building heating in 2050 is 250 TWh (or 30%) lower than it is today. Without efficiency improvements, electricity demand would be more than 1 200 TWh higher in 2050.

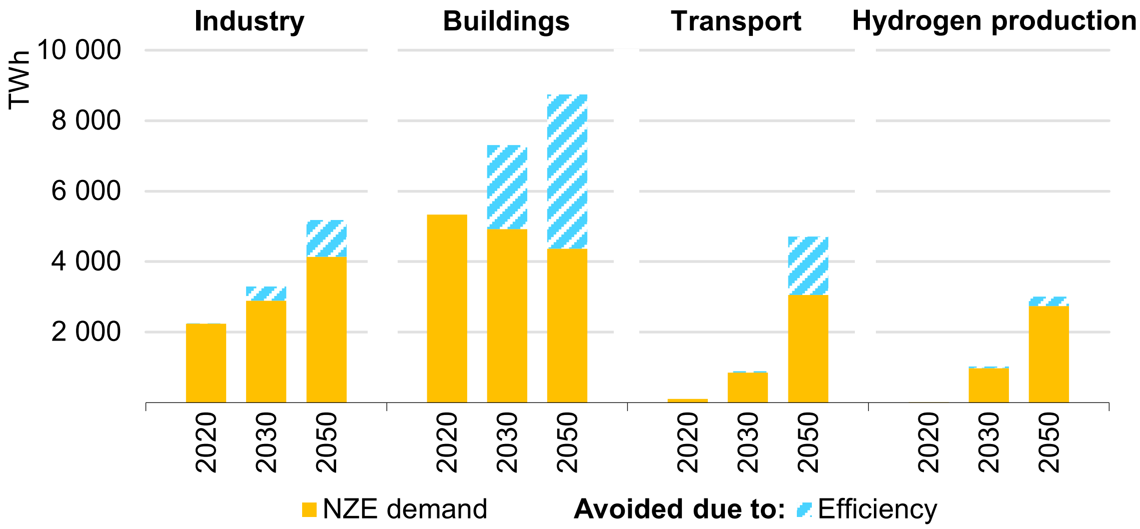
Energy efficiency

Energy efficiency is critical to electricity sector decarbonisation, mitigating the impacts of electrification on electricity demand and reducing costs for businesses and households. G7 members are at the forefront of energy efficiency progress today because of their robust policy frameworks, standards and incentives to improve the efficiency of electricity use. The NZE sees governments build on this strong foundation and increase the stringency of standards while filling gaps in coverage. By 2030, almost all major appliances sold in the G7 are at least as efficient as the most efficient technologies available on the market today. This is in line with the target to double the energy efficiency of key products by 2030 outlined in the target of SEAD and the UK and IEA-led Product Efficiency Call to Action for COP26 and beyond that was recently endorsed by the G7. Without the efficiency improvements factored into the NZE, electricity demand in the G7 would be 30% or almost 3 000 TWh higher in 2030, and 50% higher in 2050.

The largest electricity demand savings come from the buildings sector, where from 2025 all new buildings are zero-carbon-ready[2] and all lights sold are light-emitting diodes (LEDs). Improvements from household appliances and air conditioners contribute the most to efficiency savings, avoiding over 450 TWh of electricity demand in 2030 and over 1 600 TWh in 2050. Energy efficiency improvements in building envelopes and equipment performance such as heat pumps contribute close to 1 000 TWh of further avoided demand by 2050.

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

G7 electricity demand by sector and avoided demand due to energy efficiency in the Net Zero Emissions by 2050 Scenario, 2020, 2030 and 2050



Energy efficiency improvements are required across all industry processes and subsectors in the NZE, but a switch to the most efficient electric motors and motor systems delivers one of the biggest electricity demand savings, cutting demand in 2050 by 250 TWh. Efficiency standards in the NZE require all new motors sold to be best in class by 2035 at the latest: this takes time to translate into the entire stock of motors, but 80% of the G7 motor stock is best in class by 2050, compared to less than 1% today. Given the rapid scale-up of electrolyser use for hydrogen production in the NZE, improvements in the average efficiency of electrolysers also have a major impact on electricity demand. In the NZE, electrolyser conversion efficiency increases from 65% today to 75% in 2050, and this reduces electricity demand for hydrogen production in the G7 by 270 TWh in 2050.

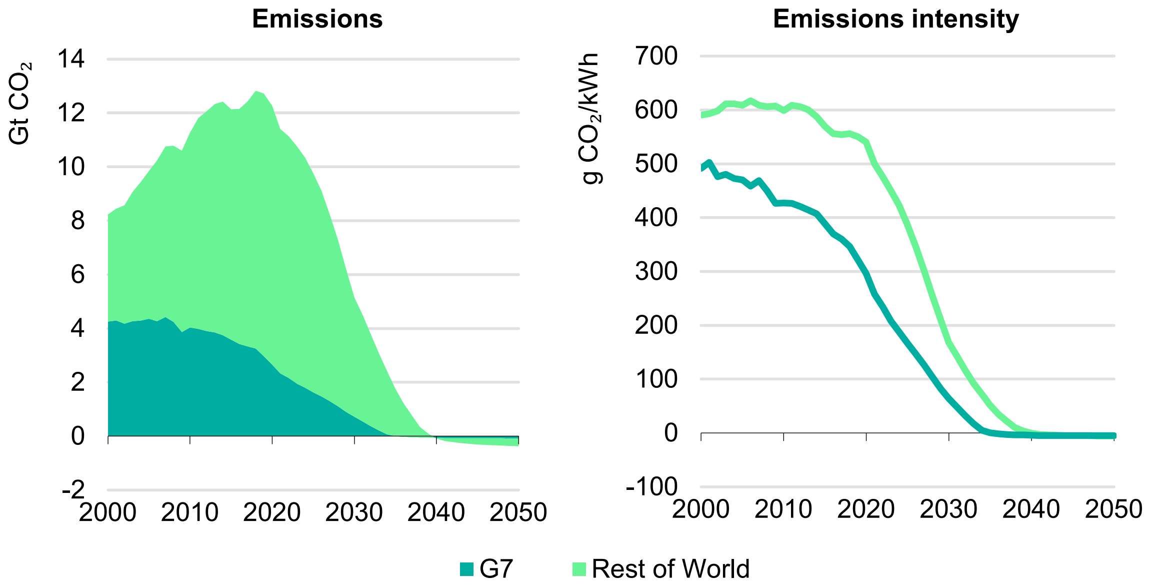
Electricity supply

G7 members have already taken a variety of steps to reduce their electricity emissions. They are positioned now to lead efforts around the world to go further and faster in decarbonising the electricity sector by accelerating their shift away from unabated coal-fired electricity generation while expanding low-emissions sources of electricity generation.

CO_2 emissions from electricity generation

Electricity sectors in the G7 emitted 2.7 Gt of CO_2 in 2020, or over one-fifth of global electricity sector CO_2 emissions The level of G7 electricity emissions intensity currently stands at 297 g CO_2/kWh and is one-third lower than the global average. This is about 15% lower than the emissions intensity of high-efficiency natural gas-fired power plants and about 60% lower than that of efficient coal-fired power plants.

Electricity sector CO_2 emissions in the Net Zero Emissions by 2050 Scenario, 2000-2050



In the NZE, G7 members lead the way by reaching net zero CO_2 emissions in the electricity sector in aggregate by 2035, which is five years before net zero is reached globally in the electricity sector. The G7's electricity emissions intensity declines rapidly, falling below 100 g CO_2/kWh by the late 2020s, and total electricity sector CO_2 emissions decline from 2.7 Gt in 2020 to 0.7 Gt in 2030 before reaching net zero. This is a much steeper decrease than in the IEA Stated Policies Scenario in which emissions fall to 1.6 Gt in 2030, 1.3 Gt in 2035 and 0.9 Gt in 2050.

Over the next 15 years, the average annual rate of decline in G7 emissions is 0.16 Gt, or 6% of the current level, compared with an average reduction of 0.13 Gt per year since emissions peaked in 2007. While the annual rates of decline in emissions stay within a narrow range, challenges grow as net zero gets closer, calling for fundamental changes in the way electricity systems are operated and new technological solutions are implemented. Beyond 2035, achieving net negative CO_2 emissions in G7 electricity sectors contributes to reaching overall net zero energy emissions by 2050.

Electricity generation and capacity

Fossil fuels accounted for about 50% of G7 electricity generation in 2020, but this changes quickly in the NZE, with electricity generation from low-emissions sources[3] nearly tripling over the next 15 years to displace coal, natural gas and small amounts of oil. Renewables become the backbone of net zero electricity systems in the G7: their share of generation rises from 31% in 2020 to 60% by 2030 to over 80% by 2050, with the contribution of each renewable energy technology depending upon each country's available resources, topography and preferences. These shares are significantly higher than those projected in the IEA Stated Policies Scenario in which renewables reach 48% in 2030 and 67% in 2050.

Wind and solar PV rise from 14% of generation in 2020 up to 42% by 2030, and by the mid-2030s each technology contributes more than any other source. By 2050, wind and solar PV provide 66% of total generation. By 2030, wind surpasses natural gas and becomes the largest source of electricity generation, capturing over a quarter of generation. By 2050, it increases nine-fold from 2020 levels to provide 43% of generation. The G7 are well positioned to develop offshore wind, with high-quality resources available and 38% of the global near-shore technical potential,[4] and offshore wind accounts for over 40% of total wind generation by 2050. Solar PV becomes the second largest source of generation by the mid-2030s, and further rapid growth leads to it generating nearly a quarter of electricity by 2050. Hydropower is the largest renewable source of electricity in the G7 and the world today, and its output continues to grow, mostly because of the modernisation of existing infrastructure. Bioenergy, geothermal and CSP also contribute to clean energy transitions in the G7, providing dispatchable low-emissions sources of electricity.

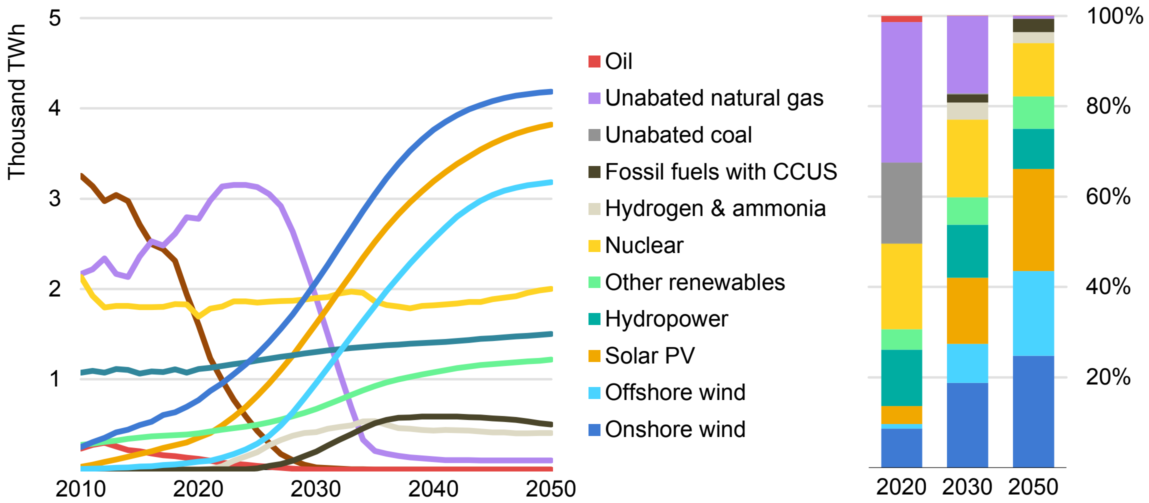
Based on our analysis in the Nuclear Power in a Clean Energy System report, the nuclear generation fleet in the G7 has prevented at least 50 Gt of CO_2 over the past fifty years, equivalent to over 1.5 years of global energy-related emissions. In the NZE, the share of nuclear power in electricity generation falls from 19% in

[3] This includes renewable sources, nuclear, fossil fuel power plants equipped with CCUS, and hydrogen and ammonia.
[4] We classify near-shore offshore wind technical potential as resource with up to 60 km to shore and with water depth of up to two km.

2020 to 12% in 2050 against a background of rapidly rising electricity demand and the retirement of many reactors. Nuclear power nonetheless continues to play a crucial role in reducing G7 emissions, in part through lifetime extensions for some of the existing nuclear fleet, and in part through the commercialisation of innovative technologies, such as the small modular reactors under development in several G7 countries.

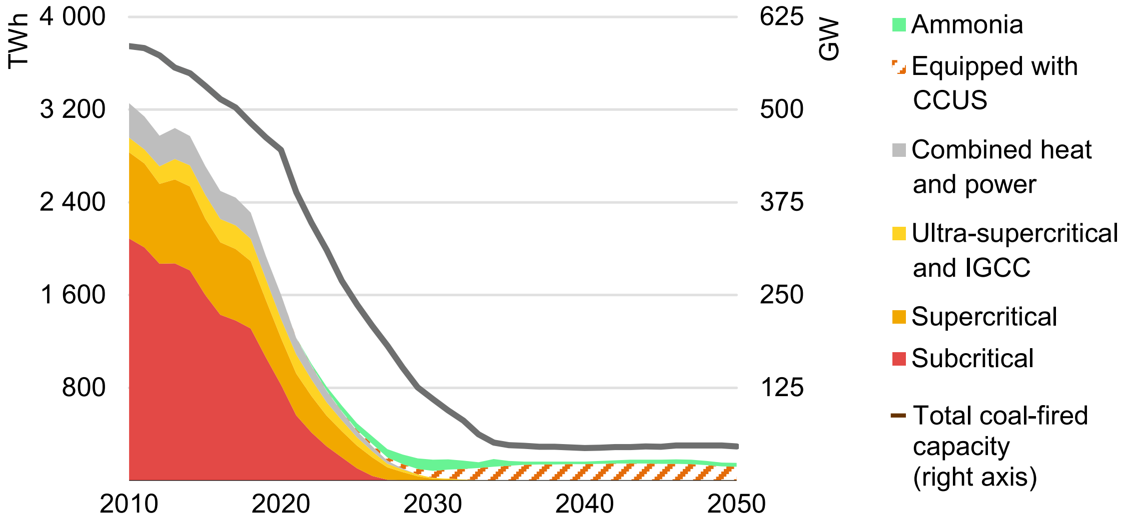
Small modular reactors, if successfully commercialised, could overcome some of the barriers that hinder large-scale nuclear deployment. Their advantages include scalable designs, lower upfront costs and the potential to improve the flexibility of nuclear power in terms of both operations and outputs such as electricity, heat or hydrogen. Successfully commercialising new nuclear technologies could offer new economic opportunities and lead to cost reductions and standardisation processes that could benefit other countries.

Electricity generation in the G7 by source in the Net Zero Emissions by 2050 Scenario, 2010-2050



Phasing out unabated coal-fired generation by 2030 is a critical milestone on the path to net zero electricity in the G7 because it is among the most carbon-intensive fuels in electricity generation and is still used extensively – it accounted for 56% of G7 electricity sector emissions in 2020. In the IEA Stated Policies Scenario, unabated coal is predicted to continue generating at least 122 TWh in the G7 through 2050. The G7 have acknowledged the need to phase out unabated coal, and have committed to end direct government support for unabated thermal coal power generation by the end of 2021. In the NZE, an ageing fleet of coal plants and rising CO_2 prices hasten coal's decline within the G7.

G7 electricity generation from coal-fired power plants by fuel and total coal-fired capacity in the Net Zero Emissions by 2050 Scenario, 2010-2050



Notes: CCUS = carbon capture, utilisation and storage; IGCC = integrated gasification combined cycle.

The phase out of CO_2 emissions from coal-fired power plants starts with closing the oldest and least efficient unabated plants, and then progresses to more efficient, supercritical designs. Reducing the amount of unabated coal-fired capacity in operation in the G7 calls for alternatives to help maintain supply security. Hence, not all coal plants are directly retired, and when they are retired the sites can be put to alternative uses (see Box). Furthermore, in the NZE, some facilities are repurposed to focus on flexibility services, while others are retrofitted to operate with CCUS or to co-fire biomass or ammonia. By the late 2020s, coal plants retrofitted with CCUS or co-fired with ammonia account in the G7 for over half of coal-fired generation and reach over 100 TWh per year. While this represents a relatively small amount of generation, proving the technology could help to facilitate deep emissions reductions in countries that are more reliant on younger coal-fired power plants.

Opportunities to make the best use of existing coal-fired power plants

The G7 had over 380 GW of coal-fired generation capacity online in 2020, most of it subcritical coal capacity. The average G7 coal power plant is over 35 years old, and about 230 GW of capacity will reach the end of its operational lifetime within the coming decade. At the same time, about 150 GW of the fleet could have 15 years or more of its operational lifetime ahead unless intervention of some kind alters the outlook. Repurposing or retrofitting newer plants could avoid stranding them, while also ensuring that they are compatible with the path to net zero electricity.

Repurposing existing coal power plants requires enhancing their capability to operate flexibly alongside wind and solar PV generation, thus shifting their role from bulk electricity generation to the provision of system services such as balancing, stability, reserve and system restoration. Since repurposed plants run less and consume less coal, this would greatly reduce emissions in the near term. However, it would only provide a short-term solution: the path to net zero emissions implies that they would need to close after 5-10 years.

Retrofitting existing coal power plants would involve reducing the emissions intensity of their electricity generation. Options could include direct capture of emissions, changes to combusted fuels, or a combination of the two. Power plants fitted with CCUS could capture more than 95% of CO_2 emissions: for some technologies, capture rates approach 100%. Another option is to convert existing coal power plants to co-fire biomass or ammonia. Full conversions with 100% ammonia or biomass firing could extend the plants operational life by decades.

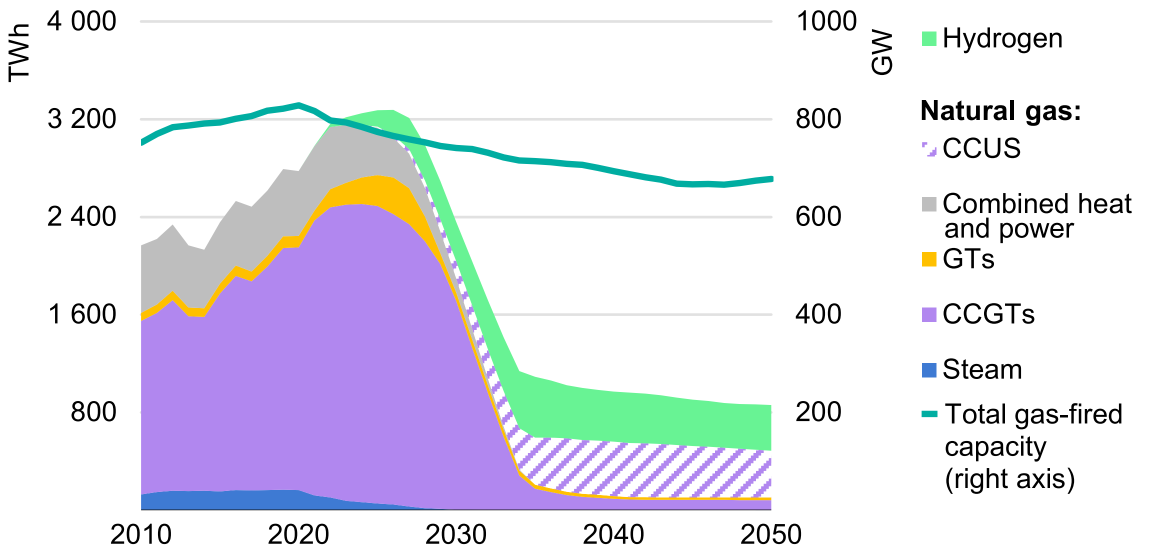
There are also other potential opportunities to convert the valuable infrastructure at existing coal power plant sites by deploying different forms of low-emissions generation, taking advantage of existing grid connections, land and approval procedures. For example, solar PV farms have been proposed at several locations, and a 200 MW capacity installation is now under development at the Navajo Power centre in the United States with potential to expand up to 750 MW over time. In addition to reduced land permit and project approval times, retired coal plants are an excellent location for new solar PV because many of the required transmission lines and connections are already in place, and because the environmental contamination typical of coal sites means that the land is often unsuitable for another use besides energy without substantial remediation efforts. Savings range by project, but could be up to a quarter of costs compared to new sites. Elsewhere in the United States, a recently retired coal plant is being converted into a 20 MW battery unit in a move that is the first of many planned, while there are plans to convert the former Moorburg coal plant in Germany into a 100 MW electrolyser for green hydrogen production in 2025.

Retired coal mines are also attracting renewed interest. Former German open-pit lignite mines could host up to 2.7 GW if fitted with floating solar PV panels. In the United States, a 400 MW solar PV installation has been approved in West Virginia on the site of abandoned coal mines. Coal mines also provide potential for multiple storage technologies: planned projects include a 600 MW pumped hydro project in Australia and gravity storage at locations in the United Kingdom.

Natural gas is the leading source of electricity in the G7 today, but generation is set to peak in 2023 and decline rapidly thereafter in the NZE. The share of unabated gas in the G7 electricity mix drops from 31% in 2020 to less than 2% in 2035 and stays below 1% from 2040 onwards. This contrasts with the outlook under the IEA's Stated Policies Scenario, where the share of unabated natural gas share in G7 generation is 24% in 2035 and nearly 20% in 2050. In the 2020s, gas-fired power plants are equipped in the NZE with CCUS or retrofitted to co-fire hydrogen, with gas CCUS generating nearly 400 TWh and hydrogen generating 500 TWh by 2035, enabling facilities to continue operating while cutting emissions.

G7 electricity generation from gas-fired power plants falls by over 80% in the NZE between 2020 and 2050. Despite this, gas-fired capacity remains relatively stable through to 2050 at around 700 GW. This reflects the changing role of gas-fired power plants, which generate less electricity as time goes by (average capacity factors fall from nearly 40% in 2020 to below 15% by 2050) but play an increasingly important role in providing system reserves and flexibility. Structural changes to electricity markets support the changing nature in the role of gas-fired generation, and lead to a higher value being placed on contributions to system adequacy and flexibility.

G7 electricity generation from gas-fired power plants by fuel and total gas-fired capacity in the Net Zero Emissions by 2050 Scenario, 2010-2050

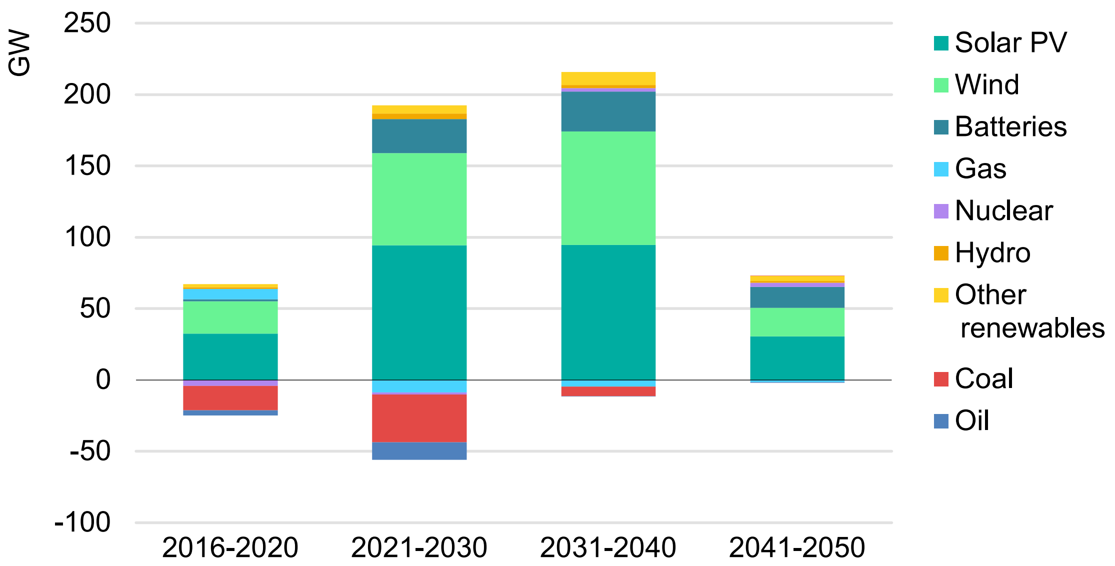


Note: CCUS = carbon capture, utilisation and storage; GTs = gas turbines; CCGTs = combined cycle gas turbines.

In the NZE, over 250 GW of capacity is added on average every year between 2021 and 2050, or four times the average level of annual capacity additions over the last five years. Wind and solar lead the way, as set out earlier in this section. In parallel, battery storage additions increase twenty-fold between today and 2030, reflecting its importance as a source of flexibility to balance variable renewables and its role in maximising the utilisation of grid assets.

Total installed generation capacity in the G7 increases by nearly 50% between 2020 and 2030. After 2035, the building of new low-emissions sources slows as unabated fossil fuels are almost completely displaced. The main requirement at this point is that new capacity keep pace with electricity demand growth. This leads to the pace of capacity additions for solar PV, wind, and battery storage declining by a one-quarter in the 2040s compared with the rate of the previous decade. Overall, renewables capacity more than quadruples between 2021 and 2050, with nearly 5 800 GW of capacity added during this period – an increase roughly equivalent to today's total capacity in China, Europe, India, North America and Japan combined.

G7 average annual net change in installed capacity by technology in the Net Zero Emissions by 2050 Scenario, 2016-2050



Note: Gas and coal capacity includes co-firing with hydrogen and ammonia respectively.

Shifting away from fossil fuels leads to rapid reductions in coal-fired capacity over the next decade, with annual G7 coal retirements peaking at 42 GW in the early 2020s and gradually decreasing thereafter. 390 GW of coal and 290 GW of gas-fired capacity are retired between 2021 and 2035 on the path to net zero electricity emissions. While G7 unabated coal plants are fully phased out by 2030, the retirement of gas-fired capacity is mostly offset by new additions to maintain electricity security and stability.

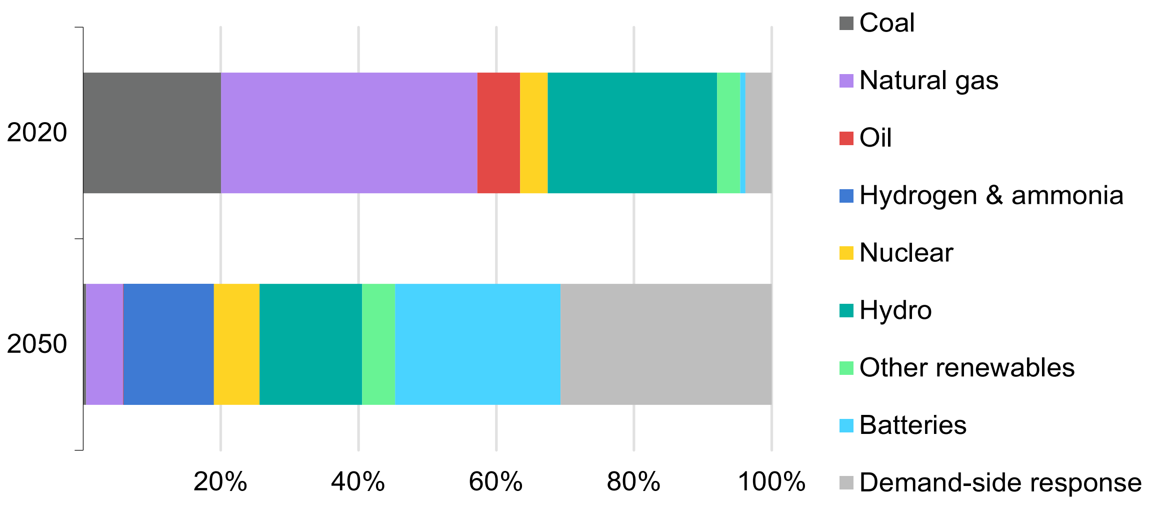
Electricity system flexibility in the G7

The transition to a predominantly wind and solar PV-based electricity system significantly increases flexibility needs. With wind and solar PV forming at least half the generation mix in most of the G7 by 2050, the ability to respond in a timely way to changes in variable generation becomes crucial. In the NZE, the need for hour-to-hour flexibility is roughly three times higher in 2050 than in 2020 (compared to doubling in Stated Policies Scenario. Strong demand for electrified heating or cooling could come at a time when wind and solar PV output is relatively low, for example. Alongside demand-side response (DSR), the amount of dispatchable capacity in the G7 increases in the NZE by almost 15%[5] by 2050 compared with 2020.

The composition of the sources of flexibility also shifts dramatically by 2050. Today, natural gas, coal and oil provide nearly two-thirds of hourly flexibility in G7 electricity systems, with hydro providing most of the rest. By 2050, flexibility needs to be provided predominantly by low-emission sources and DSR. In the NZE, more than half of the flexibility in 2050 is provided by either DSR (including electrolysers) or batteries, and natural gas and coal power plants contribute less than 10% of hour-to-hour flexibility.

[5] Excluding demand response.

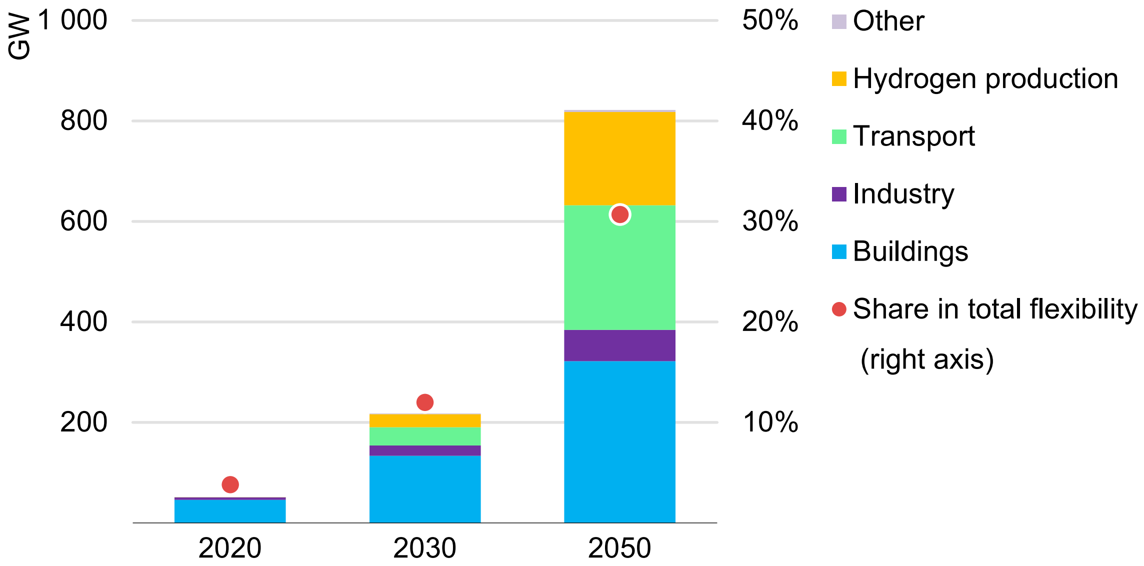
Electricity system flexibility by domestic source in the G7 at the Net Zero Emissions by 2050 Scenario, 2020 and 2050



DSR becomes the largest source of electricity system flexibility in the G7, providing more than 30% of power system flexibility needs by 2050. Less than 2% of the global potential for DSR flexibility is being utilised today, and DSR services are mostly provided by large electricity consumers responding to relatively rare critical system events. In the NZE, smaller and more decentralised end-users can provide DSR, which, with daily load shifting, opens new opportunities.

Tapping the wider potential for DSR requires policymakers to create a level playing field balance for demand-side resources in flexibility markets. It also requires them to facilitate the aggregation of loads by retailers and third parties and promote their participation in wholesale markets. In the NZE, Minimum Energy Performance Standards for appliances and equipment are expanded to include requirements for smart controls, allowing the buildings sector to provide over 130 GW of demand flexibility by 2030 at times of peak flexibility needs. Charger standards and attractive dynamic pricing plans incentivise smart charging of electric vehicles, and EVs emerge as the single largest source of flexible demand by 2030. Hydrogen electrolysis comes a close second in terms of providing demand-side flexibility during times of peak flexibility needs, with grid-connected merchant hydrogen producers increasingly adjusting production in line with wholesale electricity prices. Thanks to strong policy action and new business models, half of total electricity demand can be shifted to some extent by 2050 to provide flexibility when it's most needed.

G7 demand-side response availability at times of highest flexibility needs and share in total flexibility in the Net Zero Emissions by 2050 Scenario, 2020, 2030 and 2050



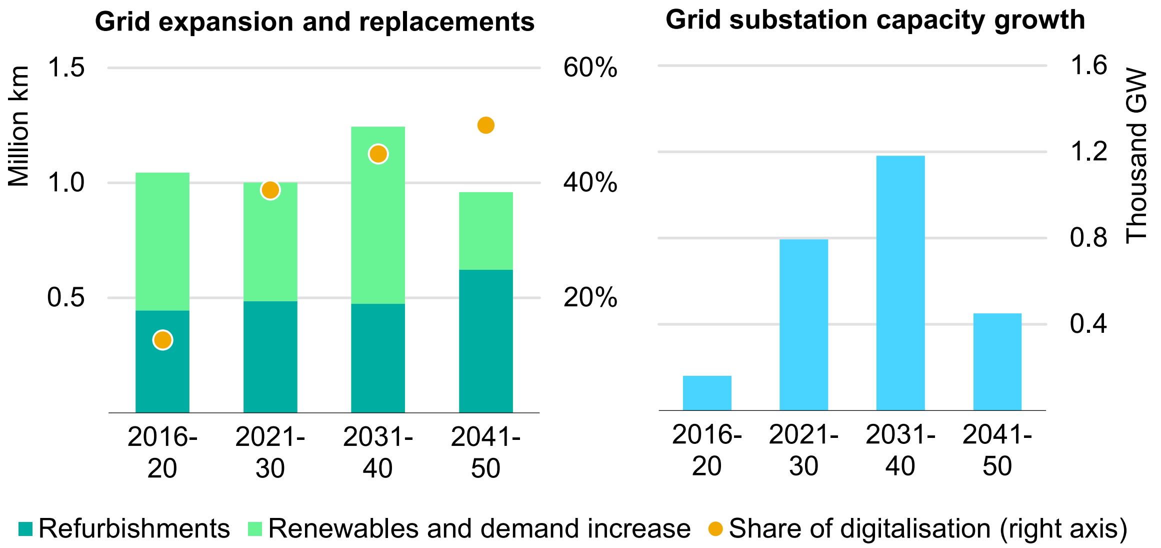
Market design is important for DSR and should ensure that flexibility is used where it has most value, as well as managing it in a way that avoids potential problems. For instance, a fleet of EVs provides flexibility to help balance supply and demand but could also generate sudden local peaks that might exceed local network capacity. Establishing coordination procedures between network and system operators at all voltage levels could be helpful.

The role of electricity networks

Electricity networks are crucial in ensuring generation resources are well-utilised and avoiding the congestion that can result in curtailment of wind and solar. Over the next three decades, the length of G7 electricity networks increases by nearly 70%, driven by increasing demand and the need to connect and integrate thousands of new renewable energy projects. The growth in total power generation capacity requires nearly tripling the electricity network substation capacity in the G7. Over the same period, millions of kilometres of transmission and distribution lines also need to be modernised.

The roll out of digital network solutions accounts for almost 50% of investment in networks in the 2040s, deferring or avoiding the need for costly network reinforcements. To incentivise investment in non-asset-based solutions, regulators are already looking to new regulatory regimes that go beyond traditional rate of return regulation. Examples of such regimes include Reforming the Energy Vision (REV) in the State of New York and the RIIO model in Great Britain.

Annual average G7 electricity grid expansion, replacement and substation capacity growth in the Net Zero Emissions by 2050 Scenario, 2016-2050



Interconnectivity within and between regions is an important source of flexibility because it creates larger markets that can draw on a wider range of resources, helping to smooth out weather patterns and balance electricity supply and demand. It enables flexible generation in one region to contribute to meeting the flexibility needs of another. The European Union has acknowledged the importance of interconnection and is considering setting a target for 15% of interconnection by 2030.[6] It has also set out a framework for cross border electricity balancing. One of the platforms that is being gradually developed as part of this framework is the Manually Activated Reserves Initiative (MARI), which trades frequency restoration and reserves services across 30 European transmission system operators. Offshore HVDC interconnectors could enable additional flexibility and provide system services such as dynamic frequency regulation.

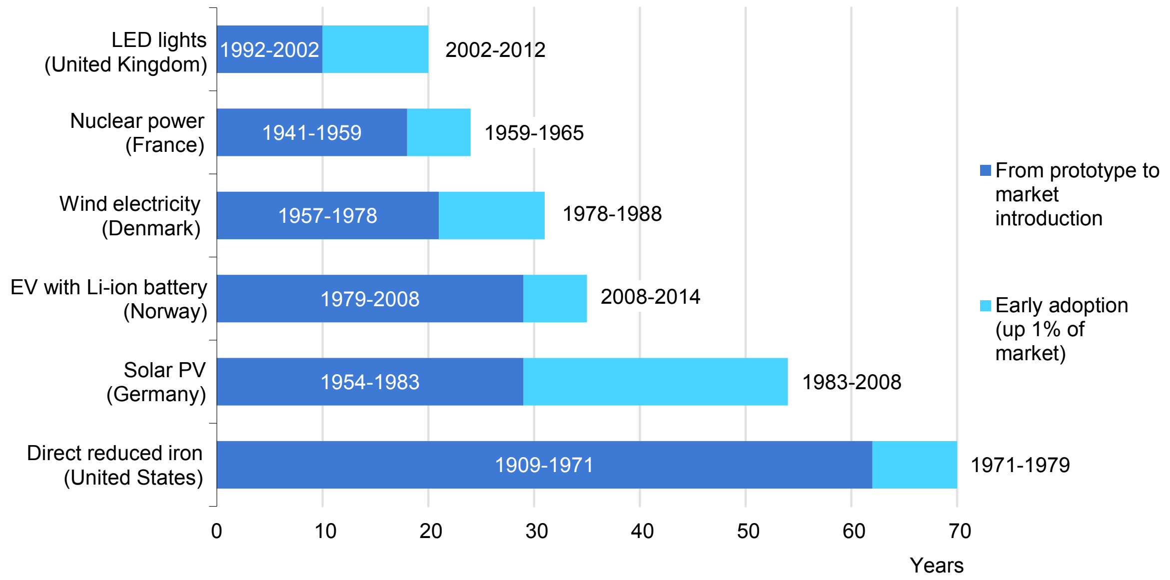
[6] Electricity interconnection targets are defined as import capacity over installed generation capacity in an EU country as explained here.

The role of innovation in achieving net zero electricity

Achieving net zero electricity emissions requires the use of a wide range of clean energy technologies in generation, transmission, distribution and operations of the electricity system. Some of the technologies needed are available and well established, while others are at an early stage of development, or exist only as prototypes. Over the next decade, significant progress is needed to bring these technologies to market at scale. Other technologies may emerge from current research work and could play important roles but are not likely to be developed quickly enough to make a significant impact by 2050.

Success will not be easy or straightforward. It depends upon technological innovation, and this takes time. Recent success stories in the electricity system – such as solar PV and the Li-ion batteries used to power electric vehicles – took almost 30 years to move from their first prototype to market introduction. It took a further 25 years for solar PV to achieve a 1% share of a national electricity supply market for the first time (in Spain, closely followed by Germany), although it took just 6 years for Li-ion battery-powered electric vehicles to achieve the same national market share for the first time (in Norway).

Prototype to market introduction and early adoption periods for selected energy technologies



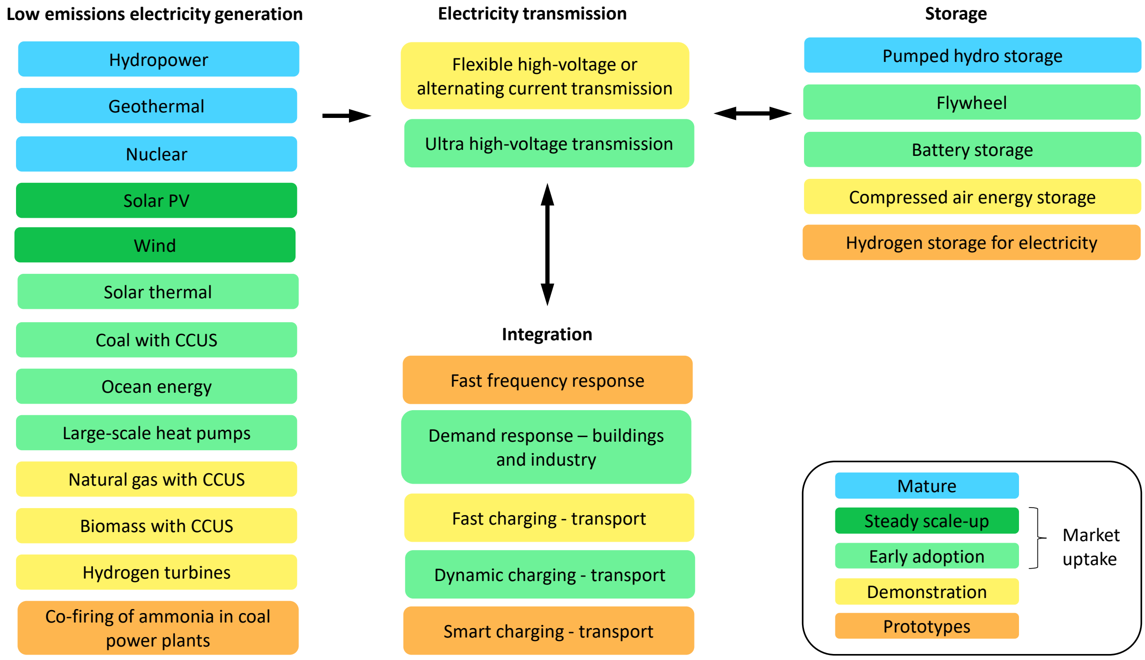
Note: Country designation applies to early adoption phase, which ends when reaching a market share of 1%.

Maturity levels of contributing technologies

A portfolio of technologies at different levels of maturity is needed to decarbonise the electricity system in the G7. These technologies can be classified under the headings of mature, market uptake, demonstration and prototype.

Mature. Several technologies being deployed in the NZE have reached maturity, such as those associated with hydropower and nuclear light-water reactors. Maturity does not preclude further incremental improvements through learning-by-doing. For example, the French company Framatome is now testing new accident-tolerant fuels (ATFs) at the Vogtle 2 nuclear station in the United States. ATFs involve new cladding and/or fuel pellet designs that could bring safety benefits to nuclear plants: they could also potentially extend the time between refuelling and reduce the amount of fuel needed.

Technology maturity along the technology value chain of electricity generation, networks and storage



Notes: CCUS = carbon capture, utilisation and storage. Each technology is assigned the highest technology readiness level of the underlying technology designs. For more detailed information on individual technology designs for each of these technologies, see:www.iea.org/articles/etp-clean-energy-technology-guide.

Market uptake. This covers technologies that are commercially available but require further efforts to lower their costs or integrate them into the electricity system. Technologies in this category can be further divided into steady scale-up and early adoption technologies. Steady scale-up refers to technologies that are competitive but need further integration into existing systems. Examples are crystalline silicon PV cells and onshore wind turbines. Early adoption refers to those technologies which are commercially available but need evolutionary improvements to be competitive. Coal-fired electricity generation with CCUS is an example in this category, and projects at two commercial coal power plants, Boundary Dam in Canada and Petra Nova in the United States. These illustrate how evolutionary improvements can come about: both plants have been retrofitted with CCUS, and both projects are providing critical information that could help bring about further cost reductions. A feasibility study based on the Boundary Dam data and costs indicate that capital costs would be about 70% lower for a second facility.

Demonstration. The first examples of new technologies are generally introduced to the market in the form at the size of a single full-scale commercial unit. The purpose is to demonstrate that the technology is effective and to reduce the perception of risk on the part of investors. Examples are compressed air energy storage, bioenergy-fired power plants with CCUS and floating offshore wind turbines (see case study below). Demonstration power plants with BECCS are currently running in the United Kingdom and Japan.

Prototype. Following its initial definition, a new concept is developed into a design and then a prototype for a new device, a new configuration of existing devices or a new component to improve a product on the market. The probability of success at this stage is low, but the costs per project are also generally low. Examples are wave energy converters and Perovskite solar cells, which use a non-silicon based thin-film PV technology capable of achieving higher efficiencies than silicon cells. The United Kingdom-based company Oxford PV is building a manufacturing plant for its tandem solar PV technology (combining a silicon solar PV cell with a Perovskite solar cell) in Germany, with an annual production capacity of 125 MW.

Case study: Unlocking the potential of floating offshore wind

Floating offshore wind is gaining momentum, providing vast opportunities to tap wind resources located in regions with water depths exceeding 50-60m and higher average wind speeds, where traditional fixed-bottom wind turbines are often considered economically unattractive. The G7 has an estimated total technical potential of over 31 000 TWh per year for offshore wind in deep waters (60-2000m) and near shore (20-60km), which is around 40% of the global technical potential assessed in the IEA Offshore Wind Outlook 2019.

The G7 accounts for around 80% of the global offshore wind generation today, and floating offshore wind projects in operation have demonstrated strong performance to date. The 30 MW Hywind Scotland project in the United Kingdom achieved an average 57% capacity factor over the twelve months to March 2021, for example. Even at demonstration level, floating offshore wind turbines have shown strong performance, including the 2 MW Floatgen turbine project in France and the 3 MW Hibiki barge-type project in Japan. Tenders and plans for licensing federal waters for floating offshore wind are now also in the pipeline for the Canada, France, Italy and the United States. These early-stage floating offshore wind projects put the G7 in a strong position to meet their individual offshore wind capacity targets. For example, the United Kingdom has set a target of installing 40 GW of offshore wind by 2030, of which 1 GW will be floating offshore wind.

Although floating offshore wind projects have demonstrated strong performance in electricity generation, there is significant potential for further cost reductions and for improving system designs. While early subsidy support has been crucial for projects including Hywind Scotland, a study by ORE Catapult suggests that floating offshore wind in the United Kingdom could be subsidy-free by 2030, and that the capital expenditure cost reduction potential of floating offshore wind in the United Kingdom could be as much as 65% from 2027 to 2040, driven by deployment and technological innovation in the long term.

The early success of floating offshore wind projects means that the G7 is well positioned to press ahead with wider deployment and to realise further cost reductions by scaling up project pipelines and technology innovation. Strong manufacturing capabilities in some G7 countries and policy and market experience are also assets for the future. Technological innovation to optimise mooring and anchoring systems and to stabilise floating turbines during extreme weather conditions would improve prospects further. Grid connections also remain an important priority so that electricity can be delivered to shore whilst minimising transmission losses. Floating offshore wind projects in operation today are at technology readiness level (TRL)[7] 6 on average, with more than half utilising the

[7] The framework provides a snapshot in time of the level of maturity of a given technology within a defined scale. More details can be found here.

semi-submersible floating foundation, and the industry is developing scalable floating substations to support commercial-scale floating offshore wind farms.

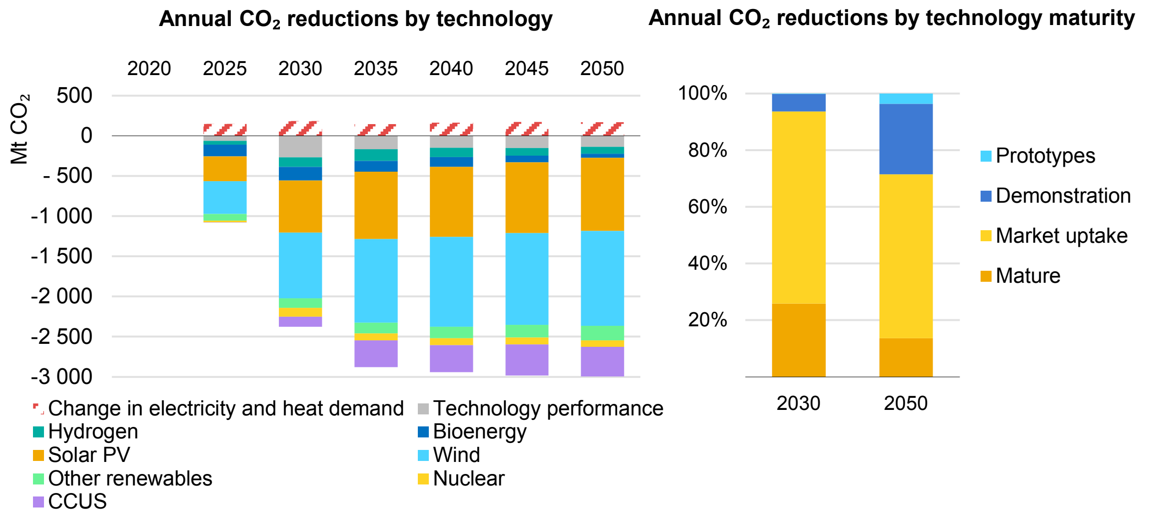
Floating offshore wind has great potential for further cost reductions driven by technological innovation, for example one study suggests that it could provide as much as one-third of offshore wind capacity in Europe by 2050. Clear government policies and investments in new technologies and large-scale floating offshore wind projects over the next decade are needed to make the most of its potential and open up opportunities in new markets around the world.

Contributions to emissions reductions by technology

Electricity was responsible in the G7 for emissions of 2.7 Gt in 2020, which is over one-fifth of global electricity emissions in that year. In the NZE, these G7 emissions are reduced by more than 70% by 2030, with wind and solar PV accounting for 60% of the reductions. When net zero for the electricity sector is reached in 2035 in the NZE, wind provides around 35% of the annual CO_2 reductions (relative to 2020), followed by solar PV with nearly 30%. All renewables combined are responsible for 75% of the CO_2 reductions, with CCUS providing 12% and nuclear a further 3%.

Emission reductions up to 2030 are largely achieved by technologies which are today either already mature (25%) or are in the phase of market uptake (almost 70%), which means that they are commercially available, but further cost reductions or integration efforts are needed. Relevant mature technologies in this context are nuclear and hydro power, while solar PV, wind and coal-fired power plants with CCUS are technologies in the market uptake. However, reaching net zero emissions in 2035 and achieving net negative emissions of -80 Mt CO_2 by 2050 depends to a greater extent on technologies which are today at demonstration or prototype stage: in the NZE, these technologies provide almost 30% of the G7's annual CO_2 emission reductions in the electricity sector by 2050. Examples of these technologies include power plants using natural gas or bioenergy together with CCUS, floating offshore wind turbines, co-firing of ammonia in coal power plants, hydrogen-fired gas turbines and more efficient solar PV cell designs.

Annual G7 CO_2 reductions in the electricity sector compared with 2020 in the Net Zero Emissions by 2050 Scenario, 2025-2050



Note: CCUS = carbon capture, utilisation and storage.

Bringing key technologies from prototype to market and scaling up deployment

Technological innovation is an uncertain process and takes time: it has taken decades for solar PV and batteries to reach their current stage of development. And not every technology that is developed will be successful: the evolution of existing and new technologies is inherently uncertain. Demonstrating new technologies at commercial scale involves more time, cost and risk than at the prototype stage, and it can be especially difficult for large-scale technologies to acquire the necessary funding. These challenges underline the importance of finding ways to innovate that are successful in bringing about rapid change.

Attributes of successful innovation

For low-emissions technologies in the electricity sector, successful innovation is often associated with the following attributes:

- **Small enough unit size to be mass produced:** small units can be prototyped and tested quickly, before building factories and starting mass production (examples: solar PV, batteries, fuel cells).
- **Modularity:** modular technologies can be standardised, which reduces costs during their production. The capacity of modular technologies can be sequentially expanded, which reduces investment risks (examples: solar PV, wind turbines, small modular reactors).

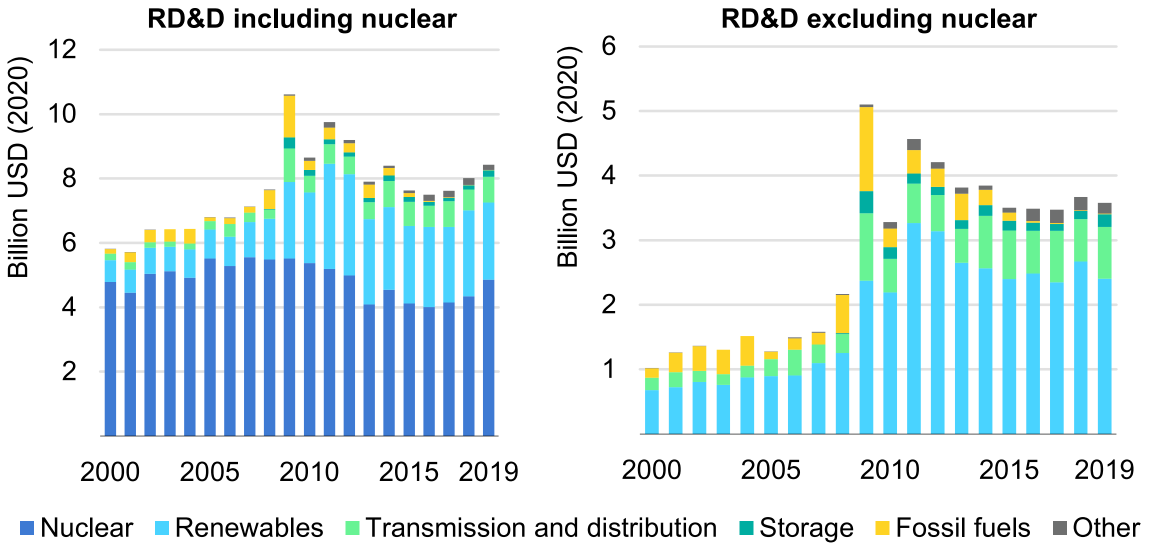
- **Potential spillovers and synergies with other technologies:** exploring similarities between technologies in different sectors and applications can reduce the need for separate R&D efforts (examples: spillovers between batteries, electrolysers, fuel cells; spillovers between oil/gas production and offshore wind foundations as well geothermal energy).
- **Minimal need for adaptation to local conditions:** technologies that do not need to be adapted to local conditions such as temperature can be more easily standardised and deployed in different parts of the world (examples: gas turbines, fuel cells).

Although these attributes offer no guarantee of success, they are worth consideration in the design of research, development and deployment (RD&D) programmes to bring technologies in the electricity sector from prototype to market, and in the development of strategies to accelerate the market uptake of low-emissions electricity technologies which are commercially available but not yet cost competitive.

Bringing technologies from prototype to market

Public and private RD&D is needed to develop new ideas and solutions in support of early-stage innovation in the electricity sector. Early-stage R&D should support a portfolio of competing designs which can be adjusted as more information from first prototypes and demonstrators becomes available. The sharing of knowledge that arises from publicly funded R&D helps to maximise its benefits. Demonstrating large-scale technologies, such as power plants with CCUS, new nuclear designs and floating offshore wind is capital-intensive, and public-private partnerships and international cooperation can reduce the risks for individual stakeholders.

Public RD&D spending for electricity generation, grids and storage in the G7



G7 members spent USD 8.4 billion of public RD&D in 2019 on electricity generation, transmission and distribution and on electrical storage technologies. After a spike in spending in 2009 as part of economic recovery packages to address the 2008 financial crisis and a decline in the following years, overall RD&D expenditures for electricity technologies have been relatively stable over the last five years, accounting for 40% of their collective total public energy RD&D spending. More than 55% of this funding was linked to nuclear power technologies: 28% was for renewable energy technologies, around 10% to transmission and distribution and 2% to storage technologies. Spending on fossil fuel combustion technologies, accounting in 2009 for 15% of electricity-related RD&D, has dropped to almost zero by 2019 (0.1%).

While still dominant today, spending on nuclear technologies has declined in absolute and relative terms since 2005, when it accounted for more than 80% of electricity sector-related RD&D spending, before increasing again in recent years, driven in particular by the United Kingdom and the United States. Annual expenditures on renewable power technologies in the G7 reached a peak in 2011 in absolute terms and declined by 2019 by 25% as technologies like solar PV reached the market and became widely commercially available. Electrical storage accounted in 2019 only for 2% of public RD&D expenditure, but in absolute terms its funding has grown rapidly, alone in 2019 by 55% compared with 2018, potentially reflecting an increasing focus on system integration as variable renewables account for a growing proportion of electricity generation.

Strengthening markets for technologies at an early stage of adoption

Several of the low-emissions technologies needed to decarbonise the electricity system are already commercially available today but require further cost reductions or performance improvements to compete with existing technologies. Market-pull policies can stimulate the demand for low-emissions technologies, triggering cost reductions and performance improvements through economies of scale and learning-by-doing effects. Solar PV provides a good example of how this can work. All G7 members have put in place market-pull instruments for low-emissions electricity generation technologies: the instruments used vary from country to country but include CO_2 performance standards for coal power plants, renewable obligations, CO_2 prices, feed-in premiums, tenders for renewables and tax incentives for low-emissions technologies.

Even after commercialisation of a technology, continuing R&D can help to stimulate the further development of new designs and components and to bring down costs and improve performance. To help drive down generation costs from solar PV to USD 20 per MWh by 2030, for example, the United States are not only providing R&D to further develop thin-film solar PV technologies such as Perovskite solar cells (now at the prototype stage), but are also providing funding to improve the lifetime of the components of silicon-based PV systems from 30 to 50 years.

The use of hydrogen and ammonia for electricity generation illustrates the range of different technology options, their maturity level and the related policy support needs. Large gas turbines handling hydrogen and gas blends and hydrogen-fired fuel cells are commercially available technologies, but support measures are needed for the use of hydrogen to close the cost gap with natural gas. Other technologies, such as co-firing of ammonia in coal power plants or ammonia-fired gas turbines are at a demonstration or prototype stage. Further R&D efforts and demonstration projects are needed to bring these technologies to the market (see case study).

Case study: Ammonia and hydrogen in electricity sectors

Hydrogen-fuelled generation is at an early stage in the electricity sector today, accounting for less than 0.2% of global electricity generation, but the increasing need for low-emissions dispatchable generation will change this. In the NZE, 2% of G7 electricity generation in 2050 is from hydrogen and ammonia, providing valuable flexibility as the use of variable renewables grows. Demonstrating the effective use of hydrogen and ammonia in the electricity sector could reduce perceived risks and support their adoption in countries that currently rely heavily on coal and natural gas for generation.

Hydrogen use in gas turbines has made considerable progress in the past decade, and both new and retrofitted turbines using up to 100% hydrogen blends are expected to be developed by 2030. These new hydrogen-ready dry low-emission (DLE) combustion systems have shown great potential, with up to 50% hydrogen blends already possible for large-class turbines and even higher blends for small-class turbines, all without additional NO_X emissions. Remaining challenges relating to combustion technology readiness are the focus of Vattenfall's Nuon Magnum project, which plans on using 100% hydrogen blends in a 440 MW-class retrofitted unit by as early as 2023. General Electric's (GE) Long Ridge system is also working up to full hydrogen blends over the next decade. Success would allow hydrogen-capable turbines to function as dual-fuel systems that are able to make use of natural gas when necessary to start up or ramp up quickly.

Fuel cells provide another option for converting hydrogen into electricity and heat. Their ability to achieve high electric efficiencies up to 60%, with higher efficiency in part load than full load, make them particularly attractive for flexible operations. Global installed stationary fuel cell capacity has been rapidly growing over the last ten years, reaching almost 2.2 GW in 2020: although most of the existing fuel cells today use natural gas, around 150 MW of capacity already uses hydrogen as fuel.

For ammonia, the focus is on co-fired use in coal plants, with the CHUGOKU Electric Power demonstration project in Japan successfully blending low levels of ammonia in a commercial plant. Building on this, JERA and IHI have announced a new project that will reach 20% ammonia-fired blends in its 1 GW large-scale plant by 2024. One concern with ammonia is the likelihood that its use may lead to increased levels of NO_x emissions, but promising results from the Chugoku case suggests that it does not. If the JERA-IHI demonstration produces similar results it will go a long way towards highlighting the potential for high-blend ammonia to play a crucial part in decarbonising coal-fired generation.

Ammonia could also potentially be used in co-fired gas turbines, although its combustion behaviour may yet point to the need for a two-stage system. As ammonia use results in NOx emissions, a key factor in its use will be the extent to which NOx can be contained, with systems designed to handle this currently in development. Although ammonia may remain best suited for smaller-scale operations, the Mitsubishi announcement of a 40 MW-class ammonia-capable unit by 2025 could create a path forward for expanded use in larger gas turbines.

High shares of variable renewables in the electricity system are likely to increase demand for cost-effective long-term and seasonal storage. Hydrogen and ammonia offer potential solutions in this area too: underground salt cavern hydrogen storage has been in use for over fifty years in the petrochemical industry, with four sites being operational in the United States and United Kingdom. These salt caverns offer high injection and withdrawal rates. In France, Hyflexpower is already demonstrating the ability to store excess renewable energy as hydrogen before reconversion into electricity via its 12 MW gas turbines. Depleted oil and gas fields and aquifers could also be used to store hydrogen but there is little experience so far of using them for this purpose, and additional feasibility studies would be needed to test the proposition. Ammonia is also well suited to act as a storage medium, and it has a higher volumetric energy density than hydrogen. A typical ammonia tank can store energy of around 150 GWh, which is enough to power the annual electricity consumption of a city with a population of 100 000. Siemens demonstrated the use of ammonia for electricity storage in 2018 in the United Kingdom by converting wind power via electrolysis into hydrogen and then ammonia for storage. When it is needed, the stored ammonia is then converted back into electricity by a combustion engine.

Enhancing international cooperation on innovation

G7 members have played a key role in developing a number of existing clean energy technologies. For example, successive policy interventions in the United States, Japan and Germany helped to invent, commercialise and bring to scale solar PV. Reaching net zero electricity globally will require the rapid diffusion of new technologies and practices. G7 members could support emerging market and developing economies through demonstration and capacity building projects and joint RD&D. Technologies such as ammonia and hydrogen co-firing which are currently being pioneered in a number of G7 members (see Box above) could help emerging market and developing economies to shift away from coal-intensive electricity generation, while G7 experience and innovation in energy storage and smart grids could help them to manage growing shares of wind and solar.

A Low International Cooperation Case was modelled in the IEA's recently published report Net Zero By 2050. In this scenario, world CO_2 emissions were 15 Gt higher in 2050 than in the net zero emissions pathway. Although most of these extra emissions came from outside the electricity sector, almost 10% came from electricity generation. In this case, existing trends in technology innovation and strong national policies enabled high penetrations of variable renewables and largely decarbonised electricity systems. However, slower innovation within key technologies and slower diffusion of these technologies to emerging market and developing economies resulted in electricity sectors that were not able to eliminate the last 10-15% of emissions.

Reaching zero emissions electricity sectors requires enhanced cooperation in several areas. Increased R&D coordination and targets could be needed for achieving low-cost, long-duration energy storage (less than 20 USD/kWh for energy capacity costs), which is critical to replacing fossil fuels for seasonal balancing particularly in regions without large hydro or natural gas resources. Hydrogen, compressed air and low energy cost, long-duration batteries are promising technologies. G7 countries could set a stretch target for achieving cost and performance metrics in long-duration energy storage in line with the needs of net zero electricity systems. Currently, for example, the G7 spends only around 2% of their energy-related budgets on energy storage, a share that has not changed in the past 10 years. Another 2% is allocated to dispatchable renewables such a bioenergy electricity, geothermal and hydropower, critical technologies in many systems to reach net zero emissions from electricity. Establishing performance objectives for dispatchable low-emissions technologies and enhancing coordination of demonstration and deployment could be critical to facilitating the level of innovation and deployment required for net zero electricity sectors.

The role of digitalisation

Digitalisation is having a major impact on electricity systems. Smart meter rollout is well advanced across most of the G7, and investment in digitalising networks is steadily increasing over the past five years, it has accounted for an average of almost USD 20 billion each year. This trend is expected to continue in the light of an increasing need to manage more diverse and distributed assets. Digital technologies mean that data on power flows, consumption and production is increasingly accessible, more granular, and closer to real time. Consumers can gain a better understanding of their consumption and bills. Utilities, systems operators and network operators get better visibility over the whole of their systems. Low voltage networks used to be a blind spot; once digitalised, the electric system can monitor and manage them, expanding opportunities for demand-side response.

Unlocking the benefits of digitalisation

The increasing electrification of end-uses (electric vehicles, heating) means evolving and more complex demand patterns. Meanwhile, changes in electricity supply (more renewables, less coal and gas) are transforming flow patterns on the networks. The result is that networks need strengthening. Digitalisation plays a major role in delivering this by complementing (and sometimes replacing) costly investment in physical assets. Sensors and smart substations support predictive maintenance, enable fault prevention, and enable outages to be fixed more quickly. Widely available and accurate consumption and production data, coupled with artificial intelligence, help operators better understand and predict consumption and production patterns, and this supports well-targeted and effective investment. Digitalisation also makes the use of non-wire alternatives such as demand-side flexibility more efficient by improving understanding of availability and reliability.

Increased digitalisation also supports enhanced electricity system flexibility. As discussed earlier in this report, one of the keys to successful electrification is to ensure that new types of consumption become flexibility resources, instead of increasing flexibility needs. Traditionally, only a few large industrial sites provided consumer-side flexibility: the amount of flexibility provided had to be enough to justify significant communication and operation costs. Digitalisation has changed that. Small, decentralised assets are now able to contribute to load management, thanks to increasing the deployment of smart metering, which enables granular metering and close to real time communication. These reductions make it possible to aggregate multiple small consumers, in unlocking a new source of flexibility known as distributed energy resources.

Many flexibility sources contribute to distributed energy resources, including batteries, demand response from EVs, heating and load-shifting appliances. In the NZE, space heating alone could provide around 40 GW of flexibility in the G7 in 2030 and around 100 GW in 2050, mainly driven by the increasing number of heat pumps (over 110 million by 2030 and approaching 170 million by 2050). Consumers provide flexibility by reacting to price signals that incentivise reducing consumption during demand peaks, or through contracts that sell flexibility services to the electricity system. Flexibility contracts need aggregators to bundle together many small sources of flexibility to provide reliable, sizeable flexibility products to the electricity system.

Policymakers can take measures to ensure that digitalisation potential is used effectively for the benefit of the system, while at the same time addressing concerns about cyber security (see Climate and Cyber resilience). Government and regulatory bodies should first remove market barriers to ensure that aggregators are able to compete on equal terms with other sources of flexibility. This means ensuring that size and metering requirements and vetting procedures offer scope for the use of flexibility provided through multiple consumers and are not geared solely to large plants.

Policymakers could also take measures that facilitate consumer engagement in the provision of flexibility. A crucial aspect for customers engaging in flexibility schemes is seamless automation of smart devices, so that appliances can react directly to signals sent from the network. This means setting standards and protocols for data exchanges between connected devices and the electricity system which ensure interoperability. It also means ensuring that appliances and buildings are enabled for demand response, so that those using them are able to enter into flexibility contracts if they wish to do so.

The opportunity to digitalise while electrifying should not be missed. In the NZE, for example, the stock of electric vehicles in the G7 grows from 10 million in 2021 to over 60 million by 2025 and nearly 190 million by 2030. Depending on whether they are equipped for smart charging, these vehicles will either add to the burdens on the electricity system or offer a welcome source of flexibility. The same applies to data access rules, data protocols and interoperability. The sooner they are implemented, the less risk of having various systems that develop independently and are difficult to reconnect later. A poor choice of smart meter protocols, for example, could have consequences that are difficult to resolve without changing all the meters. A prerequisite to the successful digitalisation of electricity systems is ensuring cyber security (see the next chapter).

Implications of the electricity sector transformation

Summary and policy recommendations

- The rapid growth of variable renewables in the NZE has important implications for energy security. The share of wind and solar PV in electricity generation rises in the G7 from 14% in 2020 to over 40% in 2030 to nearly two-thirds in 2050. This trajectory means that the G7 will need to move well beyond current experience in any country and chart new territory in terms of integrating variable renewables. The G7 has an opportunity to demonstrate that the reliability of electricity supply can be maintained with high shares of variable renewables, and to lead the way in developing technological solutions alongside appropriate market structures and system operation practices.
- The challenges to electricity and wider energy security in the NZE require a whole systems approach which goes beyond narrow operational issues to look at systems resilience in the face of threats such as climate change, natural disasters, power failures and cyberattacks. There is a strong case for G7 members to lead by example, including by putting cyber and climate resilience at the heart of their energy security policies. The NZE sees a notable reduction in G7 dependency on energy imports over time, which is helpful from an energy security perspective, but new concerns arise, notably in view of the supply chains for critical minerals needed for clean energy technologies.
- Investments in electricity generation within the G7 nearly triples in the coming decade in the NZE, and then nearly doubles in the two subsequent decades. Over 60% of this investment goes into wind and solar PV in 2030. Investments in networks double by 2030 and decline thereafter. Investments on this scale need to be underpinned by policies to ensure timely project approvals and by measures to coordinate electricity system investments across the value chain.
- The affordability of energy is crucial to ensuring a just and people-centred transition. While total energy spending across the G7 increases by 0.3% annually between now and 2050, its share of GDP declines from around 7% today to just over 4% in 2050. Household spending on electricity increases, but this is more than offset by a decline in household spending on oil products, and household energy bills in the G7 decline by a third by 2050. Taking account of additional investments in efficiency, total energy spending per household in G7 countries is about USD 200 less in 2050 in the NZE on average than today.

- The decarbonisation of energy in the NZE creates many employment opportunities and adds 2.3 million jobs (net of job losses at coal- and gas-fired power plants) in the G7 within the next decade, the majority of which are highly skilled. While the number of jobs lost in the fossil fuel sector is much smaller, the impacts will inevitably be difficult for those involved, and G7 members will need to deploy transition mechanisms and funding to ensure that affected workers and communities are not left behind.
- Behavioural changes are key to achieving net zero emissions. They reduce energy demand by 7% in the NZE, around one-sixth of which is related to electricity and cut emissions by 7 Gt more than would otherwise be the case by 2050. G7 members are well placed to encourage the necessary behavioural changes.

Energy security

Maintaining energy security is essential at every step along the way towards net zero emissions in G7 electricity sectors. As electricity makes up a greater share of final energy consumption, the security of electricity supply becomes increasingly central to overall energy security. Clean energy transitions change the nature of energy security challenges: some current threats fade, but new ones emerge.

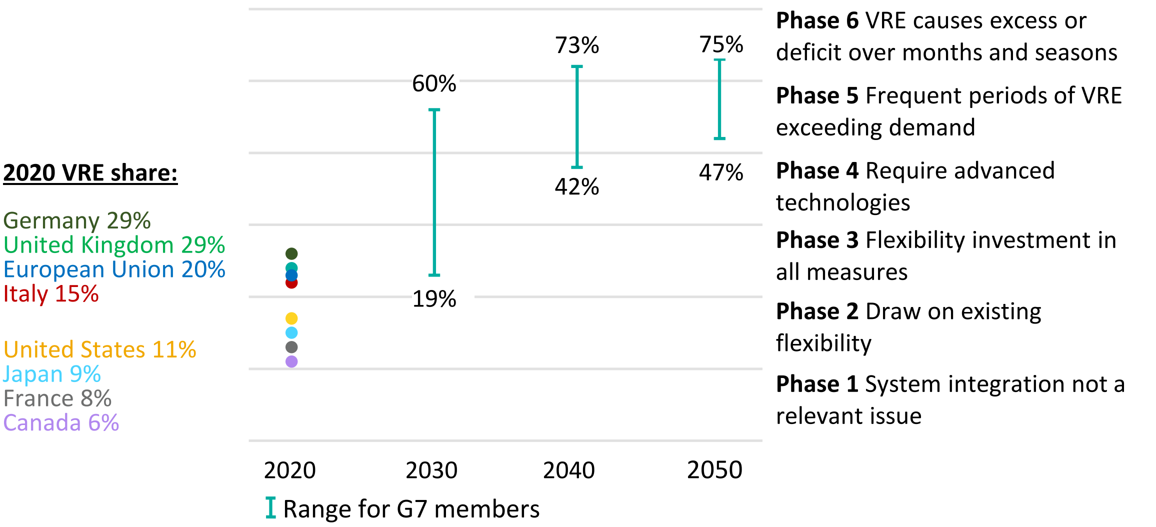
Integration of variable renewables

Wind and solar PV in the NZE generate between 47% and 75% of electricity in the G7 by 2050, a significant increase from their 2020 levels which range between 6% and 29%. This rapid move towards a generation mix in which over half of electricity is variable requires changes in the way electricity systems are designed and operated. G7 members have a key role to play in demonstrating that reliability of electricity supply can be maintained with these higher shares of wind and solar PV generation. To understand the challenges and steps that need to be taken along the way, the IEA has developed a framework to characterise the different phases of renewable integration.

The progression of the G7 through the phases of renewable integration

Our analysis suggests that at present G7 members are located between Phases 2 and 3 in the IEA's framework and that in the NZE they reach Phases 5 or 6 by 2050. Under the IEA's Stated Policies Scenario, the rate of progression in the G7 is more varied and typically slower, with countries ranging from Phase 3 to Phase 6 by 2050. The IEA framework notes that regions with similar overall shares of wind and solar are often attributed to different phases due to their specific context and underlying system conditions[1]. It is also worth noting that countries with limited low-emissions alternatives will look to transition more quickly to higher shares of wind and solar PV, and therefore would encounter challenges related to more advanced phases of integration earlier than others.

G7 phases of system integration and shares of variable renewables in the Net Zero Emissions by 2050 Scenario, 2020-2050



Many G7 members are already either at Phase 3 or will progress to it by 2030. In this phase, countries begin to experience a more prominent impact on system operation due to greater variability in net load[2] and power flow patterns. By the early 2020s, some G7 members get close to Phase 4, which is where countries like Denmark and Ireland are today. By 2040, all the G7 reach Phase 4, which describes systems in which wind and solar PV make up almost all generation in certain periods.[3] In Phase 4, action needs to be taken by system operators to ensure the robustness of electricity supply during periods of high wind and solar

[1] This includes, among others, generation mix (including composition of wind and solar PV), distinct demand patterns, or interconnectivity with neighbouring regions.
[2] Refers to the electricity demand after generation from wind and solar PV is being subtracted. High variability in net load requires dispatchable generation and storage to ramp-up and down quickly.
[3] Examples include Texas and South Australia regions. Phase 4 may take place at overall wind and solar PV shares of 30% and 40% in certain subsystems or regions, which are isolated or weakly interconnected.

generation, for example through frequent interventions to ensure inertia levels are kept at safe levels.

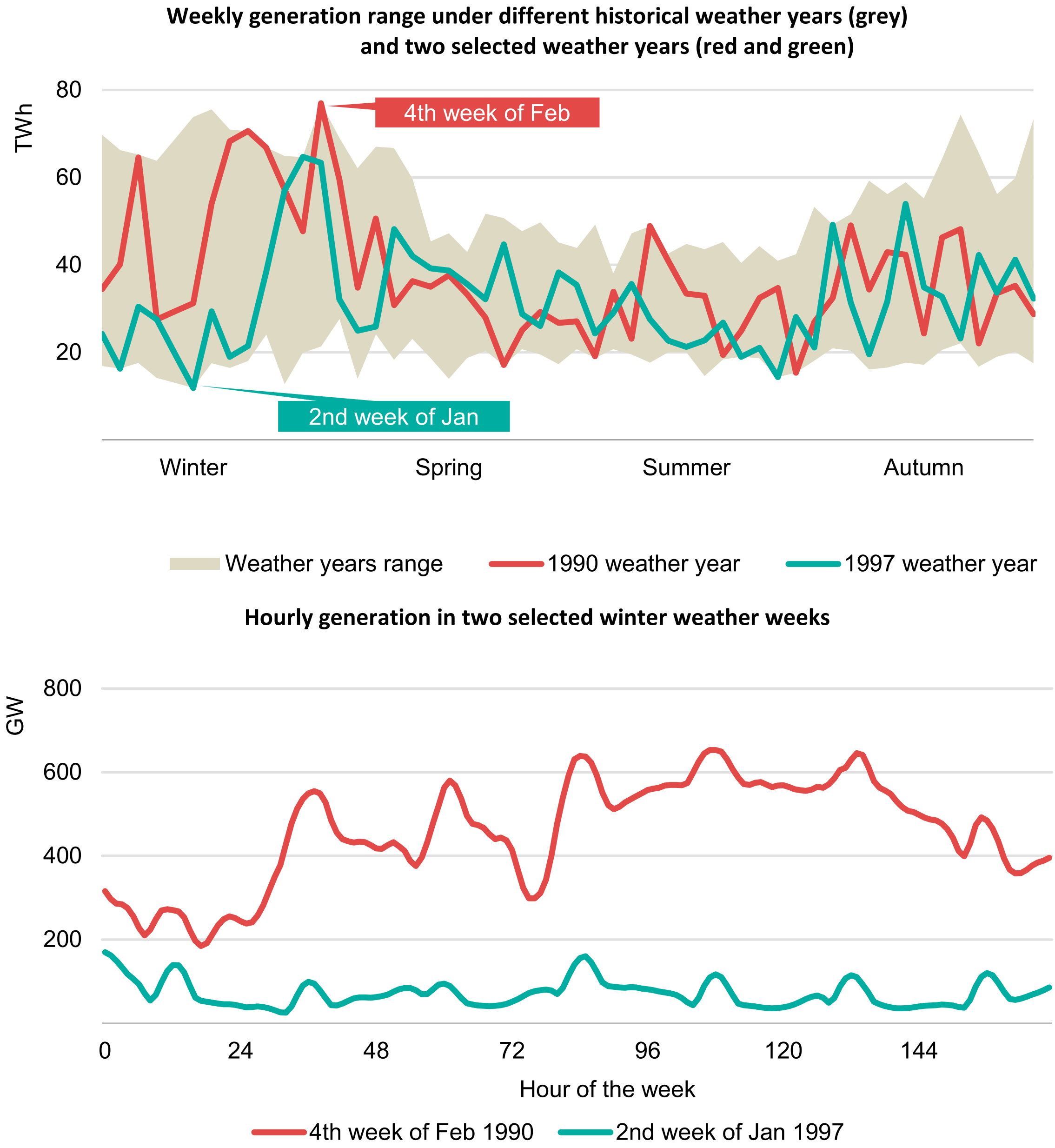
By 2030, a few G7 members reach Phase 5, and by 2050 all of them do. Phase 5 is broadly categorised by more frequent and continuous periods of structural imbalances between wind and solar PV generation and demand, which could be days or weeks long, and which result in increased curtailment of wind and solar PV generation.

By 2040, several G7 members are generating over two-thirds of their electricity from wind and solar PV and are reaching Phase 6. At this point, structural imbalances between wind and solar generation and demand occur for prolonged periods, and the frequency and volume of curtailed generation increases.

Wind and solar PV generation can vary significantly across weeks, seasons and years. Our analysis based on NZE results for the G7, shows that the capacity factors for combined wind and solar PV can range between 10% and 64% in a Phase 6 region depending upon the weather in any given week. This means that weeks with low wind and solar PV generation would require dispatchable capacity to meet most demand, and weeks of high wind and solar PV generation could result in prolonged periods of curtailment in the absence of storage. In addition to weekly variation, wind and solar PV generation can vary by as much as 50% between seasons within the same year, and by up to 20% across different years.

This variation across different time frames stresses the importance of system planning to ensure sufficient adequacy levels. This could be done by deploying storage, which can shift energy between time frames ranging from weeks to seasons. Alternatively, adequacy could be ensured by maintaining sufficient levels of low-carbon fuels for use by dispatchable generation technologies. Market structures would need to evolve to incentivise investment in long-term storage of electricity or low-carbon fuels, which might be used sparsely but would be essential to the maintenance of reliable supplies.

Combined wind and solar PV generation under different historical weather years for a Phase 6 G7 region based on 2050 capacity in the Net Zero Emissions by 2050 Scenario



Note: Based on analysis of 30 historical weather years using data from Renewables.ninja. Applies 2050 NZE wind and solar PV capacity to different weather years' wind speeds and solar radiation.

Enabling measures for the transition to integration Phases 5 and 6

Phases 5 and 6 represent uncharted territory which G7 members are likely to reach ahead of most countries. Some of the inertia and system strength challenges that are occasionally experienced today in some small regions would become bigger and more frequent. A coordinated approach to system stability issues involving the development of new infrastructure (e.g. grid-forming inverters, synchronous condensers, interconnection), and innovative system services markets would be required, together with additional short-term flexibility options).

Structural imbalances in supply and demand would also need to be addressed. As in earlier phases of integration, short-term storage (4 hours or less) and demand-side response would have an important part to play. However, at more advanced phases of integration, the increased length of periods of structural imbalance would require longer lasting storage options which are not incentivised by existing market structures. Some G7 members have started to address this need. The United States has taken the first steps towards commercialising long-duration storage solutions, proposing a target and related funding to help drive down the cost of grid-scale energy storage by 90% for systems that deliver over ten hours of duration within the decade. The United Kingdom is taking a slightly different approach: it has started exploring market structures that could attract investment in long-duration storage, and recently issued a call for evidence.

Another way to manage structural imbalances is to increase interconnectivity within and between regions. The expansion of electricity networks across large geographical areas helps to smooth demand and takes advantage of varying solar and wind generation patterns within those areas, thus reducing the frequency and duration of structural imbalances. It also means that electricity demand from weather-dependent heating and cooling can be spread across larger areas. This underlines the importance of investment in networks and interconnections in a coordinated way across neighbouring regions.

G7 members need to consider how best to advance and commercialise technologies that would enable them to increase their uptake of wind and solar PV generation and move through the phases of integration, and that would subsequently make it easier for other countries to follow them along this path. Early investment in the required technologies would drive cost reductions which would help to make the transition more affordable for all countries, while the operation of predominantly wind and solar PV-based systems by G7 members could instil confidence in others' countries to follow their example and contribute at the same time to the development and dissemination of vital system operation knowledge. The G7 could also lead by proving market structures that appropriately value contributions from all sources of flexibility, including demand-side response.

Electricity adequacy and stability

System adequacy means the ability to meet electricity demand at all times and is central to electricity security and to the avoidance of shortages that could cause rolling brownouts or other disruption. Power plants burning coal, oil and natural gas have been the cornerstones of system adequacy in most countries, including in the G7, complemented by hydropower, nuclear power and other dispatchable sources. Rising electricity demand and the widespread retirement of fossil fuel power plants in the G7 will make it more difficult to maintain system adequacy in the future.

There are several ways to address this that are consistent with the pathway to net zero emissions. They include repurposing unabated coal-fired power plants to focus on flexibility and retrofitting power plants that use natural gas or coal to co-fire hydrogen and ammonia or use carbon capture technologies. They also include the taking of steps to coordinate the retirement of higher-emissions sources of generation with the introduction of new low-emissions dispatchable sources and energy storage technologies. Where there is excess capacity in the system, retirements may not require one-to-one replacements. This is the case in many emerging market and developing economies, where excess capacity has been on the rise in recent years, as discussed in the IEA World Energy Outlook 2018.

System stability ensuring that systems remain in balance and are able to withstand disturbances such as sudden generator or grid outages and is another key feature of electricity security. Historically, conventional generators such as nuclear, hydro and fossil fuels have been and will continue to be central to electricity system stability, providing inertia with rotating machines which store kinetic energy that can be instantly converted into power in case of a system disturbance, and generating a voltage signal that helps all generators remain synchronous. In contrast, technologies such as solar PV, wind and batteries, which are connected to the system through converters, do not generally contribute to system inertia and are configured as "grid-following" units, synchronising to conventional generators. Maintaining system stability in systems with high variable renewable shares (beyond Phase 4) will call for new approaches as elaborated in our Power System Transformation report. There are various methods and metrics for the assessment of the complex issue of stability. One useful metric looks at the extent of the instantaneous non-synchronous penetration. It measures the share of the power injected in the system through power electronic interfaces at any given moment. This includes infeed from variable renewables, batteries and imports through DC interconnectors.

There is also a growing body of knowledge and studies about stability in systems with high shares of variable renewables. For example, a recent joint study by the IEA and RTE, the transmission system operator in France, analyses the conditions under which it would be technically feasible to integrate high shares of variable renewables in France. This study suggests strategies to manage stability in a system with growing share of converter-based generation.

Options for managing system stability

Minimum level of synchronous generation: this can ensure stability in the transition to net zero power systems by maintaining a minimum amount of conventional generation from low-emissions technologies during hours with high shares VRE output. This approach to maintaining stability comes at the cost of solar and wind curtailment at high shares. In the study conducted for France, it was found that current operational practices remain valid up to 40% of instantaneous converter-based generation.

Updated grid codes: these can be used to call for equipment with advanced features. On the one hand, equipment can be designed to withstand higher rates of changes of frequency. On the other hand, variable renewables and batteries can provide fast frequency response services, which can help reduce the amount of conventional generation needed for stability. This approach has been applied in Quebec and Ireland. In the latter, it has enabled up to 70% of instantaneous non-synchronous penetration in secure operation, and trials may push this threshold further.

Synchronous condensers: these operate like synchronous generators. Their motors provide inertia and short-circuit power, but they rotate freely without generating electricity. The technology is already proven at GW-scale in Denmark and in South Australia but needs to be tested at larger scale.

Grid-forming converters: these allow variable renewables and batteries to generate a voltage signal, though experience with this approach needs to move beyond micro-grids and small islands to large interconnected systems. HVDC interconnectors using VSC (voltage source converter) technology, based on transistors, also behave like grid-forming converters.

In the NZE, instantaneous non-synchronous penetration would exceed 80% in many G7 countries by 2050 at least 25% of the time on a yearly basis if VRE generation were not curtailed due to operational constraints to maintain system stability. At those penetration levels, all listed options might be required. The menu of options chosen would depend on the characteristics of each country’s electricity system, in particular the local energy mix.

The large-scale deployment of converters and the introduction of grid-forming converters require system design and operation practices to be enhanced. For example, the Spanish grid operator has started shifting from distance protection to differential protection. Interactions between converters and their digital controllers also have to be better understood and managed. The rising share of digital controllers along with higher shares of distributed PV and batteries mean that digital resilience will be an essential component of power system security at both transmission and distribution level.

There is a scientific consensus on the theoretical stability of power systems without conventional generation. The technical solutions, mainly focused around power electronics, have been identified, but are not yet commercially available at large scale. Demonstration projects, stakeholder consultations and international collaboration will be necessary to understand fully the merits of each of these four approaches and the scope for a portfolio of options that would most cost-effectively achieve net zero emissions while maintaining electricity security.

The stability challenge goes beyond technical issues, important as they are. Policymakers need to choose the regulatory instruments or incentives that they think will be most effective in leading to the deployment of the technologies that are needed. They also need to allocate responsibility for providing the corresponding 'stability' services. Their choices will shape the stability of the future electricity sector.

Climate and cyber resilience

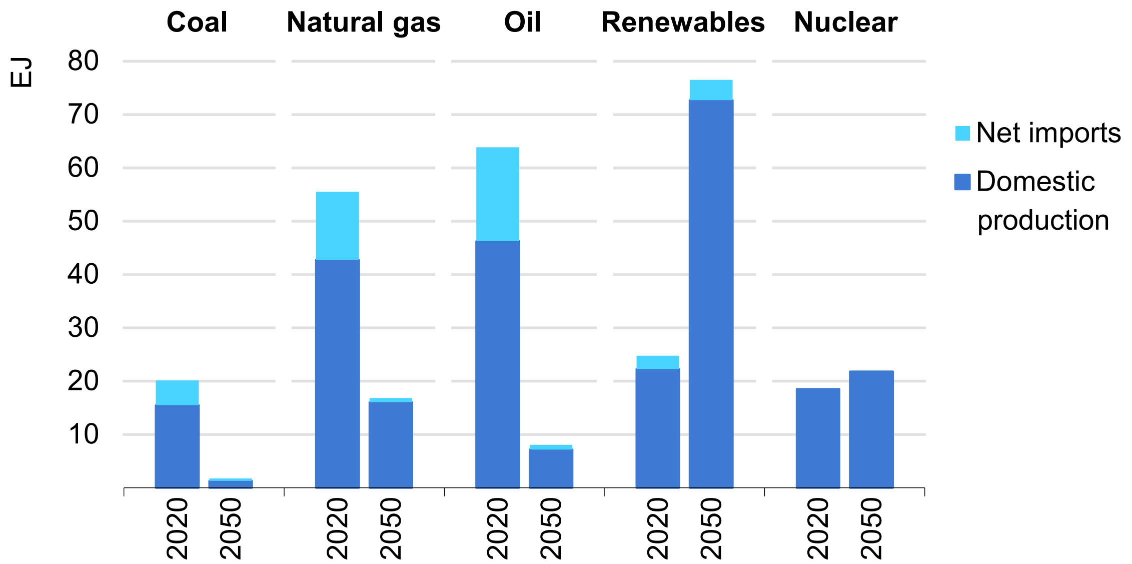
Resilience of electricity supply goes beyond the daily operations of the electricity system and includes preparedness against rare events and external threats. This means protecting infrastructure against gradual changes in the climate, extreme weather events which are increasing in frequency and magnitude due to climate change, and increased exposure to cyberattacks because of increased digitalisation. The IEA has recently provided guidance to policymakers outlining measures for strengthening climate and cyber resilience.

Climate change brings a variety of risks to electricity infrastructure and system operations ranging from increasing temperatures and changing precipitation patterns through to rising sea levels and extreme weather events. The impacts could affect the entire value chain of the electricity system, for example by reducing the available capacity of generators and transmission infrastructure, increasing the number and extent of outages, and changing generation and demand patterns. A number of measures could improve the resilience of the system to these impacts, ranging from the hardening of infrastructure against climate risks to better coordination for recovery, but the first requirement is a set of climate risks and impact assessments to inform national strategies and plans in the electricity sector. Such assessments should be used to identify cost-effective resilience measures as well as the required incentives for utilities to implement these measures. The G7 could take a lead by setting high standards for the mainstreaming of climate resilience in energy policies, implementing resilience measures and improving knowledge of the risks through scientific assessments.

The digitalisation of electricity systems presents many opportunities for improved cost efficiency in power system operation and decarbonisation. At the same time, it exposes power systems to cyber threats, and this underlines the importance of devising cybersecurity strategies to protect against such threats. Across the G7, there is a variety of policy approaches towards securing the power system against cyber threats, ranging from standards-based regulatory requirements to performance-based regulation and the development of response preparedness plans. From a policymaker's perspective, the key is to ensure security through transparent and trackable policies while maintaining the flexibility to adapt to changes in technology. Given the global nature of cyber threats, international cooperation within the G7 and beyond will remain crucial to ensuring electricity security.

Energy self-sufficiency

Energy supply from domestic production and imports in the G7 by source in the Net Zero Emissions by 2050 Scenario, 2020 and 2050



Note: Domestic production includes all production within G7 members. Trade volumes may be significantly larger than net imports.

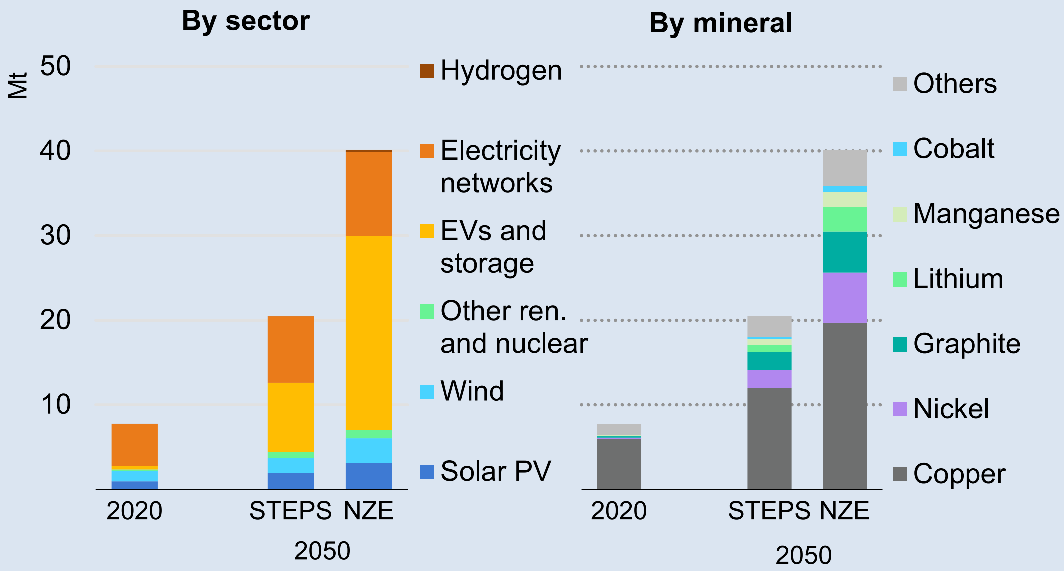
The G7 as a group is largely energy self-sufficient today, meeting 80% of its energy needs from its own resources. G7 members nevertheless imported large volumes of coal, natural gas and oil products and some renewable energy in 2020, mainly in the form of biofuels and solid biomass. Individual G7 members relied on net imports to varying degrees in 2020, with domestic production exceeding total energy supply in Canada and the United States, and net imports representing some 25% of total energy supply in the United Kingdom (and about a third of fossil fuel supply) and close to 90% of the energy used in Japan (almost all fossil fuels).

The G7 reaches over 90% self-sufficiency in STEPS and 95% in the NZE. Significantly lower demand for coal, natural gas and oil products enables the G7 to be nearly self-sufficient in respect of remaining fossil fuel requirements. Although renewable energy use overall triples from 2020 to 2050 in the NZE, and is mostly derived from domestic resources like wind and solar PV, the G7 does import some biofuels and solid biomass. The use of nuclear power also helps reduce import dependency since fuel assemblies are only replaced at intervals of 18 to 24 months. In addition to these primary sources, low-carbon hydrogen and ammonia is imported by the G7 for use in electricity, industry, transport and buildings.

Critical minerals: enabler or bottleneck for net zero electricity sectors?

Achieving net zero emissions globally by 2050 will require record levels of clean energy deployment. This implies a significant increase in demand for minerals as many clean energy technologies require more mineral inputs than their fossil fuel-based counterparts. For example, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% since 2010 as the share of renewables has risen. In the NZE, record levels of clean energy deployment require up to six times more mineral inputs in 2050 than today. EVs and battery storage are the leading force in driving demand growth, with large contributions from the expansion of electricity networks and low-emissions generation.

Mineral requirements for clean energy technologies by scenario



Notes: Includes most of the minerals used in clean energy technologies but does not include steel and aluminium. See The Role of Critical Minerals in Clean Energy Transitions for a full list of minerals assessed. Ren. = Renewables.

The prospect of a rapid increase in demand for critical minerals raises important questions about the availability and reliability of supply. Today's supply and investment plans are generally geared towards a world of gradual and insufficient action on climate change, raising the risks of supply lagging behind projected demand in climate-driven scenarios such as the NZE. The challenges are compounded by long lead times to develop new projects, declining resource quality, growing scrutiny of environmental and social performance and the lack of geographical diversity in extraction and processing operations. For example, the world's top three producing nations control well over three-quarters of global output for lithium, cobalt and rare earth elements. The level of concentration is even higher for processing operations with China's strong presence across the board.

The impacts of inadequate mineral supplies are different from those of an oil supply shortage. While there are no immediate impacts on consumers driving EVs or using electricity powered by solar, higher and volatile prices or supply disruptions could make global progress towards a clean energy future slower or more costly. Over the past decade, technology learning and economies of scale have pushed down the costs of key energy technologies significantly. However, this also means that raw material costs now form a larger share of the total cost of clean energy technologies. The recent commodity price rallies in the first half of 2021 demonstrated possible market strains. Prices for new wind turbine contracts have reportedly increased in 2021, reversing recent trends. Likewise, rising prices for silicon and silver have driven up the price of solar PV modules considerably in the first half of 2021. It is estimated that the magnitude of the rise in raw material prices seen in the first half of 2021 could generate upward pressure on total capital costs, adding USD 700 billion to the investment needs for solar PV, wind, batteries and electricity networks over this decade in the NZE.

The recent IEA Special Report on the *Role of Critical Minerals in Clean Energy Transitions* identified key areas of action to ensure mineral security and facilitate a rapid and orderly energy transitions. Efforts to scale up investment in new mining and processing facilities in diversified sources would be vital. To attract capital to new projects, policymakers must provide clear signals about their climate ambitions and how their targets will be turned into action, together with efforts to strengthen geological surveys and streamline permitting procedures. These should go together with a broad strategy that encompasses technology innovation, recycling, supply chain resilience and sustainability standards. The response from policymakers and companies will determine whether critical minerals remain a vital enabler for clean energy transitions or become a bottleneck in the process.

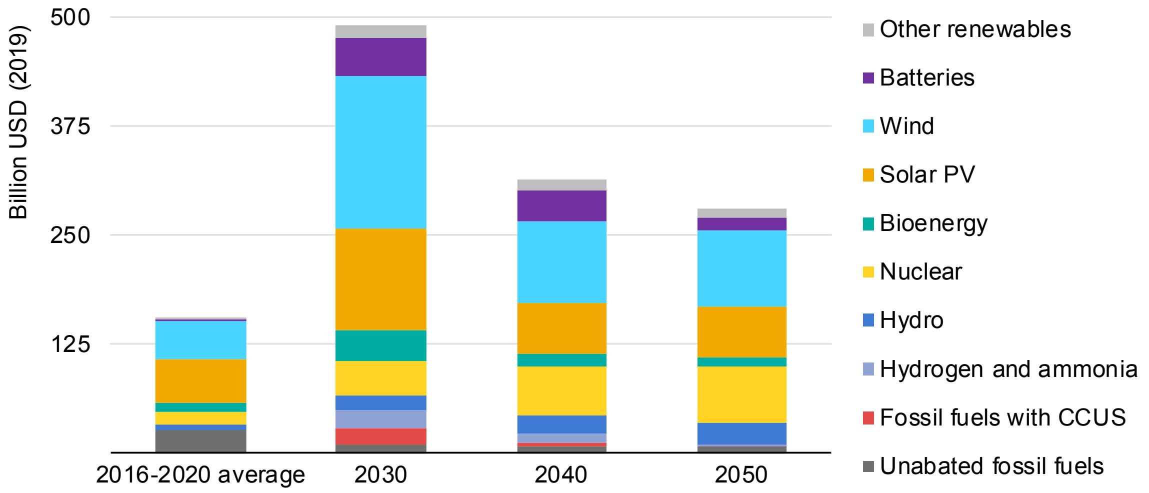
Investment needs

Electricity generation

The transition to net zero electricity systems requires a substantial increase of investment in low-emissions sources of generation. Wind and solar have dominated G7 investments in electricity generation capacity over the last few years and continue to do so in future.

By 2030, G7 investment in generation capacity triples compared to the level of recent years and then stabilises at nearly double the current level in the 2030s and 2040s. In the period 2016 to 2020, annual average wind and solar investments amounted to slightly more than USD 90 billion. This jumps to about 300 billion by 2030, with solar PV representing one-quarter of total investment in new capacity and with wind taking a slightly larger share. Investment in batteries grows even more strongly, expanding by more than 14 times between 2020 and 2030. Investment in generation capacity is more than double in the NZE in 2030 than it would be under the IEA's Stated Policies Scenario.

Annual G7 investment in generation capacity in the Net Zero Emissions by 2050 Scenario, 2016-2020, 2030, 2040 and 2050



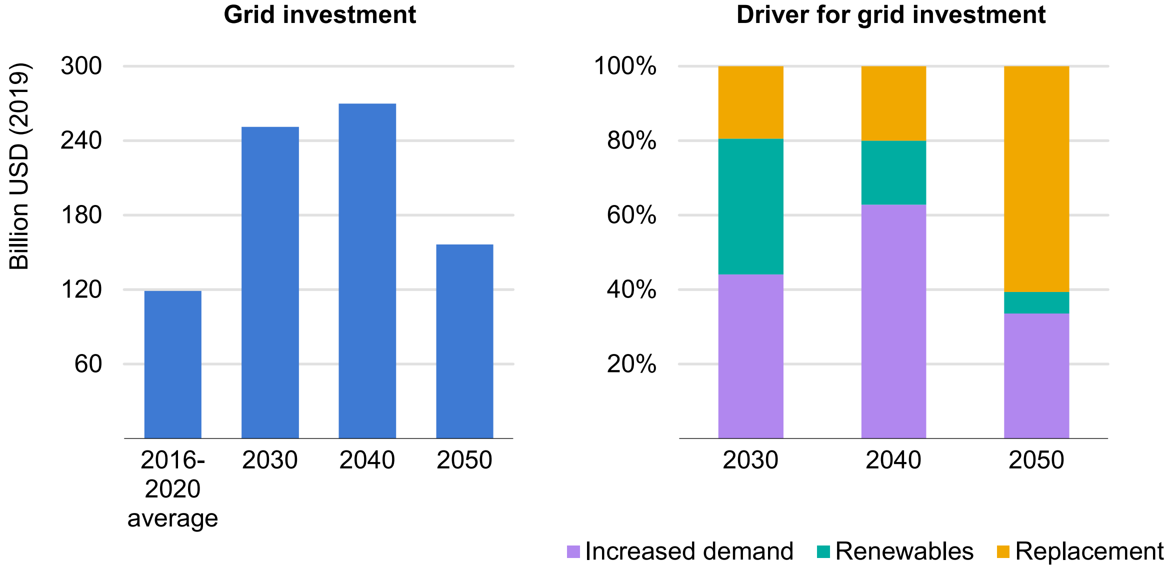
Investments in coal and gas-fired generation capacity decline marginally from 2020 to 2030, and a large share of investment in 2030 is equipped with CCUS. This helps meet the goal of net zero electricity by 2035 and provides a low-emissions source of seasonal flexibility to the electricity system.

After the 2030s, investment in new supply capacity slows down, as the need to displace electricity generation from unabated fossil fuels diminishes. Demand growth and replacing low-emissions sources as they retire become the main drivers of investments. Although large in absolute terms, the total investment in electricity generation peaks at around 0.8% of G7 GDP in around 2030.

Networks

Expanding and strengthening transmission and distribution infrastructure is crucial to managing the new demands that come with electrification and the integration of large shares of wind and solar. From a recent annual average of around USD 120 billion, G7 investments in transmission and distribution grid infrastructure double by 2030 in the NZE.

G7 average investments in electricity grids in the Net Zero Emissions by 2050 Scenario, 2016-2020, 2030, 2040 and 2050



In the near term, a key driver of grid investment in the NZE is the growth in renewables generation. After 2035, when the electricity system reaches net zero emissions, the rate of investment in generation capacity slows down to the level necessary to meet demand growth and to replace worn out capacity. As a result, investments in grid expansion also slow down after 2035, and demand growth becomes the major driver of grid investments.

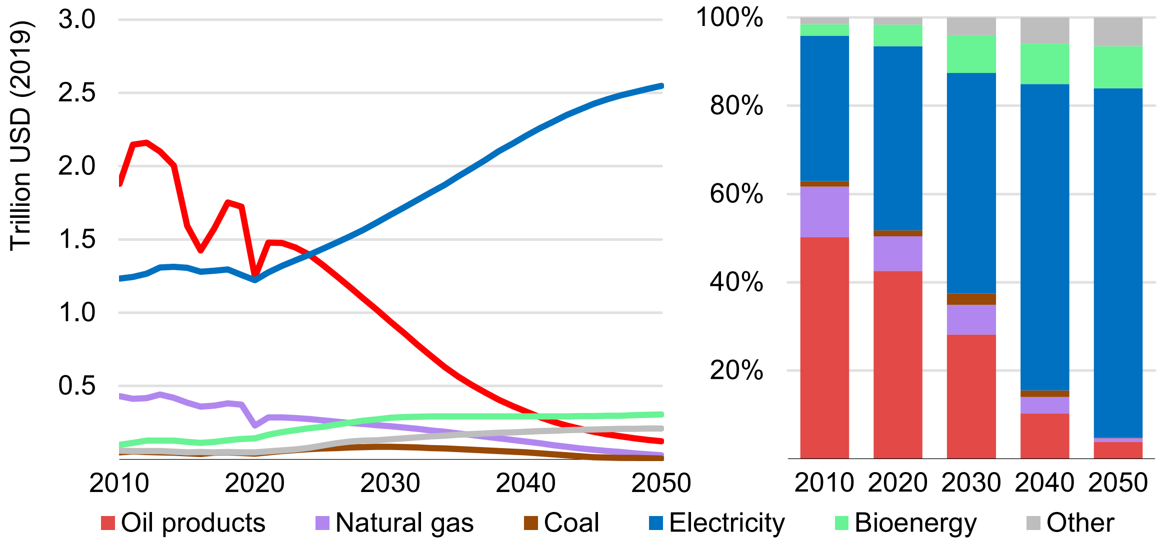
Taken together, investments in electricity generation, storage and grids peak around 2030 at more than USD 700 billion. This represents around 1.3% of G7 GDP. Given the low costs of capital enjoyed by the G7, their well-developed financial markets, and growing investor appetite for clean energy assets, attracting this amount of financing is feasible. However, government action will be necessary to ensure timely project approvals and to coordinate the buildout of the electricity system across the value chain.

Affordability

Total energy spending

Total G7 energy spending increases from USD 2.9 trillion in 2020 to USD 3.4 trillion in 2025, and broadly stabilising at around USD 3.2 trillion after the mid-2030s in the NZE. Energy spending increases at an average annual rate of 0.3%, but assumed economic growth rises faster than this, which means that total energy spending as a share GDP of declines from about 7% today to just over 4% in 2050. Outside of the G7, total energy spending accounts for higher shares of GDP, about 9% of GDP today falling to 7% of GDP in 2050, mainly due to significantly lower GDP per capita.

G7 total energy spending by source in the Net Zero Emissions by 2050 Scenario, 2010-2020



The composition of energy spending by consumers in the G7 shifts away from fossil fuels towards electricity and renewables in the NZE. Over the past decade, the share of oil in total energy spending has declined. This trend accelerates on the pathway to net zero emissions, thanks to a strong push to move away from internal combustion engines in transport in favour of electric and fuel cell vehicles. Spending on electricity rises above that on oil by 2025 and then surges upwards, doubling to over USD 2.5 trillion in 2050, by which point it accounts for 80% of all energy spending because of the widespread electrification of end-uses in all sectors. This electrification reflects improved cost-competitiveness on the part of electricity stemming from energy efficiency gains, higher CO_2 prices and broader coverage of CO_2 prices across fuels in the NZE. At the same time, electricity prices in the G7 rise by an average of 40% from 2020 to 2050. Outside of the G7, there is a similar shift of energy spending away from fossil fuels towards electricity, accentuated by a 75% increase in average retail electricity prices over the next three decades.

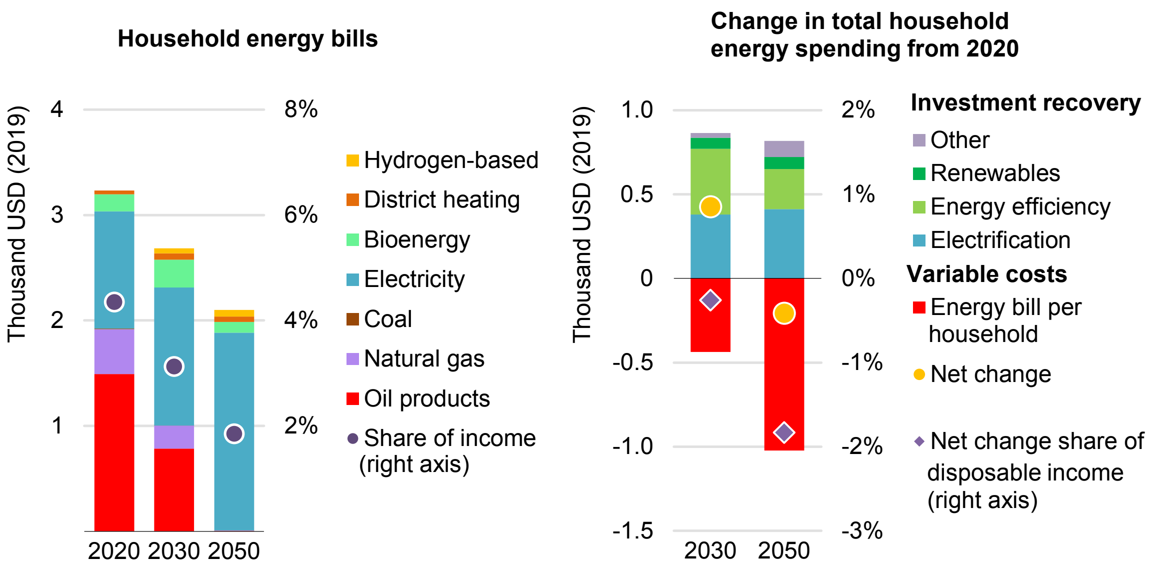
The NZE brings major changes to revenues from energy taxes and CO_2 prices, with important implications for government budgets. Excise taxes on natural gas and oil in the G7 were an estimated USD 500 billion in 2020 and they fall by nearly

70% by 2035 and some 90% by 2050. At the same time, CO_2 price revenues rise to a peak of USD 350 billion just before 2030 before declining to USD 40 billion in 2050 as all sectors decarbonise.

Household spending

Achieving net zero electricity in the G7, together with progress towards net zero emissions in other sectors, makes energy more affordable for G7 households. Total household energy spending, including purchases of new energy-consuming equipment, decreases as a share of disposable income in the NZE slightly in 2030 and by almost 2% in 2050 compared with today; households spend about USD 200 less than today on average. Households spend more to purchase efficient and low-emissions energy equipment – including for transport, heating, cooling and appliances – totalling about USD 240 more spent per household in 2050 in the NZE compared with today. However, this is more than offset by significant reductions in energy bills. G7 energy bills were about USD 3 100 per household in 2020, of which about 45% was spent on oil, nearly 40% on electricity and 10% on natural gas. By 2050, the average G7 energy bill is cut by over USD 1 000 per household, and nearly all remaining household energy expenditure goes on the purchase of carbon-free electricity. In emerging market and developing economies, huge increases in demand for modern energy services mean that households spend about USD 750 more on energy in 2050 in the NZE than today. However, their disposable income rises by significantly more as economies grow, making them far better off than today.

G7 household fuel spending and total change in energy spending in the Net Zero Emissions by 2050 Scenario, 2020, 2030 and 2050



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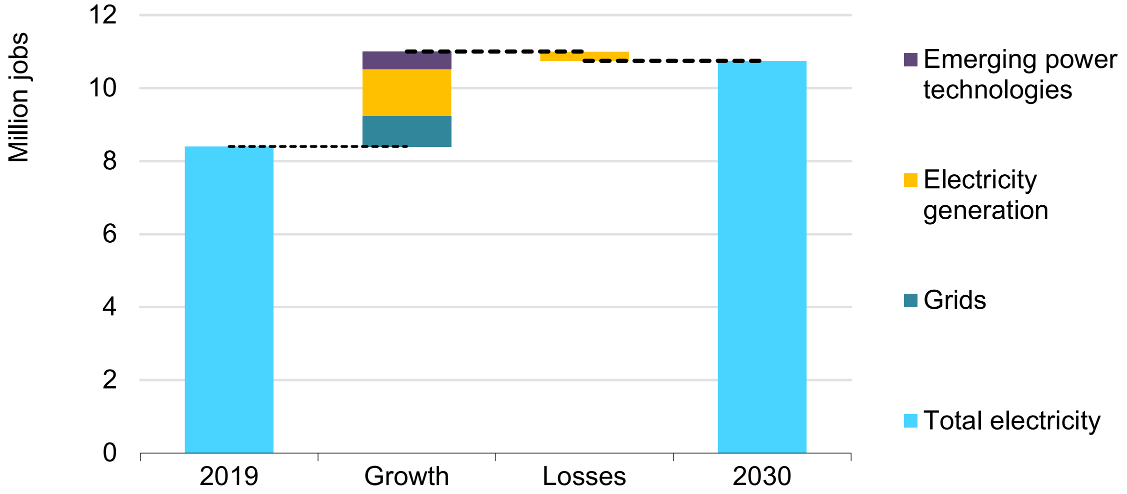
Employment and people-centred clean energy transitions

Job losses and gains

The NZE pathway brings about marked changes in energy sector employment, and the electricity sector experiences one of the most drastic shifts. Globally, employment in storage, power generation, grids and emerging technologies like CCUS and hydrogen rises significantly, adding around 12 million people by 2030 to an electricity sector workforce which is already 17 million strong. This total includes jobs building new plants, including for the upstream manufacturing of components, as well as the jobs involved in operating and maintaining those plants. In G7 members, many of which are major manufacturers of grid and power generation components, electricity employment grows from an estimated 8.5 million to about 10.5 million, after netting off job losses in coal and natural gas power generation.

Electricity sector employment impacts for G7 members in the Net Zero Emissions by 2050 Scenario, 2019-2030



Notes: All jobs' figures consider those directly related to constructing, operating, and manufacturing energy-specific components for each technology. Electricity generation includes employment across coal, gas, oil, nuclear power, hydro, bioenergy, wind, solar, geothermal, and other types of generators. Grids includes employment for all transmission, distribution, grid-specific digital and communications infrastructure, and utility/public charging infrastructure. Emerging technologies includes employment for CCUS, hydrogen and ammonia, and battery storage.

Job losses at coal and natural gas power plants are minimal by 2030, since many plants already operate with streamlined crews, and these plants still operate in 2030, even if they run for fewer hours and may be using blended low-carbon fuels or CCUS. Original equipment manufacturers upstream of fossil fuel power plants are more immediately impacted in the NZE as the building of new fossil fuel plants comes to a halt, and as G7 members increase their commitments to stop supporting fossil fuel investment in other countries. However, it is upstream jobs in fuel supply, processing, and delivery that are affected the most. Job growth in clean energy sectors would be likely after the 2030 horizon, however investment levels in the NZE stabilise afterward to 2050, meaning the most rapid shifts in energy employment are set to happen in this decade.

The impact of all job losses cascades through the communities supported by the earnings of fossil fuel workers, putting jobs at local shops, restaurants and other businesses at risk and jeopardising local government revenues that support education and public services. These impacts are distributed unevenly. Many in the service sectors are not eligible for retirement or comprehensive severance benefits. The service sector also has a high concentration of part-time workers, many of them women, who are often laid off work first, diminishing female participation in the workforce.

Many G7 members have already deployed just transition mechanisms and funding, particularly in effected coal communities, to help transition workers by providing retraining support, funding environmental remediation, and seeding new industries in fossil fuel regions. A growing body of best practice emphasises the important of long-term, community-wide transition planning, helping displaced workers and others in the community to access training that enables them to move into other employment, both within and outside the energy industry. Many place a particular emphasis on equal access to training services to help rebalance participation in the workforce.

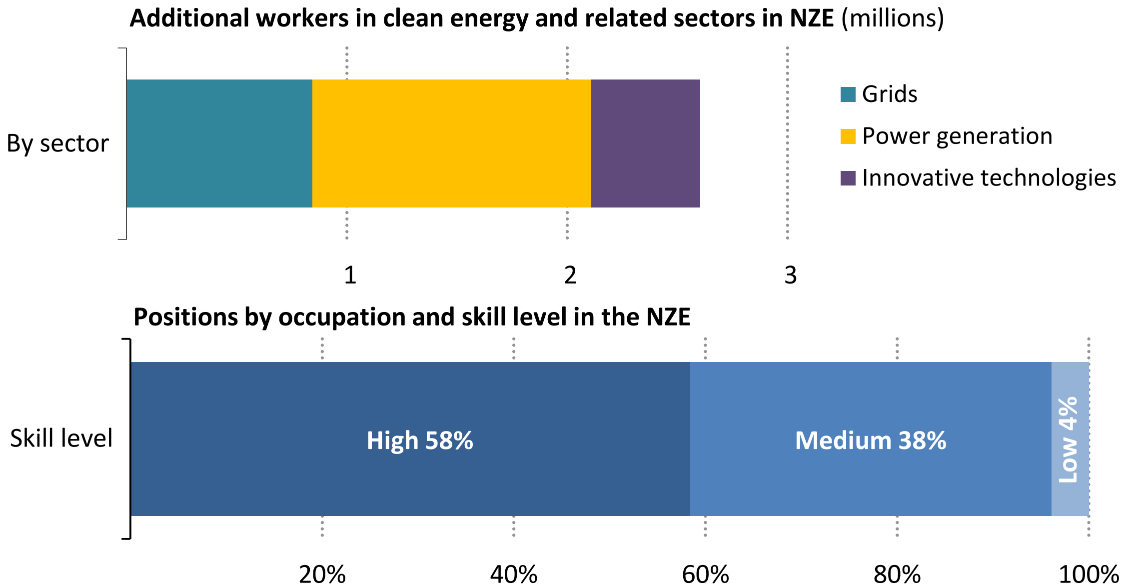
Further developing these best practices is part of the focus of the Global Commission for People-Centred Clean Energy Transitions. Led by Prime Minister Mette Frederiksen of Denmark and supported by the IEA, the commission has brought together 30 global leaders to develop recommendations for making clean energy transitions more inclusive, diverse and people-centred. These recommendations will be released in advance of COP26 to ensure transition pathways bring all people along to ensure continuous, substantial progress that can endure political cycles.

Skills

Workers within the electricity sector have much higher skill levels than those in most other segments of the economy, with a high percentage of the workforce requiring a 4-year degree or a postgraduate qualification. This continues in the NZE, where nearly 60% of all new jobs created require highly skilled workers.

Many current workers whose jobs disappear have skills that position them well to find jobs working with new electricity sector technologies, but a skills gap could, nevertheless, be a potential bottleneck to scaling up electricity sector investments quickly unless effective education and training arrangements are put in place. This is particularly pertinent given the weight that G7 members place on innovation and scaling up emerging technologies, and the emphasis given to hydrogen, CCUS, and other innovation programmes in the G7 economic recovery packages mobilised in the wake of Covid-19. Innovation partnerships and educational exchanges could also help advance skills and know-how.

Electricity sector employment skills needs for G7 in the Net Zero Emissions by 2050 Scenario, 2019-2030



Behavioural changes in electricity

The role of behavioural changes in electricity

The NZE pathway cannot be achieved by a move to clean technologies that takes place quietly behind the scenes. The active and willing participation of consumers of energy services – both people and companies – is also required. Over half of emissions reductions from 2020 to 2050 in the NZE require the deployment of low-emissions technologies that depend on decisions by consumers, e.g. installing a solar water heater or buying an EV. But there is also a crucial role for behavioural changes[4] - such as replacing car use with cycling or walking or reducing air conditioning in buildings - to cut energy demand and emissions, especially in sectors where technical options to eliminate emissions remain limited in 2050.

Behavioural changes in the NZE scenario help cut emissions and reduce energy demand in buildings, on roads and in the aviation sector. Overall, these changes mean that CO_2 emissions in the G7 between 2021 and 2050 are almost 7 Gt less than they would be in the NZE if such behavioural changes were not to happen.

[4] "Behavioural changes" here refer to changes in ongoing or repeated behaviours on the part of consumers that affect the energy service demand or the energy intensity of an energy-related activity. For example, purchasing an electric heat pump instead of a gas boiler is not considered to be a behavioural change, as it is both an infrequent event and does not affect energy service demand.

These behavioural changes also reduce final energy demand by around 5.6 EJ, or 7%, in 2050, around one-sixth of which is related to electricity.

Key electricity-related behavioural changes in the G7 in the Net Zero Emissions by 2050 Scenario, 2030 and 2050

Sector	Key behavioural change in the NZE	Key policy options	Related policy goals	CO_2 emissions impact	Electricity savings (TWh)	
					2030	2050
Road transport	Phase out ICE cars from large cities Rideshare all urban car trips Reduce motorway speeds to less than 100 km/h	Low-emission zones Access restrictions Parking restrictions Congestion charges Investment in cycling lanes and public transportation Speed limits	Public health Reduced congestion Beautification and liveability Road safety Lower noise pollution	🟢	120	160
Shift regional flights to high-speed rail	Replace all flights <1h where high-speed rail is a feasible alternative	High-speed rail investment Subsidies for high-speed rail travel Price premiums	Lower air pollution Lower noise pollution	🟡	-1	-210
Moderate heating and cooling in buildings	Target average set-point heating temperature of 19 °C and cooling temperature of 24 °C	Awareness campaigns Corporate targets	Public health Energy affordability	🟢	180	175
Electricity saving measures in homes	Lower hot water and laundry temperature by 10 °C; line dry clothes if possible Switch off lighting and appliances when not in use	Awareness campaigns Consumption feedback	Energy affordability	🔴	60	70

🟢 = high impact 🟡 = medium impact 🔴 = low impact

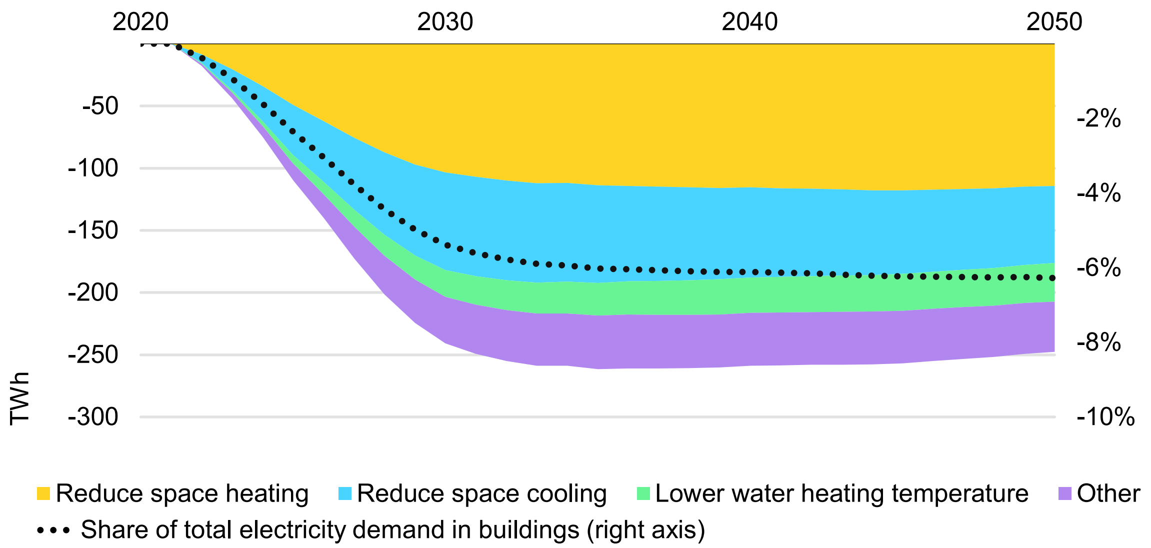
Note: Negative savings for the shift of regional flights to high-speed rail reflect an increased electricity demand in the rail sector from catering for those passenger kilometres that would otherwise have involved flights <1h.

Behavioural changes and electricity demand

In the NZE, behavioural changes in the G7 reduce electricity demand by 360 TWh (3.8%) in 2030 and 200 TWh (2%) in 2050. The reduction in impacts between 2030 and 2050 is due to efficiency improvements in end-use equipment and increased digitalisation.

Most of the savings happen because of measures in the buildings sector, where a range of behavioural changes in homes and commercial buildings cuts electricity consumption by 5%-6% between 2030 and 2050. By 2050, the savings from behavioural changes are around 250 TWh. Three-quarters of the savings are from just two behavioural changes: moderating space heating temperatures to 19 °C (from an average of 22.4 °C today) and raising space cooling temperatures to 24 °C (from an average of 22.7 °C today).

Impact of behavioural changes on electricity consumption in buildings in the Net Zero Emissions by 2050 Scenario, 2020-2050



Note: "Other" includes saving electricity in lighting and appliance-use, decreasing laundry temperatures by 10°C on average and line-drying instead of using the tumble dryer 6 months of the year.

Not all behavioural changes reduce demand for electricity. Shifting travel away from regional flights to high-speed rail is a key measure[5] in the NZE: without it, emissions from regional flights in the G7 would be more than double their level in the NZE in 2050. However, the increase in high-speed rail travel adds 210 TWh to electricity demand in the G7 in 2050 (an increase of about 1.4%), with the result that electricity demand for rail in the G7 in 2050 is six times what it was in 2019.

How to bring about the behavioural changes

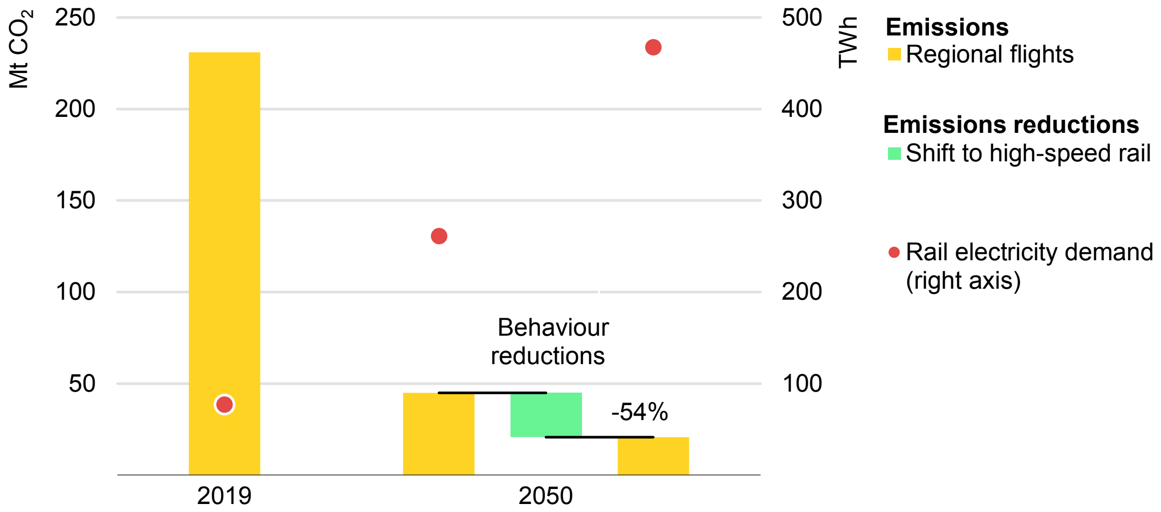
Most of the behavioural changes in the NZE could be directly influenced or mandated by governments, using a variety of policy instruments. Most measures on roads, for example, could be tackled using pricing schemes or direct legislation (as in the case of reducing speed limits). The more discretionary behavioural changes, such as reducing wasteful energy use in homes and offices, could be promoted via awareness campaigns and other means. Ultimately, all the behavioural changes in NZE will rely to some extent on the active support of

[5] This happens to the maximum extent possible in the NZE subject to the following constraints: travel times are similar to aviation; new rail routes avoid water bodies and tunnelling through elevated terrain; and centres of demand are sufficiently large to ensure that high-speed rail is economically viable.

people and businesses, as even legislative and regulatory changes depend on public acceptance.

Unlocking behavioural changes would also require governments to invest in public infrastructure and services. For example, the reduced reliance on private cars in the NZE is accompanied by a 16% increase in trips in the G7 made by bus in 2050, and there would also need to be provision of extra cycle lanes and other measures to support active mobility. Similarly, the shift in the NZE from regional flights to high-speed rail would necessitate building around 40 thousand kilometres of new track in the G7 by 2050.

Impacts in the G7 of shifting regional aviation to high-speed rail in Net Zero Emissions by 2050 Scenario, 2019 and 2050

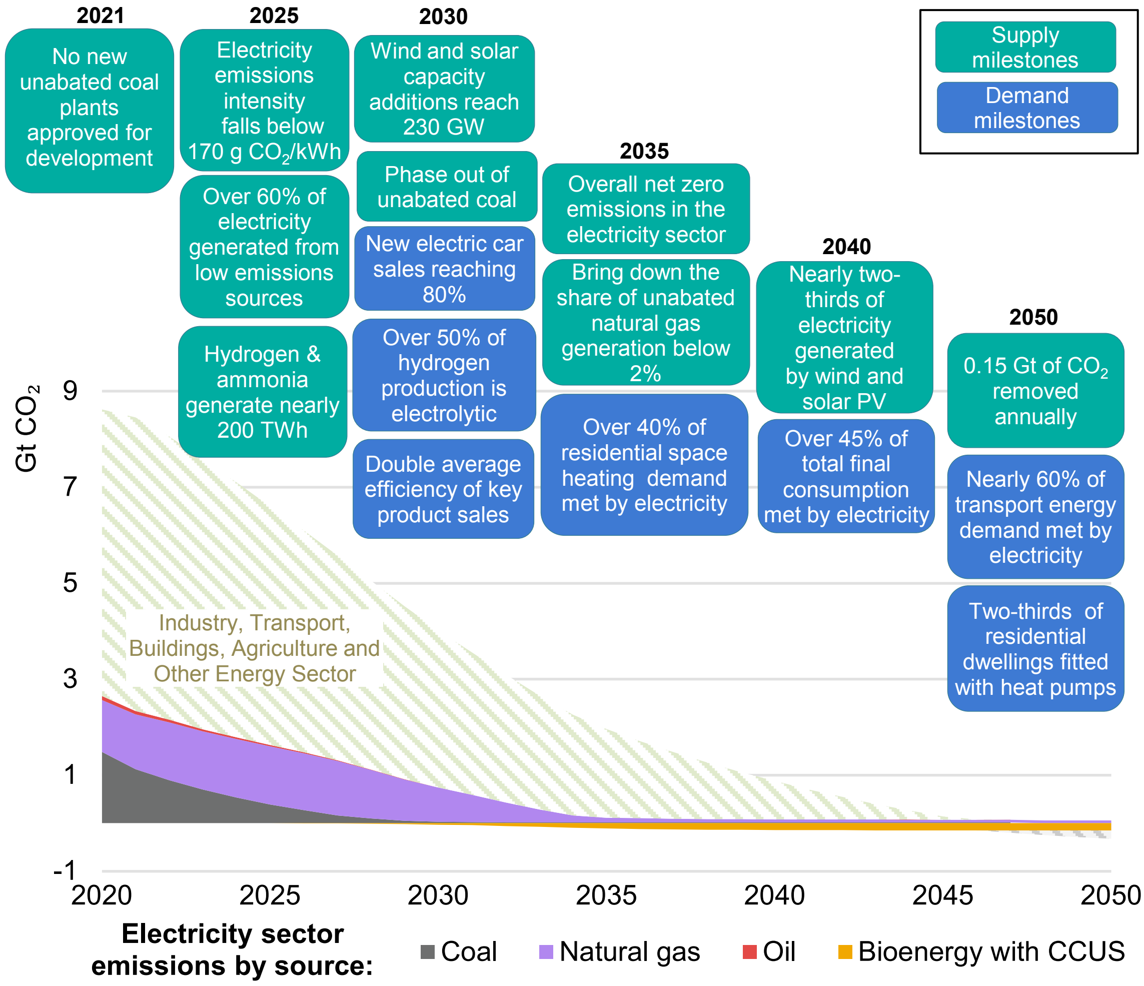


With good public infrastructure, high levels of urbanisation and widespread public awareness of environmental issues, the G7 is well placed in terms of the behavioural changes in the NZE. Over time, G7 leadership on promoting and enabling behavioural changes could help make such changes the norm elsewhere, which is an essential condition for the achievement of net zero emissions by 2050 globally. However, policy interventions in all countries would have to take into account cultural preferences and existing behavioural norms to be effective, and the onus would rest on governments to explain clearly and convincingly what changes are needed and why these changes are necessary.

Milestones and principles for action

Achieving net zero electricity in the G7 by 2035 calls for taking immediate steps to accelerate the clean energy transitions that are already underway in G7 countries. The pathway described in this report, which is consistent with the one set out in the IEA report *Net Zero by 2050: A Roadmap for the Global Energy Sector*, provides a comprehensive and cost-effective route to achieve net zero electricity in the G7 without compromising energy security, and includes milestones for both electricity demand and supply.

G7 energy-related emissions and electricity sector milestones in the Net Zero Emissions by 2050 Scenario, 2020-2050



The milestones for G7 electricity in the NZE are intended to help inform stakeholders of the scale and pace of change needed as well as to provide benchmarks for policy ambitions and progress. They cover both electricity demand and electricity supply.

On the supply side, critical milestones for the G7 include the full phase-out of unabated coal by 2030, sharply cutting unabated gas use by mid-2030s, and scaling up wind and solar PV capacity additions to a combined 230 GW by 2030. On the demand side, the efficiency of major new appliances needs to double, and most electric car sales be electric by 2030. The roadmap also calls for tripling the amount of electricity system flexibility over the next decade to maintain electricity security throughout the accelerated transition. The challenge of meeting additional flexibility needs is common to all G7 countries and is one that awaits most countries on the path to net zero.

While other pathways to net zero are also possible, the pathway described in this report benefits from the IEA's world-class energy market data and its access to the latest technology information, builds upon a detailed review of policies, pledges and preferences in G7 countries. Like other IEA reports, this report also benefits from continuous consultation with leading experts in energy from around the world.

Principles for action

The G7 can lead by example in moving to net zero electricity in aggregate by 2035. Doing so would help to maintain the hope of limiting global average temperature increases to 1.5 °C. The G7 could demonstrate their leadership specifically by phasing out unabated coal by 2030, and by developing and implementing the technologies needed to address rising flexibility needs, while maintaining electricity security and supporting the accelerated electrification of transport, industry and buildings. Ambitious visions need to be backed up by clear strategies for implementation, and the IEA stands ready to support governments with this work.

The G7 also has significant potential to support accelerated transitions around the world through the steps it takes to move to net zero electricity. International cooperation to drive innovation forward on critical technologies would help to clear the way for all countries by widening the range of commercial options available to address their own specific challenges. Sharing knowledge and lessons learned among governments would also be an efficient and effective means of addressing common barriers to electricity sector transitions. Areas in which there could be value in sharing experience include the use of new technologies, sector coupling, the expansion of digitalisation, and efforts to enhance climate resilience and overall electricity security. There are a broad range of international initiatives to support collaboration and several international forums, such as the Clean Energy Ministerial and the IEA Technology Collaboration Programmes (see Annex), could provide appropriate platforms to report progress on a regular basis to the global energy community. Supporting networks of system operators and regulators could also facilitate the exchange of enabling information for clean energy transitions.

The G7 could, in addition, strengthen support for electricity sector transitions in emerging market and developing economies. International collaboration needs to go beyond technology to cover policy frameworks, market design and programme costs, while recognising that every country faces different circumstances. It also needs to cover finance. The recent IEA report on Financing Clean Energy Transitions in Emerging and Developing Economies estimated that the average cost of reducing emissions in these economies is around half the level in advanced economies. Mobilising capital to finance these transitions is essential to reaching global climate change objectives and reducing the cost of capital for clean energy technologies could play a big part in making transitions as affordable and inclusive as possible. Assisting emerging market and developing economies with technology demonstration and adoption would similarly facilitate a rapid move away from unabated coal-fired electricity generation and achieving net zero electricity around the world.

The transition to a cleaner energy system will benefit everyone, and it is worth noting in this context that the consequences of climate change are felt with particular severity in many lower income countries. The transition will however involve some difficult changes, and it is crucial that domestic energy policies address affordability and fairness in a progressive manner so as to ensure that benefits of the transition are shared across individuals and communities. This is as relevant to G7 members as it is to other countries. One example of a policy in this domain is the European Green Deal, which will devote a quarter of carbon pricing instrument revenue to a Social Climate Fund to alleviate fuel poverty. Another is the US Government Justice40 Initiative, which plans to deliver 40% of the overall benefits of climate investments to disadvantaged communities. To inform future discussions, the IEA has established the Global Commission on People-Centred Clean Energy Transitions, which brings together government leaders and ministers, energy experts and prominent thinkers. Commission members will explore questions related to the social and economic impacts of clean energy transitions on individuals and communities and will put forward key recommendations in advance of COP26 in November 2021.

Annexes

Tables for scenario projections

General note to the tables

This annex includes aggregated historical and projected data for G7 members for the following four datasets:

- Electricity generation by total and by source in terawatt-hours (TWh)
- Installed electrical capacity in gigawatts (GW)
- Carbon dioxide (CO_2) emissions in electricity and heat sectors in million tonnes of CO_2 emissions (Mt CO_2)
- Share of electricity in total final consumption in percentages (%).

Each dataset is given for the Net Zero Emissions by 2050 Scenario.

Common abbreviations used in the tables include: CCUS = carbon capture, utilisation and storage. Consumption of fossil fuels in facilities without CCUS are classified as “unabated”.

Both in the text of this report and in these annex tables, rounding may lead to minor differences between totals and the sum of their individual components. Nil values are marked “-”.

Data sources

The World Energy Model (WEM) is a very data-intensive model covering the global energy system. Detailed references on databases and publications used in the modelling and analysis may be found on the IEA website.

The formal base year for the scenario projections is 2019, as this is the most recent year for which a complete picture of energy demand and production is available. However, we have used more recent data when available. Estimates for the year 2020 are based on updates of the IEA Global Energy Review reports which are derived from a number of sources, including the latest monthly data submissions to the IEA Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA Market Report series that cover coal, oil, natural gas, renewables and electricity.

Historical data for gross electrical capacity are drawn from internal and external sources, including the S&P Global Market Intelligence World Electric Power Plants Database (March 2021 version) and the International Atomic Energy Agency PRIS database.

Definitional note: Electricity tables

Electricity generation expressed in terawatt-hours (TWh) and installed electrical capacity data expressed in gigawatts (GW) are both provided on a gross basis (i.e. includes own use by the generator). Projected gross electrical capacity is the sum of existing capacity and additions, less retirements. While not itemised separately, other sources are included in total electricity generation. Installed capacity for hydrogen and ammonia refers to full conversion only, not including co-firing with natural gas or coal.

Definitional note: Indicators

Total final consumption (TFC): Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens), transport, buildings (including residential and services) and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

CO_2 emissions from the electricity sector include carbon dioxide emissions from the combustion of fossil fuels and non-renewable wastes.

G7 electricity generation (TWh)

	Historical			Net Zero Emissions by 2050 Scenario					Shares		
	2010	2019	2020	2030	2035	2040	2045	2050	2020	2030	2050
Total generation	**9 458**	**9 258**	**8 953**	**11 093**	**12 821**	**14 974**	**16 348**	**16 944**	**100**	**100**	**100**
Renewables	1 635	2 535	2 733	6 627	9 675	11 997	13 354	13 907	31	60	82
Solar PV	29	300	356	1 616	2 519	3 192	3 609	3 821	4	15	23
Wind	258	770	858	3 035	4 863	6 318	7 120	7 368	10	27	43
Hydro	1 074	1 075	1 116	1 303	1 367	1 408	1 456	1 501	12	12	9
Bioenergy	245	353	365	559	726	797	829	841	4	5	5
Nuclear	2 134	1 830	1 695	1 901	1 862	1 818	1 887	2 002	19	17	12
Hydrogen and ammonia	-	-	-	417	538	433	413	407	-	4	2
Fossil fuels with CCUS	-	1	1	201	515	587	569	501	0	2	3
Unabated coal	3 255	1 939	1 601	24	0	0	0	0	18	0	0
Unabated natural gas	2 168	2 793	2 777	1 898	207	115	102	103	31	17	1
Oil	234	131	118	1	0	0	0	0	1	0	0

G7 electrical capacity (GW)

	Historical			Net Zero Emissions by 2050 Scenario					Shares		
	2010	2019	2020	2030	2035	2040	2045	2050	2020	2030	2050
Total capacity	**2 446**	**2 765**	**2 830**	**4 196**	**5 387**	**6 237**	**6 710**	**6 948**	**100**	**100**	**100**
Renewables	600	1 064	1 143	2 830	3 935	4 686	5 090	5 239	40	67	75
Solar PV	36	274	321	1 264	1 834	2 211	2 424	2 517	11	30	36
Wind	130	312	341	987	1 453	1 782	1 944	1 981	12	24	29
Hydro	371	390	391	429	444	453	460	466	14	10	7
Bioenergy	57	79	81	119	149	161	165	165	3	3	2
Nuclear	313	273	269	256	265	279	294	308	10	6	4
Hydrogen and ammonia	-	-	-	67	353	386	384	397	-	2	6
Fossil fuels with CCUS	-	0	0	33	86	114	125	131	0	1	2
Unabated coal	585	462	446	77	3	-	-	-	16	2	-
Unabated natural gas	752	822	829	674	319	236	202	196	29	16	3
Oil	194	137	134	12	9	8	6	4	5	0	0
Battery storage	1	7	9	247	416	526	608	673	0	6	10

G7 electricity indicators

	Historical			Net Zero Emissions by 2050 Scenario				
	2010	2019	2020	2030	2035	2040	2045	2050
Share of electricity in TFC	**21%**	**21%**	**22%**	**30%**	**38%**	**46%**	**52%**	**56%**
Electricity CO_2 emissions (Mt CO_2)	**4 258**	**3 128**	**2 805**	**753**	**0**	**-61**	**-76**	**-83**
Coal	3 125	1 875	1 567	30	14	14	15	12
Oil	181	103	93	1	0	0	0	0
Natural gas	952	1 150	1 145	752	101	66	59	58
Bioenergy and waste	-	-	-	-30	-115	-142	-150	-152

Opportunities for Scaling Up Power System Collaboration for Glasgow COP26 – Overview of international collaboratives on clean power transitions

Launched by the UK COP26 Presidency, the Energy Transition Council (ETC) brings together 21 countries and international organisations to boost technical, economic and social solutions enabling the transition to low-cost, low-carbon, inclusive and resilient power systems. A major focus, the ETC helps to improve access to finance through country dialogues, policy analysis and advice on investment and an international ecosystem of priority projects and blended finance and by mobilising guarantees and risk-mitigating instruments from Development Finance Institutions and Donor Governments. The ETC aims at doubling the rate of investment in new power generation by 2030, attract private capital, boost universal access to energy under the UN SDG7 goal, and support a just transition for people and communities heavily reliant on the coal economy.

In 2021, the United Kingdom and India set up the Global Green Grids Initiative (GGI), which will be officially launched at the UK COP26 in Glasgow, building upon India's vision of "One Sun One World One Grid" and the UK India Climate Compatible Growth (CCG). The GGI engages countries across ASEAN, African Union, European Union, India, Latin America and the Caribbean, United Kingdom and the United States on interconnected grids that enable the fast uptake of renewable energy. The ETC wants to accelerate existing global, regional and national initiatives on green grids, such as One Sun One World One Grid (ISA), North Sea offshore grids (UK, EU), regional integration projects in ASEAN, in Central Asia, in Africa, such as the continental transmission masterplan and regional power pools, as well as China's Global Energy Interconnection Development and Cooperation Organisation. GGI will support the collaboration of regulators to lift the barriers to grid development and work jointly with Mission Innovation on RDD&D investment needs. Under the GGI several initiatives will be launched, one of which is a global accelerator for regulatory collaboration. This initiative seeks to create a platform where regulators can share experiences and facilitate peer-to-peer learnings, thus enabling regulators to tackle the challenges that are related to the clean energy transitions.

Led by China, Italy and the United Kingdom, the new Mission Innovation's Green Powered Future Mission aims to demonstrate by 2030 that power systems can effectively integrate up to 100% variable renewable energy (VRE) in their generation mix while maintaining a cost-efficient, secure, and resilient system.

Launched in 2021 by a large coalition of countries and companies around the world, this mission works on three technical preconditions for the system integration of VRE: 1) affordable and reliable VRE technologies – reducing cost and increasing efficiency, resilience, and reliability of VRE technologies in various climates and system configurations, 2) system flexibility and market design – unlocking a range of cost-effective flexibility options, including storage, smart power grids infrastructure and AI advanced control solutions and 3) system integration, data and digitalisation support to enable cross-sectoral flexibility and deliver a cost-efficient, fully integrated power system.

A global collaborative of power system operators around the world, the Global Power System Transformation Consortium (G-PSTC) aims to dramatically accelerate the transition to low-emission and low-cost, secure, and reliable power systems, contributing to >50% emission reductions over the next 10 years. The mission and activities are developed by the National Grid Electricity System Operator UK, California Independent System Operator (CAISO), Australia Energy Market Operator (AEMO), Ireland's System Operator (EirGrid), Electric Reliability Council of Texas (ERCOT), and Denmark's System Operator (Energinet). The work is supported by a core team of leading international scientific research organisations, international organisations and multilateral and regional development banks, including IEA, World Bank, USAID, GIZ, ADB and EBRD. The G-PSTC mobilised USD 2 billion of government and donor support for technical, market, and workforce solutions that will unlock more than USD 10 trillion of private sector investment.

The Super-Efficient Equipment and Appliance Deployment (SEAD) has been elevating the discussion on equipment and appliance energy efficiency policies globally for over a decade and is recognised as a key international platform for global and regional exchanges on policymaking for product energy efficiency. A CEM initiative led by the UK, EU, India and Sweden and coordinated by the IEA, SEAD has 21 members with a strong economic and geographical diversity. In 2021 the UK and the IEA joined forces to launch a Product Efficiency Call to Action for COP26 and beyond to encourage governments to increase the ambition of product policy. The Call to Action is being coordinated through SEAD and aims to set countries on a trajectory to double the efficiency of key products sold globally by 2030 in four categories: industrial motor systems; residential lighting, ACs and refrigerators. The collective ambition of the membership, to be announced at COP26, should deliver USD 140 billion in savings or more as the partnership grows. SEAD is forging partnerships with the private sector and development assistance donors to help countries achieve this ambition. In addition to being a CEM initiative, SEAD is also expected to be associated with the Energy Efficiency

Hub, hosted by the IEA. The Energy Efficiency Hub started its work in 2021 and will develop its work programme to encourage and foster exchange and collaboration on key energy efficiency policies across its members from IEA and G20 countries.

The Clean Energy Ministerial (CEM), was established in 2009 and its multilateral Secretariat has been hosted by the IEA since 2017. The CEM promotes a wide range of country-driven initiatives and campaigns in support of the global clean energy transition. In the power sector, there are several relevant collaborative activities, notably the International Smart Grid Action Network (ISGAN), the 21st Century Power Partnership (21CPP), the Nuclear Innovation: Clean Energy Future (NICE Future) initiative and Flexible Nuclear Campaign, the Super-Efficient Equipment and Appliance Deployment (SEAD) initiative and a Power System Flexibility workstream. CEM and MI are jointly hosting Ministerial meetings each year and many initiatives are closely interlinked, together with the IEA TCP network.

The International Smart Grid Action Network (ISGAN) is an IEA Technology Collaboration Programme (TCP) established as part of the CEM in 2011 which operates under the leadership of Italy, India and the US. ISGAN promotes smarter, cleaner electric grids for maintaining a reliable, resilient, and secure electricity infrastructure that can meet future demand growth, respond to a growing range of customer power needs, and integrate increasingly diverse energy sources. Working closely with Mission Innovation, ISGAN supports governments and industry with insights and recommendations to high-level decision-makers, development and exchange of knowledge and expertise on smarter, cleaner, and more flexible and resilient electricity grids.

The CEM's 21CPP Initiative was established in 2012 to provide a mechanism for government and the private sector to help advance the development and deployment of integrated power sector policies and programs. It currently operates under the leadership of Brazil, India and the US. Its focus lies in energy supply, delivery, and end-use, and aims to synthesize knowledge and technical analysis from the domains of energy systems integration, smart grids, and energy efficiency. 21CPP produces global "thought-leadership" reports on relevant topics associated with power system transformation. 21CPP also conducts technical assistance in selected member countries through its operating agent the National Renewable Energy Laboratory (NREL), hosts technical exchanges with select institutes, and collaborates closely with the CEM on cross-cutting activities.

Launched at the G20 Energy and Climate Ministerial 2021, the Digital Demand-Driven Electricity Networks (3DEN) aims to accelerate progress on power system modernisation and effective utilisation of distributed energy resources through policy, regulation, technology and investment guidance. With the support of Italy's Ministry for Ecological Transition, the IEA runs a four-year work programme to develop and disseminate actionable tools and guidance based on IEA analysis, case studies and experiences from across the world. Created at the 2019 Climate Action Summit, 3DEN has a global focus and contributes to and works in coordination with the IEA Clean Energy Transitions Programme.

The IEA TCP of User-Centred Energy Systems (UsersTCP) has the mission to provide evidence from socio-technical research on the design, social acceptance and usability of clean energy technologies to inform policy making for clean, efficient and secure energy transitions. The UsersTCP encourages peer-to-peer learning and offers the Global Observatory as a forum for international collaboration to understand the policy, regulatory, social and technological conditions necessary to support the wider deployment of peer-to-peer, community self-consumption and transactive energy models.

Another active TCP of the IEA supports the Energy Conservation and Energy Storage (ECES) with a view to facilitate integral research, development, implementation and integration of energy storage technologies to optimise the energy efficiency of all kinds of energy system and to enable the increasing use of renewable energy instead of fossil fuels. ECES is looking, among others, into electrical energy storage technologies such as batteries, and pumped hydro, and sector coupling through the electrification heating and transport.

Launched by the UK and Canadian governments at COP23 in 2017, the Powering Past Coal Alliance (PPCA) has created momentum globally with a strong international coalition of national and sub-national governments, businesses, finance and organisations working to advance the transition from unabated coal power generation to clean energy. In 2021, PPCA has over 100 members who are playing a pivotal role in driving global coal phase-out efforts. The PPCA aims to 1) secure commitments from governments and the private sector to phase out existing unabated coal power; 2) encourage a global moratorium on the construction of new unabated coal-fired power plants; 3) shift investment from coal to clean energy, including by working to restrict financing for coal-fired projects; and 4) achieve coal phase-out in a sustainable and economically inclusive way, including appropriate support for workers and communities.

Abbreviations and acronyms

IEA	International Energy Agency
AC	alternating current
ATF	accident-tolerant fuels
bbl	barrel
bbl/d	barrels per day
bcm	billion cubic metres
bcm/yr	billion cubic metres per year
BECCS	bioenergy carbon-capture and storage
CAD	Canadian dollar
CCGT	combined cycle gas turbine
CCUS	carbon capture usage and storage
CEM	clean energy ministerial
cm/s	centimetres per second
CO_2	carbon dioxide
COP26	the 26th Conference of the Parties
CSP	concentrated solar power
DAC	direct air capture
DLE	dry low emission
DSR	demand-side response
ECES	energy conservation and energy storage
EJ	exajoule
ETS	Emissions Trading Scheme
EU	European Union
EUR	Euro
EV	electric vehicle
FID	final investment decision
GBP	pound sterling
gCO_2	gram
gCO_2/kWh	grams of carbon dioxide per kilowatt hour
GDP	gross domestic product
GE	General Electric
GHG	greenhouse gasses
GJ	gigajoule
Gt	gigaton
GT	gas turbine
GW	gigawatt
GWh	gigawatt hour
HVDC	high voltage direct current
IHI	Ishikawajima-Harima heavy industries
ISGAN	international smart grid action network

JPY	Japanese yen
km	kilometre
kWh	kilowatt hour
LED	light-emitting diodes
Li-ion	lithium ion
m	meter
MARI	manually activated reserves initiative
Mt	megaton
NDC	nationally determined contributions
NOx	nitrogen oxide
NZE	Net Zero Emissions by 2050 Scenario
ORE	offshore renewable energy
PJ	petajoule
PV	photovoltaics
PVPS	programme on photovoltaic power systems
R&D	research and development
RD&D	research development and deployment
REV	reforming energy vision
RIIO	revenue incentives innovation outputs
SMR	small modular reactor
t	tonne
TCP	technology collaboration programmes
TES	total energy supply
TFC	total final consumption
TPED	total primary energy demand
TPES	total primary energy supply
TRL	technology readiness level
TWh	terawatt-hours
USD	United States dollar
VRE	variable renewable energy
yr	year

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Typeset in France by IEA - October 2021
Cover design: IEA
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