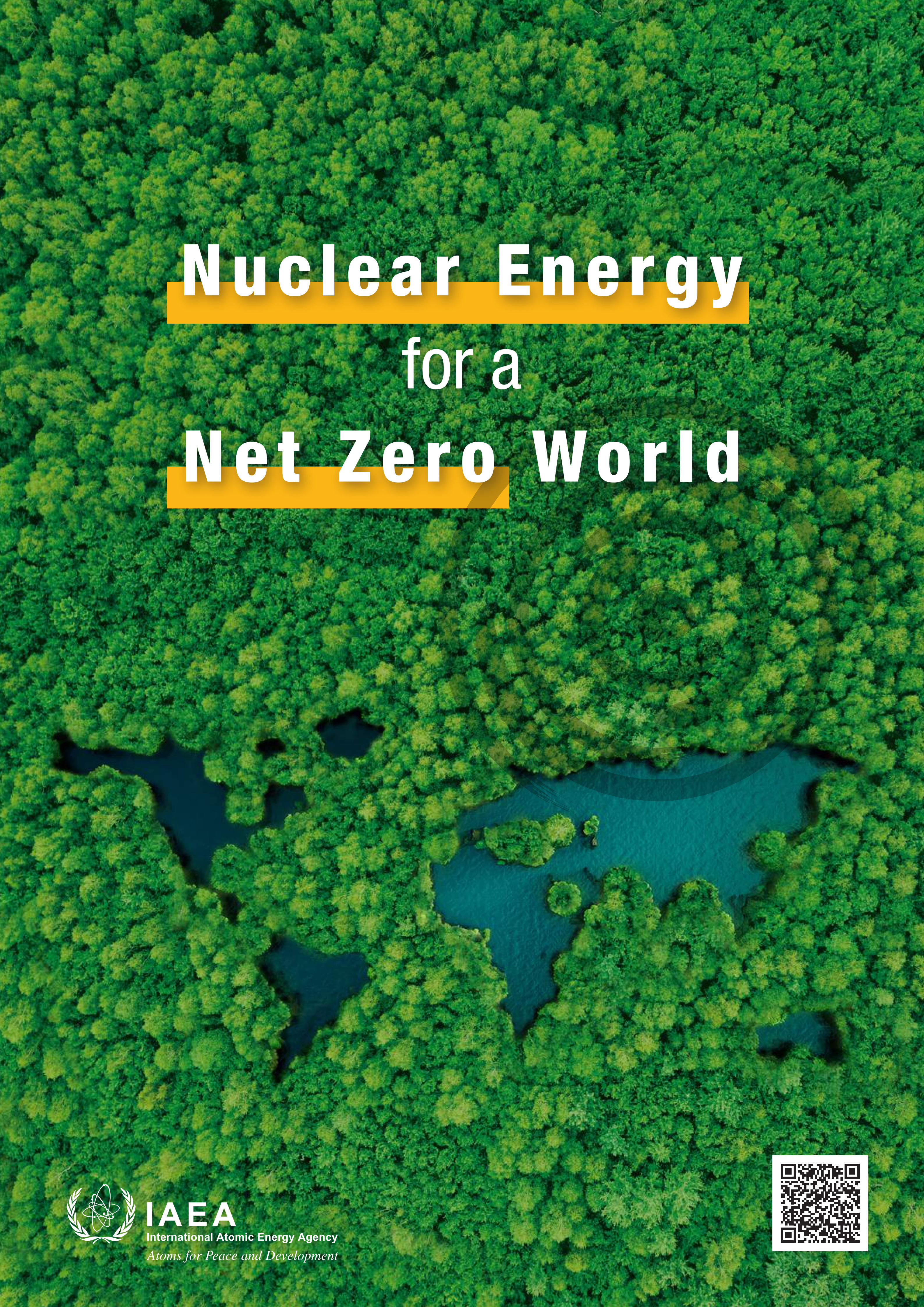
Nuclear Energy for a Net Zero World



IAEA
International Atomic Energy Agency
Atoms for Peace and Development

FOREWORD

Climate change presents us with a stark challenge: to reduce greenhouse gas emissions to net zero much faster than we have done so far, or to face the increasingly catastrophic consequences of an inexorably warming planet. Warnings are all around us. The ever more frequent and devastating wildfires and floods are the result of a changing climate, confirmed in the most sombre report yet by the experts of the Intergovernmental Panel on Climate Change (IPCC). Human activity is changing the Earth's climate in unprecedented and irreversible ways. The IPCC's findings tell us the world must mobilize faster and at greater scale than it has done so far.

Policy makers, investors, scientists and citizens must act decisively. One crucial action is to make science based decisions to determine an energy strategy. It is time to put nuclear on an even footing with other clean technologies. Without it, we will not meet the challenge that stands before us.

Globally, nuclear power plants produce more than one quarter of all low carbon electricity. Over the past five decades, nuclear power has cumulatively avoided the emission of about 70 gigatonnes (Gt) of carbon dioxide (CO_2) and continues to avoid more than 1 Gt CO_2 annually. In addition, nuclear power is a dispatchable and flexible source of electricity. At a time when the use of variable renewables is growing, nuclear power makes a key contribution to energy supply security and grid stability. We caught a glimpse of a future low carbon energy mix in several countries when the world went into its pandemic driven lockdown. The ensuing drop in electricity demand partly priced out fossil fuels leaving nuclear and hydro to ensure continuity of supply, while wind and solar operated when conditions allowed.

The choice of energy sources remains a sovereign decision and every country has different needs. It is notable, however, that more and more scientists, policymakers and members of the public are recognizing nuclear as a critical part of decarbonized energy systems. In addition to the IPCC's clear recognition of nuclear energy's role in addressing the climate crisis, a similar message has been reiterated by energy experts, including those at the International Energy Agency. The United Nations Economic Commission for Europe calls nuclear power an "indispensable tool" for achieving the Sustainable Development Goals. Opinion polls in countries such as the USA, for example, are showing that the public supports strong political action on climate change and that a clear shift in favour of nuclear power is under way.

The use of nuclear power continues to grow, albeit more slowly than many other low carbon sources. Today, it provides 10% of the electricity produced worldwide. In 2020, the number of IAEA Member States operating nuclear power plants increased to 32 after Belarus and the United Arab Emirates connected their first reactors to the grid. Of these operating countries, 19 have projects in place to expand their nuclear power capacity. Around 30 newcomer countries are embarking on, or considering, nuclear power. Bangladesh and Turkey, for example, are already well advanced in the construction of their first nuclear power plants. These are small but encouraging steps: nuclear generation will need to double by 2050 if we are to reach our net zero climate goals, according to experts at the IEA.

The IAEA's high case projection envisages a doubling of nuclear's present electricity production capacity by 2050. This relies on both lifetime extensions of existing plants and about 550 gigawatts (GW) of new build. According to our low case scenario, however, a lack of willingness to embrace nuclear could lead to almost no change in capacity by 2050, causing us to fall well short of doing what is necessary to avoid a climate catastrophe.

While electricity generation is responsible for close to 40% of the global CO_2 emissions produced by the energy sector, the other 60% or so is generated primarily through the use of fossil fuels in industry, heating in buildings and transport. Hard-to-abate areas will require us to shift to low carbon fuels such as hydrogen. Of all low carbon energy sources, nuclear power is one of the few that can generate electricity, heat and hydrogen. Many innovative nuclear technologies, such as small modular reactors (SMRs) and advanced nuclear reactors, are providing plenty of options.

Governments, industries and international organizations have important roles to play in supporting innovation and the early deployment of all clean energy technologies. This is particularly critical because almost half of the emissions reductions needed to reach net zero by 2050 will have to come from new low carbon technologies, including advanced nuclear reactors. Clearly nuclear must have a seat at the table anytime energy and climate policies are discussed. As we head toward this year's vital United Nations Climate Change Conference (COP26) in Glasgow, it is time to make evidence based decisions and ramp up the investment in nuclear. The cost of not doing so is far too high to bear.

Rafael Mariano Grossi
Director General, IAEA

COUNTRY STATEMENTS

Canada

Climate change is the greatest challenge of this generation. In December 2020, the Government of Canada introduced A Healthy Environment and a Healthy Economy — Canada's Strengthened Climate Plan (SCP) — that details plans to enhance our price on carbon and advance the next wave of non-emitting technologies that can enable a just transition toward a net zero future by 2050. During the Leaders' Climate Summit in April 2021, Canada committed to enhancing its 2030 emissions reduction target under the Paris Agreement to 40–45% below 2005 levels.

To help reach these targets, Canada committed to phasing-out coal-fired power by 2030, with several provinces also taking action to support this commitment. The Government of Canada has provided $C185 million to help transition impacted communities by diversifying their economies and helping workers develop new skills so they can lead and succeed in the transition to a zero emissions future.

Internationally, Canada is co-leading the Powering Past Coal Alliance — a network of over 125 national and sub-national governments, businesses and organizations — to advance the transition from coal power generation to clean energy.

Nuclear energy is also an important part of Canada's non-emitting energy mix. As a driver of innovation and a source of expertise, we are well positioned to be a world leader in the safe and responsible development of this resource. The Government of Canada's first priority when it comes to nuclear energy is protecting the health and safety of Canadians and the environment, and that is why Canada is currently undertaking reviews for both our radioactive waste policy framework and the nuclear liability limit for power reactors. Both of these initiatives will ensure Canada maintains its leadership in providing clean energy in a safe and environmentally conscious manner.

Our robust supply chain is ready to support global emission reduction and energy security goals with both our Canadian Deuterium Uranium (CANDU) reactors and advanced nuclear technologies, including small modular reactors (SMRs). In fact, Canada continues to refurbish reactors at home and abroad, and continues to work on the potential of CANDU new build projects internationally.

SMRs represent the next wave of nuclear innovation that could play a critical role in reaching net zero by 2050 by enabling a deep decarbonization of the electricity, industry and mining sectors, and could be an alternative to diesel for remote communities.

That's why in December 2020, the Government of Canada launched Canada's SMR Action Plan with over 100 partners from across the country outlining over 500 concrete actions that partners are taking to advance the development, demonstration and deployment of SMR technologies at home and around the globe. This built off the momentum of Canada's Small Modular Reactor Roadmap, released in 2018. The federal government has also recently announced funding of over $C70 million to support research and development for SMR technologies in Canada.

It is clear that in order to achieve Canada's ambitious climate targets by 2050, we must incorporate the use of all available sources of non-emitting energy and technology. That is why Canada, with a full spectrum of nuclear capabilities, innovative technology and expertise in low carbon and sustainable solutions, is ready to work with like-minded countries on the road to a just and clean transition that incorporates a diverse energy mix including nuclear energy.

Jean-François Tremblay, Deputy Minister of Natural Resources

China

In September 2020, President Xi Jinping announced at the 75th UN General Assembly that China will strive to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. This is a major strategic decision made by China to promote building a community with a shared future for mankind, and achieve sustainable development. As a participant, contributor and leader in combating global climate change, China adheres to the conviction that lucid waters and lush mountains are invaluable assets, and is dedicated to building a clean, low-carbon, secure and efficient energy system.

As of the end of 2020, China's non-fossil energy sources, accounting for 44.8% of the total installed electricity generating capacity, provided 15.9% of primary energy consumption. The carbon emissions intensity of the economy was down by 18.8% compared with 2015, and down by 48.4% compared with 2005, exceeding the 2020 climate action target set by China as a commitment to the international community. The Chinese government intends in the period 2021–2025 to vigorously develop new energy sources, to take active and well-ordered steps to develop nuclear energy on the basis of ensuring safety and security, and to promote the clean and efficient use of coal. Energy consumption and carbon dioxide emissions per unit of GDP will be reduced by 13.5% and 18% respectively.

As a clean, low-carbon and efficient base-load energy source, nuclear power plays an important role in the achievement of the UN 2030 Agenda for Sustainable Development. It is also an important option for China to secure the energy supply, optimize the energy mix, and achieve the goals of peak carbon emissions and carbon neutrality. As of June 2021, there were 51 operating nuclear power plants with an installed capacity of 49.569 gigawatts (GW), and 17 under construction with an installed capacity of 18.616 GW on the Chinese mainland. At present, the world's first HPR1000 — China's independent third-generation Hualong One reactor technology — and the first overseas HPR1000 have been put into operation successively. Projects to demonstrate fast reactor and multi-purpose small modular reactor (SMR) technologies are under construction. The applied research on using nuclear energy for heating and hydrogen production has also steadily advanced. In addition, a next generation experimental magnetically-confined fusion device, China Tokamak HL-2M, has achieved its first discharge, while another fusion installation, the Experimental Advanced Superconducting Tokamak recently achieved plasma operation for 101 seconds.

With adherence to the new development concept of Innovation, Coordination, Green, Open And Sharing, and the principles of safety first and innovation-driven growth, China has blazed a trail of nuclear energy development with Chinese characteristics, and built strong capacities across the whole industry supply chain. China stands ready to strengthen mutually beneficial cooperation with other countries to share its best practices and experiences and make joint efforts to upgrade global nuclear energy infrastructure, advance scientific and technological innovation, and promote human resources development, so as to make positive contributions to the safe and peaceful uses of nuclear energy for the benefits of the mankind, as well as to play a constructive role in addressing the global challenges of climate change, and achieving the UN Sustainable Development Goals.

ZHANG Kejian, Chairman, China Atomic Energy Authority

Finland

In Finland, nuclear power is an integral and growing part of our energy mix. Our national goal is to become climate neutral — net zero — by 2035, a task where we clearly need all available clean energy technologies.

Today about 30% of our electricity production comes from the four operating nuclear power plants, two at the Loviisa site and two at the Olkiluoto site. In the near future, the nuclear production will grow when Olkiluoto 3 enters into operation with 1600 megawatts (MW) of electrical capacity. We expect the nuclear generation to amount to over 40% of total electricity production then. Moreover, there is a plan to build a new nuclear power plant at Hanhikivi with a capacity of 1200 MW; this project is in construction license application phase.

Today, there is increasing interest in new small and modular reactor technologies. In Finland the main focus is on heat production at this stage. We are running a governmental project to assess the needs for legislation and licensing of these reactor types. At the same time research institutes are studying the technology feasibility and needs for development.

For the use of nuclear energy, the solution of waste management is essential. In Finland we have decided that waste management needs to be solved and implemented during the electricity production phase. This is to guarantee the responsibility and sustainability of using nuclear energy in the society. We require waste management solutions as a condition of NPP operating licenses. In the 1980s it was stated in the in-principle decision of our parliament that a high level waste repository should be available around the 2020s for spent nuclear fuel. This is now accomplished by Posiva in Olkiluoto. The underground repository is under construction and Posiva is preparing the first operating license application for a spent nuclear fuel repository in the world.

Stable and predictable regulation in general is very important in the energy field. The industry is very capital-intensive and the investment lifespan is long. This is the case also concerning energy-intensive industries. Regarding nuclear energy, safety always comes first. However, we have to reflect more closely on the requirements of economics as well. Regulation should focus on the essential outcome: safe and reliable facilities and processes. Policies and legislation should also be neutral when it comes to the choice between sustainable energy sources. It is evident that the same sustainability criteria should apply to all energy sources.

In Finland we have just started an overall assessment and renewal of Finnish nuclear energy legislation. The Nuclear Energy Act has worked quite well so far and enabled power plant new-build as well as the construction of a spent fuel final disposal facility.

In this renewal we want to ensure more legal clarity and consistency. We must also prepare for new technological developments such as small and modular reactors. At the same time it’s necessary to take a look at the interplay with other fields of regulation as well as EU and international provisions.

Regarding the future, finding flexible ways for international regulatory cooperation is also crucial. Wide deployment of new solutions might prove very difficult if every state adopts different rules and requirements. This is a common challenge we should undertake.

Riku Huttunen, Director-General, Energy, Ministry of Economic Affairs and Employment

France

When the International Atomic Energy Agency was created in 1957, nuclear science was recognized as an asset to build peace. As globalization scaled up and exacerbated global inequalities, the United Nations adopted the Sustainable Development Goals and nuclear technology played its part to support fairer development policies. Today, the planet faces the urgent challenge of climate change, and nuclear energy is a major asset in the fight against it.

The objective is clear: limit global warming to 1.5°C, as set in the Paris Agreement. However, achieving this goal takes strong, immediate and collective effort. Globally, all available carbon-free technologies will play a role to decarbonize the economy. Nuclear power is an available, sustainable, carbon-free and reliable energy source which already plays and will continue playing a key role in the fight against climate change. Moreover, nuclear energy, being flexible and non-intermittent, will directly contribute to meeting tomorrow's increasing electricity demand, to the challenge of decarbonized hydrogen mass production and to the massive deployment of renewables and their integration in our networks. It could also directly power energy-intensive and remote sites or smaller electricity grids.

As the President of the French Republic Emmanuel Macron recalled in December 2020, nuclear power will be an essential part of France's ecological and energy future. By 2035, it will account for 50% of electricity production, along with renewables whose share will increase to reach 40% by 2030 in a balanced and resilient mix. France will continue modernizing and investing in the nuclear sector. To that end, nuclear innovation has been included in our national COVID-19 recovery plan with up to €500 million of new investments in key skills development, radioactive waste management, fuel cycle R&D, research facilities and the development of the French small modular reactor (SMR), known as NUWARD™. In addition, France recognizes the need to retain the possibility to build new nuclear power plants beyond 2035.

Indeed, innovation is key to making the best of nuclear technology to tackle the challenge of climate change, in the near term with improved large scale reactors, SMRs and Generation IV reactors and in the next decades with the promises of nuclear fusion. France, along with its international partners, will continue playing a leading role in this collective duty and in full support of the IAEA's work.

Moving from research designs and projects to industrial realities in our efforts to mitigate climate change will take important financing from both states and private players around the world. France has spearheaded this global effort through the One Planet Summit since 2017. Because nuclear energy is a major asset to fight climate change, global efforts are needed to ensure that nuclear energy also benefits from favourable financing conditions.

It is now our duty to make this integrated vision of a low-carbon energy system a reality, through technological, organizational and social innovation, making the best sustainable use of all relevant energy sources.

Jean-Yves Le Drian, Minister for Europe and Foreign Affairs

Japan

I would like to express my gratitude to the IAEA, most recently under the leadership of Director General Grossi, for its cooperation in the efforts to decommission the Fukushima Daiichi Nuclear Power Station (FDNPS). Japan and the IAEA signed an important Terms of Reference this July regarding the IAEA's support for the handling of water treated with the advanced liquid processing system (ALPS) at FDNPS, including the planned IAEA review missions to Japan. Incorporating the experience and lessons learned from the FDNPS accident while maintaining a perspective of the regrets of the event are essential for the development of energy policy in Japan. Japan will continue to share updates on the status of the FDNPS, including the handling of the ALPS treated water, with the international community in a transparent manner based on scientific evidence and in cooperation with the IAEA.

Addressing climate change and advancing decarbonization is an immediate challenge, which the whole of humankind should aim to solve together. Japan announced in late 2020 our target to reduce greenhouse gas emissions to net zero by 2050, to realize carbon neutrality.

The Government of Japan (GOJ) launched the Green Growth Strategy in 2020, which is a comprehensive industrial policy to help realize a virtuous cycle of the economy and the environment targeting 14 industrial sectors including the nuclear industry.

While making efforts to improve nuclear safety and reduce reliance on nuclear power as much as possible, the GOJ will continue to seek to make the most of nuclear power, as well as to thoroughly conserve energy and introduce renewable energy to the greatest possible extent. With this in mind, it is necessary to proceed with the restarting of reactors while placing utmost priority on safety.

Nuclear power is a proven technology for decarbonization. To realize carbon neutrality, it is important to pursue every option, including nuclear power. Therefore, in addition to the further safety improvement of light-water reactors, it is necessary to proceed with R&D for nuclear power innovation by advanced technologies.

Japan is supporting several specific technological developments for promoting nuclear innovation. Fast reactor development is important for nuclear fuel cycle policy in Japan. We will continue to promote competition among various fast reactor technologies through the end of 2023 by supporting R&D in an efficient manner, in cooperation with other countries.

Japan will also actively support small modular reactor (SMR) innovation by private companies developing original designs, as well as companies cooperating with foreign SMR demonstration projects.

Further, in connection with development of high-temperature gas-cooled reactors, which can provide electricity, heat and hydrogen, Japan's High-Temperature Test Reactor achieved a world record by operating at 950°C for 50 days. We will continue to support the technology necessary for achieving low-cost mass production of carbon-free hydrogen by 2030.

International society needs further solidarity to realize a decarbonized society. Japan is determined to take the lead in solving the challenge of climate change for the whole of humankind by cooperating with other countries and international organizations.

KAJIYAMA Hiroshi, Minister of Economy, Trade and Industry

Poland

As the minister responsible for climate and the President of COP24 (the 24th Conference of the Parties to the United Nations Framework Convention on Climate Change) I can confirm that Poland fully understands the necessity of achieving the goal of climate neutrality by 2050 and is strongly committed to make efforts towards its accomplishment. A thorough transformation of the Polish energy sector is necessary to turn around the energy and climate future in a sustainable and responsible way.

However, the unfavourable structure of the Polish energy mix is predetermined by the significant share of coal. In 2020, approximately 70% of electricity was still produced from coal and the sector provided direct employment to over 80 000 people. Accounting for indirect employment associated with coal, this number rises to up to 200 000 people; therefore reducing the use of coal in the energy sector should be considered with special attention. The Polish clean energy transformation is driven by many different external and internal factors, such as global and EU climate and energy policy, rising costs of mining and emission allowances, and depleting coal resources. Coal-dependent regions should be the primary beneficiaries of the fair transformation that is ahead of Poland. It is estimated that new industry sectors linked to renewables and nuclear power will help create around 300 000 new jobs. The government is engaged in an intensive dialogue with trade unions and we are aware of the importance of providing new jobs and opportunities to make up for the impact on traditional industries.

Reducing the share of coal in electricity production will be possible by taking advantage of diversified energy sources. We envisage that in 2040 no more than 28% of electricity will be derived from coal, significantly below current levels.

I am convinced that when building a clean energy system in 20 years and moving forward with the decarbonization goal, we must deploy all technologies — nuclear, solar, wind and hydrogen obtained therefrom. The introduction of nuclear energy will allow for the reliable diversification of the country's energy mix. Last year, the Polish Council of Ministers updated the "Polish Nuclear Power Program" (PNPP).

The objective is the construction of nuclear power plants (NPPs) with a total installed capacity from 6 to 9 gigawatts, which will account for 15% of the national generation mix. The plan includes the construction of 6 units in total of Generation III (+) pressurized water reactors by 2043. The rationale of the PNPP is based on three pillars: energy security, climate and the environment, and the economy. The addition of NPPs will provide opportunities to reinforce the national energy mix and significantly reduce greenhouse gas emissions. The operation of NPPs in our country will help achieve the climate neutrality objective, positively affect the economy while creating new, highly specialized industry branches, and enhance the country's energy security. It will also allow Poland to fulfil its external obligations in the field of climate and energy policy. Poland recognizes the importance of investment in nuclear power to bring a greener future and move away from coal.

Concluding my short statement, I would like to express my conviction that joint efforts and international cooperation will finally allow us to mitigate climate change and ensure a bright future for our planet.

Michal Kurtyka, Minister of Climate and Environment

Russian Federation

The Russian Federation is pursuing a consistent policy to fight climate change at both the international and national levels.

The President of the Russian Federation has set a strategic goal to mitigate significantly greenhouse gas emissions in Russia over next 30 years, including emissions generated in the fuel and energy sector.

Nuclear power is the major source of low-carbon electricity generation in our country. Its share in the electricity generation mix is more than 20%. Greenhouse gas emissions from nuclear power plants (NPPs), throughout the entire life cycle, are close to those from wind power. NPPs in Russia prevent more than 100 million tonnes of carbon dioxide equivalent emissions annually — a reduction of approximately 7% of total emissions in Russia.

We fully understand that compliance with the requirements of sustainable development means not only reducing greenhouse gas emissions, but also minimizing negative impacts on the environment and human health. The nuclear industry in Russia complies with these criteria too, adhering to strict safety requirements that are aligned with IAEA standards. We are developing technologies for closing the nuclear fuel cycle with spent nuclear fuel processing, with the objective to significantly reduce the amount of radioactive waste sent to final disposal and, consequently, the environmental burden.

We are also taking a responsible approach to fulfilling our international obligations in combating climate change, foremost in implementation of the UN Framework Convention on Climate Change, the Kyoto Protocol and the Paris Agreement.

It is clear that international and local regulations, along with policies for strategic development of national economies and industries, should not restrict the use of nuclear energy, provided that all safety requirements are met.

We are absolutely convinced that nuclear energy is a high-tech, environmentally friendly and safe industry — for both the present and the future. It is impossible to solve problems of the climate agenda without the peaceful atom.

Ruslan Edelgeriev, Special Presidential Representative on Climate Issues and Adviser to the President

United Kingdom

In 2019, the UK became the first major economy to adopt a legally binding obligation to reach net zero greenhouse gas emissions by 2050. Between 1990 and 2018, the UK's economy-wide emissions fell by 43% while GDP rose by 75%.

Decarbonising the power sector has been pivotal to the UK's efforts to reduce greenhouse gas emissions. Over the same 28-year period, the share of emissions from electricity generation fell from 25 to 15%. In 1990, fossil fuels provided nearly 80% of electricity supply, while today the country gets over half of its power from low-carbon technologies.

As we make these strides towards net zero, the demands on the electricity system are expected to increase. Electricity could provide more than half of final energy demand in 2050, up from 17% in 2019. This would require a four-fold increase in clean electricity generation with the decarbonisation of electricity underpinning the delivery of our net zero target.

In our electricity system analysis, we have modelled almost 7,000 different electricity mixes in 2050, for two different levels of demand and flexibility, and 27 different technology cost combinations. This has produced a dataset comprising of over 700,000 unique scenarios, allowing us to identify common features of a low emissions, low-cost electricity system. All low-cost solutions include significant levels of renewables, but low-cost solutions that achieve low emissions (of 5 grams of carbon dioxide per kilowatt-hour or below) can only be realized with a combination of new nuclear and gas carbon capture, utilization and storage.

Nuclear power continues to be an important source of reliable clean electricity, supplying around 17% of the electricity generated in the UK in 2019. It is an energy-dense technology which provides large volumes of power from a very small land area and can reduce system costs at low levels of emissions. But, with the existing nuclear fleet largely retiring over the next decade, we are taking steps to maintain nuclear's important place in our energy mix.

In addition to building Hinkley Point C, the first new nuclear power station in the UK in a generation, we aim to bring at least one large scale nuclear power plant to the point of final investment decision by the end of the current Parliament (2024), while investing up to £395 million to help develop the next generation of nuclear technologies. To help bring these technologies to market, the UK will invest an additional £40 million in developing the regulatory frameworks and supporting UK supply chains. And of course, we will work closely with the IAEA on developing the international regulatory framework necessary to support new nuclear technologies.

For those countries interested in nuclear energy, we believe nuclear innovation will play an important role in supporting the transition to net zero and we stand ready to collaborate with the global community in this important field.

Greg Hands, Minister of State for Energy, Clean Growth and Climate Change

United States of America

The task ahead of us — limiting global average temperature rise to 1.5°C and achieving net zero emissions by 2050 — is a formidable challenge and an immense economic opportunity. The global clean energy transition will require deploying, at massive scale, the full range of clean energy technologies available, including nuclear energy, over the next decade and beyond. The United States pioneered the peaceful uses of nuclear around the world and remains the world's largest producer of nuclear power, which accounts for 20% of our electricity mix, and more than half of our carbon-free power.

Further, the International Energy Agency tells us that we will need to innovate and commercialize many new clean energy technologies to achieve our 2050 goals. Nuclear energy can play a critical role in decarbonizing hard-to-abate sectors beyond electricity — for example, by producing cost-competitive, low-carbon hydrogen, industrial process heat, and water desalination to meet decarbonization goals, air quality standards, and clean water needs. The Biden Administration maintains the United States' decades long commitment to advancing nuclear energy as a solution to the climate crisis at home and abroad.

President Biden has outlined a plan to establish the United States as a leader in climate and clean energy innovation by funding the procurement and demonstration of advanced nuclear technologies, including small modular reactors (SMRs) and microreactors to create good-paying jobs and reinvigorate local economies. SMRs could be a game-changer for climate change efforts. SMRs offer many advantages owing to their small size, flexibility, and complementarity to renewables. They can be scaled to meet the grid size and have benefits in terms of safety, affordability, and capacity to partner with other clean power sources. SMRs and other advanced reactor technologies, including Generation IV designs, will help the world achieve net zero by 2050.

At President Biden's Leaders' Summit on Climate, convened within the first 100 days of his administration, the United States was pleased to launch the Foundational Infrastructure for the Responsible Use of Small Modular Reactor Technology (FIRST) program, with an initial US $5.3 million investment, which supports capacity-building efforts in partner countries so that a wide swathe of countries can benefit from advanced nuclear technologies under the highest standards of nuclear security, safety, and non-proliferation. The FIRST program is one of many initiatives, through which the United States intends to lower the cost and increase the pace of clean energy deployment and innovation, including for nuclear energy.

We know that many countries are identifying nuclear energy — whether expanding existing generation or building new nuclear energy programs — in developing ambitious climate plans. The United States stands ready to support those efforts in partnership with like-minded countries and the IAEA on the road to the 2021 UN Climate Change Conference in Glasgow (COP26) and beyond.

John Kerry, Special Presidential Envoy for Climate

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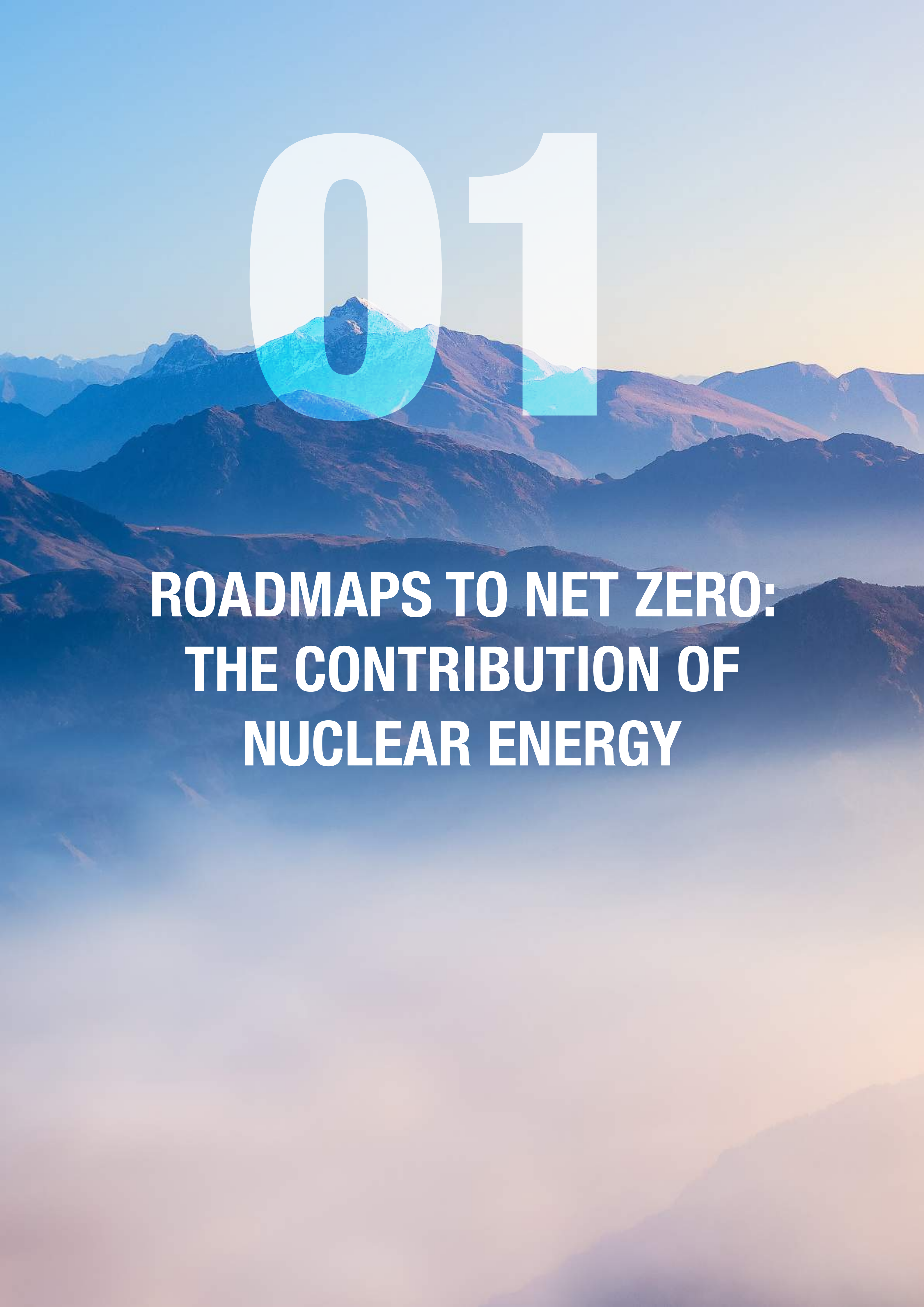


01

ROADMAPS TO NET ZERO: THE CONTRIBUTION OF NUCLEAR ENERGY

Key Points:

- Nuclear energy is key to achieving global net zero objectives, working in partnership with renewable energy sources and other low carbon options, as part of a sustainable energy system to decarbonize electricity and non-electric energy production.
- Nuclear power can help complement and integrate the expected large shares of renewable generation by ensuring 24/7 energy supply reliability and dispatchability.
- Maintaining low carbon generating capacity is essential, by safely extending the operational lifetimes of existing nuclear power plants. In addition, around 550 GW of new nuclear capacity will be needed by 2050.
- Many nations opt for nuclear energy to meet their climate objectives, and uptake by countries is increasing.

Recent history and the challenge ahead

In 2015, the international community adopted the Paris Agreement on climate change, pledging to hold the increase in global average temperature to less than 2°C above pre-industrial levels, and if possible, to limit it to 1.5°C. This requires very ambitious and urgent efforts to reduce greenhouse gas (GHG) emissions across all activities and sectors, including a complete transformation of the energy sector to eliminate unabated fossil fuel production and use, which is the main source of carbon dioxide (CO_2), the principal GHG. This is increasingly recognized as requiring the energy sector to become carbon neutral with any CO_2 emissions offset by CO_2 removals — i.e. to reach ‘net zero’ emissions — by around the middle of the century. While there are multiple possible pathways for realizing this objective, long term energy and climate scenarios, such as those outlined in the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Global Warming of 1.5°C and the International Energy Agency’s (IEA) Net Zero by 2050 Roadmap [1–2], identify two key elements: extensive electrification of the economy with low carbon electricity (from renewables and nuclear), and deployment of other low carbon energy carriers (heat, hydrogen, synthetic fuels, among others) in applications that are less suited to electrification, including so called ‘hard-to-abate’ sectors in industry and transportation.

In the context of net zero and increasing climate ambition, nuclear energy is increasingly recognized not only as a climate friendly energy option, but also as an enabler of the broader transformation of the energy sector. This stems from nuclear energy’s unique attributes, which include among the lowest GHG emissions of all energy technologies [3–4] 24/7 availability, operational flexibility, a small land footprint and the versatility to decarbonize hard-to-abate activities. However, even though neutral scientific assessments from the IPCC, IEA and others recognize nuclear power’s significant potential to contribute to climate change mitigation and other global challenges, the extent to which the world will capitalize on this low emission, reliable and sustainable source of energy remains uncertain, owing partly to limited — albeit increasing [5–6] — public acceptance and policy support. Between 2011 and 2020 global nuclear electricity generation capacity grew modestly, with a total of 59 gigawatts (GW) added. While programmes in several countries also enabled the continued operation of existing nuclear power plants, in some cases up to 80 years, 48 GW was still retired during the same period due to reactor shutdowns.

As nations around the world increase their climate ambitions and accelerate their plans to decarbonize (see Figure 1), the next decade and beyond bring the prospect of increased deployment of nuclear power, reflecting the plans of a number of countries. The IEA Net Zero by 2050 Roadmap also projects that nuclear electricity generation will need to double between 2020 and 2050 if the world is to meet its net zero ambitions, noting that “at its peak in the early 2030s, global nuclear capacity additions

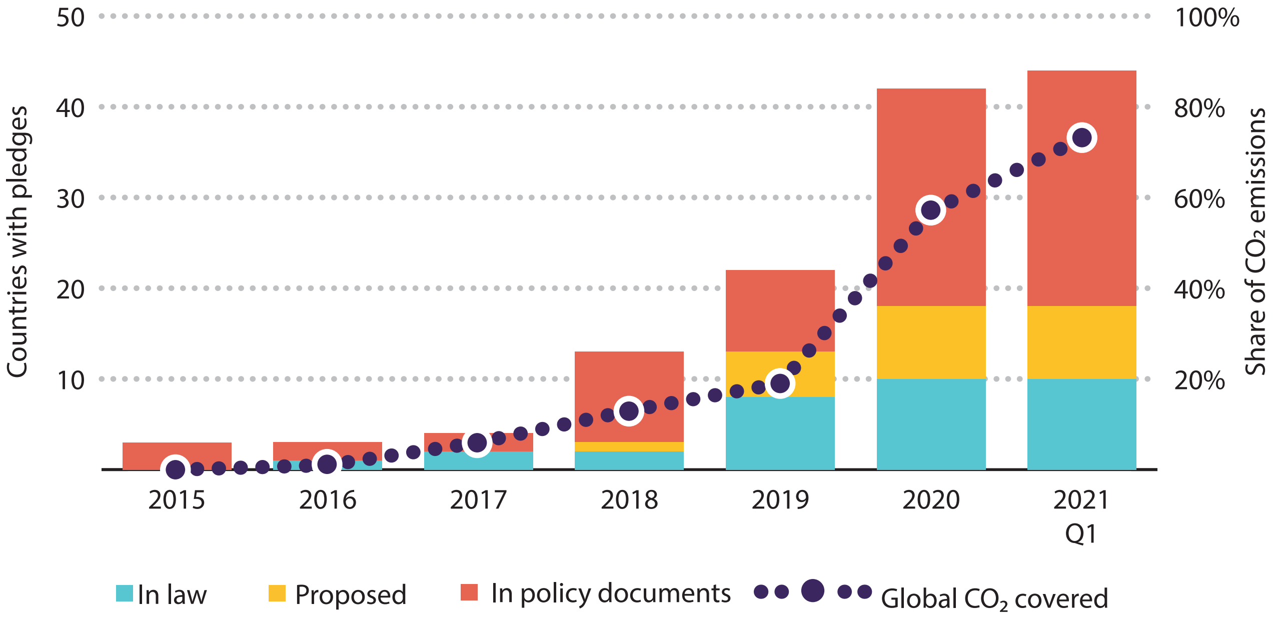


Figure 1. Number of countries with net zero commitments (incl. EU countries with national pledges) and share of global CO_2 emissions (incl. all EU countries) (based on data from [1, 9] as modified by IAEA).

reach 30 GW per year, five-times the rate of the past decade" [1]. These numbers match closely with the International Atomic Energy Agency's (IAEA) high projection case, based on a detailed country by country 'bottom-up' assessment, of around 550 GW of new capacity by 2050 [7].

It is important to note that other low carbon energy technologies are expected to deliver the bulk of decarbonization, in particular variable renewable energy technologies (including solar and wind) which are likely to dominate the electricity mix, as well as energy storage technologies (for example, batteries) and other low carbon fuels such as hydrogen. Nuclear power, while playing a more modest role, can however help complement and integrate the expected large shares of renewable generation by ensuring energy supply reliability and dispatchability. Combining nuclear energy and renewable energy sources can also ensure a more rapid transition: nuclear power's relatively low material intensity means that it is unlikely to face bottlenecks in the supply of critical minerals that may hamper the deployment of other low carbon options [8]. This underlines the importance of keeping nuclear energy as part of the portfolio of solutions for the successful transition to a net zero future.

The need for urgent action

Time is rapidly running out to curb global emissions and avoid major impacts from climate change [10]. This urgency requires the deployment of all low carbon options to move away from fossil fuels, particularly options that are proven, cost effective and supportive of broader development and environmental goals. Nuclear power plants operating today in 32 countries (see Figure 2) are already reducing global power sector CO_2 emissions by around 10% [11], and 19 countries are currently constructing around 50 additional power reactors with a capacity of some 54 GW [12]. Bangladesh and Turkey are building their first reactors while Belarus and the United Arab Emirates started generating nuclear electricity in 2020: many such newcomer countries recognize nuclear power's role in both climate change and long term economic development, and around 30 countries are working with the IAEA to explore the introduction of nuclear power for the first time. Still, the current pace of reactor construction remains far slower than what is needed to achieve a net zero world. While the nuclear industry is working to control newbuild costs through streamlined supply chains and modular construction, accelerating the launch of new projects will also require a more favorable policy framework to increase investor confidence and lower financing costs in most countries (see Chapter 5).

Another pressing challenge is the ageing of the nuclear reactor fleet. More than two thirds of operational nuclear power capacity, accounting for around 18% of the world's low carbon electricity generation, is over 30 years old and facing an uncertain future, particularly in Europe, Japan and the USA [12]. Avoiding a substantial low carbon electricity 'cliff edge' as these plants are retired will require continued efforts to extend plant lifetimes, through investments and plant modernization. On the positive side, around 100 power reactors have already received lifetime extension licences for varying periods following refurbishment (e.g. see [13–14]). However, while electricity produced from these older, fully amortized reactors is among the cheapest sources of low carbon power, the competitiveness of these plants may be challenged by even cheaper fossil fuels or subsidized renewable energy sources. This can be alleviated to some extent by measures to value and remunerate the contribution of existing plants to low carbon generation, such as via production tax credits, thereby supporting plant lifetime extensions [15–16].

Ensuring that existing nuclear reactors remain economically competitive, while maintaining safety and reliability, will support global efforts to reduce GHG emissions and bridge the gap before new low carbon technologies critical for net zero reach commercial maturity. These include some advanced reactor designs, where additional development and demonstration is underway to establish proof of concept to support licensing and attract investors.

Beyond electricity: a key opportunity for net zero

Energy production and use are responsible for around three quarters of global CO_2 emissions, of which the electricity and heat plants account for about 40%. Global electricity needs, moreover, are poised to rise in the decades to come. Switching from fossil fuels to low carbon electricity generation is thus key to cutting a substantial proportion of emissions and mitigating climate change. However, decarbonizing electricity production through greater use of nuclear power, hydro, wind and solar is only the first step, and the remaining energy related emissions — primarily from direct heat production in industry and buildings, and transportation — also need to be abated, either by electrification (assuming low carbon technologies are used to generate electricity) or by replacing fossil fuels with other means, including clean heat sources and alternative energy carriers such as hydrogen and other synthetic fuels. Low carbon

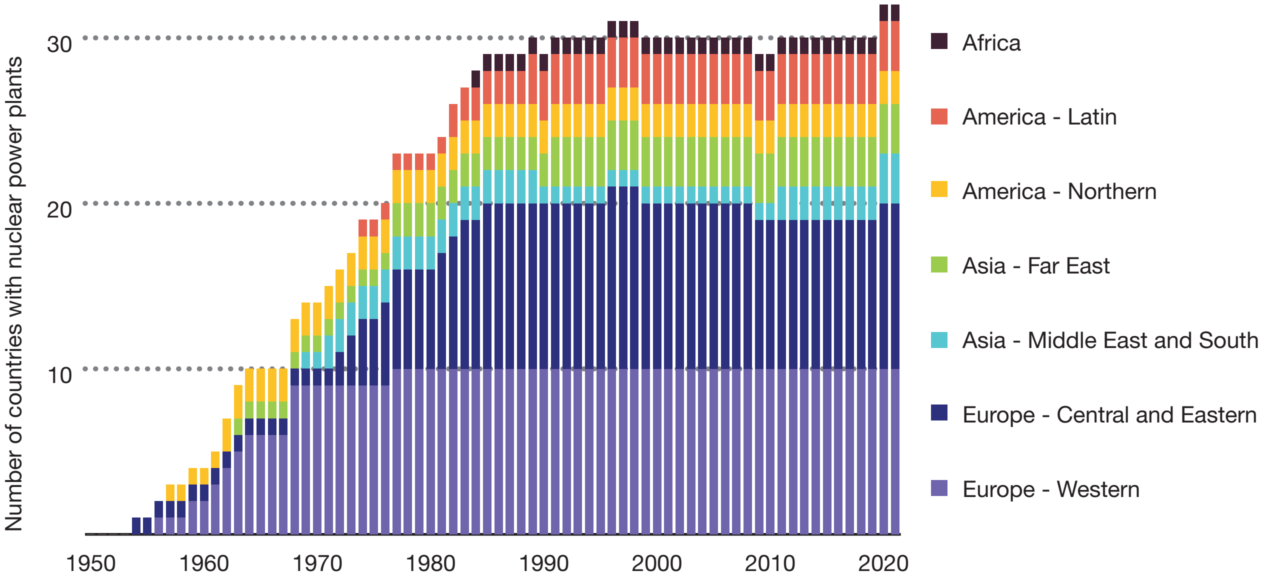


Figure 2. Number of countries with nuclear power reactors [12].

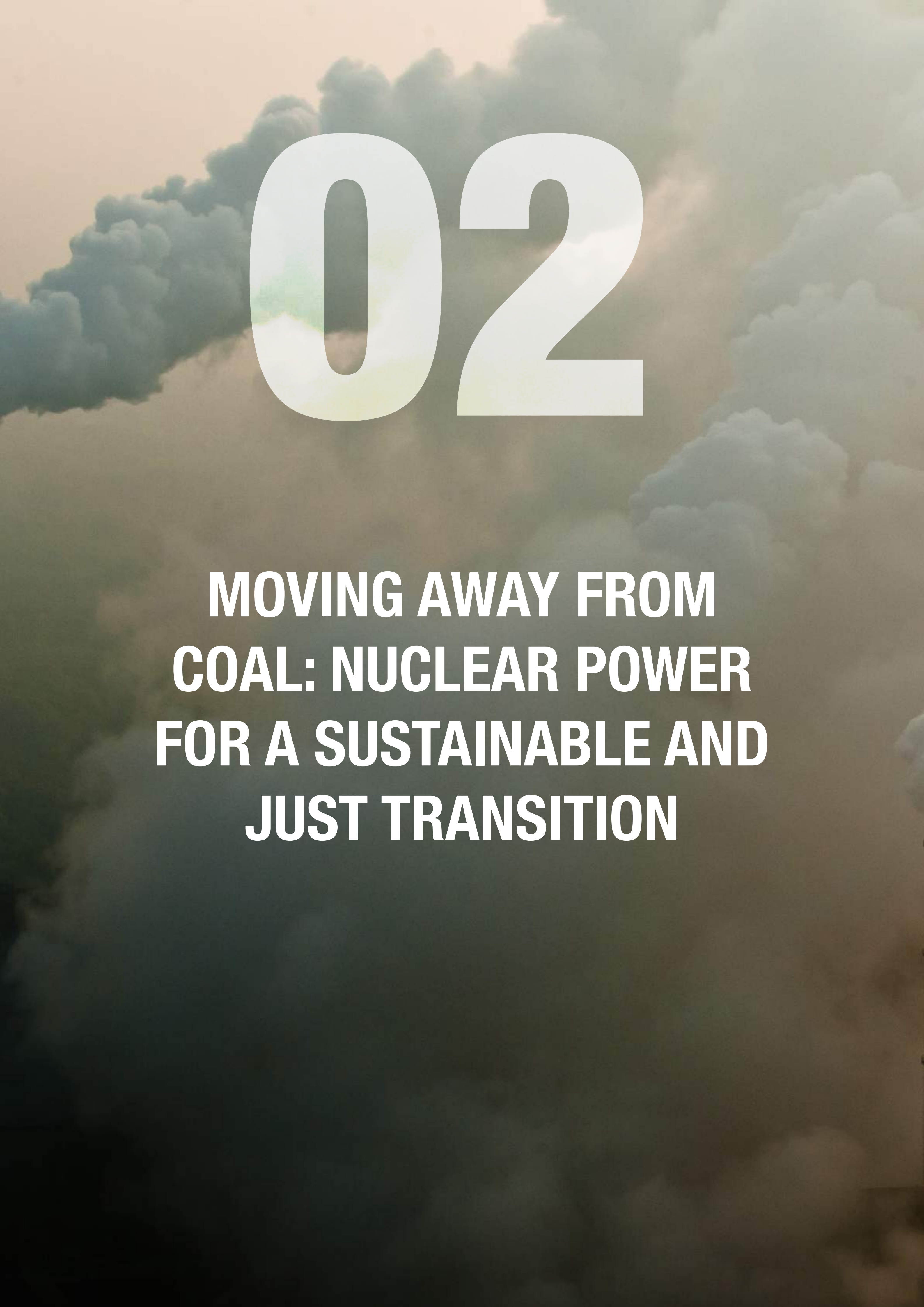
hydrogen, in particular, is seen as a key future option for the transport sector, especially heavy duty and maritime transport. Hydrogen can also be used for energy storage and can potentially replace fossil fuels in hard-to-abate industrial processes such as steelmaking, the cement industry and chemical production.

Nuclear power is well suited to decarbonizing both electricity and heat production, and it can also produce low carbon hydrogen on a massive scale and at an increasingly competitive cost (see Chapter 3). In addition to hydrogen, nuclear can deliver heat for district heating while innovative reactors under development are expected to be able to provide the high temperature heat needed by many industries. While crucial to reaching net zero, the potential of nuclear energy for these non-electric applications is not reflected in policies and investment decisions, which risks delaying the development and deployment of these low carbon options. Addressing this potential barrier, such as through public–private partnerships to accelerate technology development and commercialization, is critical for reaching net zero by 2050: as emphasized by the IEA, almost half of the needed emissions reductions are expected to rely on technologies that have not yet reached the market [17], including advanced nuclear energy systems.

In addition to responding to the need for urgent climate action, by providing reliable low carbon electricity, heat, and hydrogen, nuclear energy is also well suited to powering new economic development pathways of the fourth industrial revolution [18]. New technologies, including advanced nuclear designs, are expected to enable emerging and developing economies to bypass (or ‘leapfrog’) conventional historical development paradigms built around fossil fuels and energy intensive industry [19], and instead put low carbon energy technologies — including renewables and nuclear — at the heart of economic development. However, there is emerging evidence that electrification through renewable generation alone, particularly off-grid solar technologies, is not sufficient to fully realize economic growth potentials. For example, while expanding access to electricity with renewable energy sources in rural Africa has been positive for individual wellbeing, it has only had a limited effect on economic development, and partnerships with other low emission, reliable technologies could help to scale up energy production to rapidly lift millions of people out of poverty and power the megacities of tomorrow [20].

Against this backdrop, this booklet highlights the key contributions that nuclear energy can make to climate action, by displacing fossil fuels — coal being the most carbon intensive — in electricity and heat applications and enabling the continued integration of renewables, by contributing to grid stability and flexibility. Nuclear energy has also demonstrated its potential to bolster the climate resilience of the energy system, support employment and economic development in the wake of the COVID-19 pandemic, and contribute to broader sustainable development.

For the world to succeed in meeting the ambitious targets in the Paris Agreement, reflected in recent aspirations to reach carbon neutrality around mid-century, nuclear energy will be key. Later in 2021 at COP26 — the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change, in Glasgow — the global community can ensure nuclear energy fulfills its potential to accelerate climate action and avert the worst impacts of climate change.



02

MOVING AWAY FROM COAL: NUCLEAR POWER FOR A SUSTAINABLE AND JUST TRANSITION

Key Points:

- Nuclear power plants are well suited to replace coal fired power plants for low emissions electricity generation.
- Nuclear power plants can substitute coal fired boilers for district heating and industry.
- Nuclear power is a significant driver of economic growth, generating jobs in many economic sectors, and enabling a just transition away from coal.

Transition away from coal

Coal is among the most CO_2 emissions intensive fossil fuels per unit of energy produced. Combustion of coal accounts for almost 45% of energy sector CO_2 emissions worldwide as well as substantial local air pollution linked to millions of premature deaths every year [1, 21–23]. Recognizing the threat posed to the international community's goals in the Paris Agreement, the UK has made the shift away from coal, as part of the clean energy transition, central to COP26 in late 2021. COP26 President-Designate Alok Sharma has said that the 2021 climate conference must consign coal to history, while working to end international coal financing [24]; a message echoed in UN Secretary-General Antonio Guterres' call for an end to "the deadly addiction to coal" [25].

To date, however, policy and regulatory incentives supporting low carbon technology deployment and a shift away from coal have had mixed success. In Europe and North America, coal use has declined in recent years, having been replaced by natural gas for both economic and environmental reasons. In comparison, a relatively strong increase in coal use has been observed in the Asia Pacific, with moderate growth in Africa. As a result, cumulative global coal use has remained roughly stable since 2011, although there are some early indications that consumption may begin declining in the near future given increasing challenges in financing new coal power projects. However, policy and regulatory frameworks will likely need to provide additional incentives to greatly accelerate the shift from all fossil fuels — not only coal but also natural gas and oil — to low carbon energy sources, including via carbon pricing, which is often viewed as the optimal economic instrument to support low carbon energy sources. To date, carbon prices and other incentives have generally been far too low in many markets to deter fossil fuel investment and will need to increase significantly in order to become effective [4].

The majority of emissions from coal use arise in electricity generation, accounting for 30% of the total emissions from the energy sector. Coal fired electricity generation is also among the highest CO_2

Figure 3. Map of countries with operational nuclear power programs [12].

emitters per kilowatt-hour (kW·h) produced, and a significant source of local and regional air pollution, further highlighting urgent need to shift to cleaner energy sources. Given that nuclear and coal fired plants have certain similarities — e.g. they are both thermal power plants relying on similar components (and supply chains) — nuclear power can be a suitable replacement for coal on the path to net zero. To illustrate the potential for nuclear power vis-à-vis coal, the IEA's Net Zero by 2050 Roadmap envisages an increase of over 2100 terawatt-hours (TW·h) in annual nuclear electricity generation between 2020 and 2040, during which time unabated coal fired electricity generation declines to zero [1]. Retaining 2100 TW·h of unabated coal generation instead of expanding the use of nuclear power would increase annual emissions by up to 2 gigatonnes (Gt) of CO_2 [21], raising global energy emissions by roughly one third in 2040.

Among either the 32 countries currently (2021) operating nuclear power plants (see Figure 3) or the 10 countries that have decided to include nuclear energy in their generation mix with plants under construction or in advanced stages of preparation, are several of the countries most dependent on coal for electricity generation (see Figure 4). These countries not only have the experience and infrastructure (such as the regulatory framework) in place to support a relatively rapid switch from coal to nuclear energy, but also account for around 85% of the world's coal generation, and most of this is produced on a scale that is well matched to the output of one or more large nuclear power plants. Replacing just one percentage point of this coal generation with nuclear power would reduce annual emissions by around 100 Mt CO_2 (requiring around 12.5 GW of nuclear capacity); likewise, replacing 20% with 250 GW of nuclear generation would reduce emissions by 2 Gt CO_2 (or around 15% of power sector emissions).

In addition to offering low carbon electricity, nuclear power plants have the potential to replace coal in other applications. To illustrate, besides generating around 2550 TW·h of low carbon electricity (about 10% of global electricity generation) in 2020, nuclear power plants in 10 countries also supplied heat used for district heating, industrial processes or desalination [26], building on decades of experience using nuclear power for district heating, particularly in Eastern Europe but recently also in China, and industrial heat (e.g. in Canada, Switzerland and Germany). Among the 42 countries using nuclear power or in the advanced stages of adoption, 22 also utilize coal for heat generation. Surplus heat from large nuclear power plants could potentially replace much of the coal used for low temperature applications. Higher temperature requirements could potentially be supplied by, for example, various small modular reactor (SMR) designs currently under development, over the short to medium term.

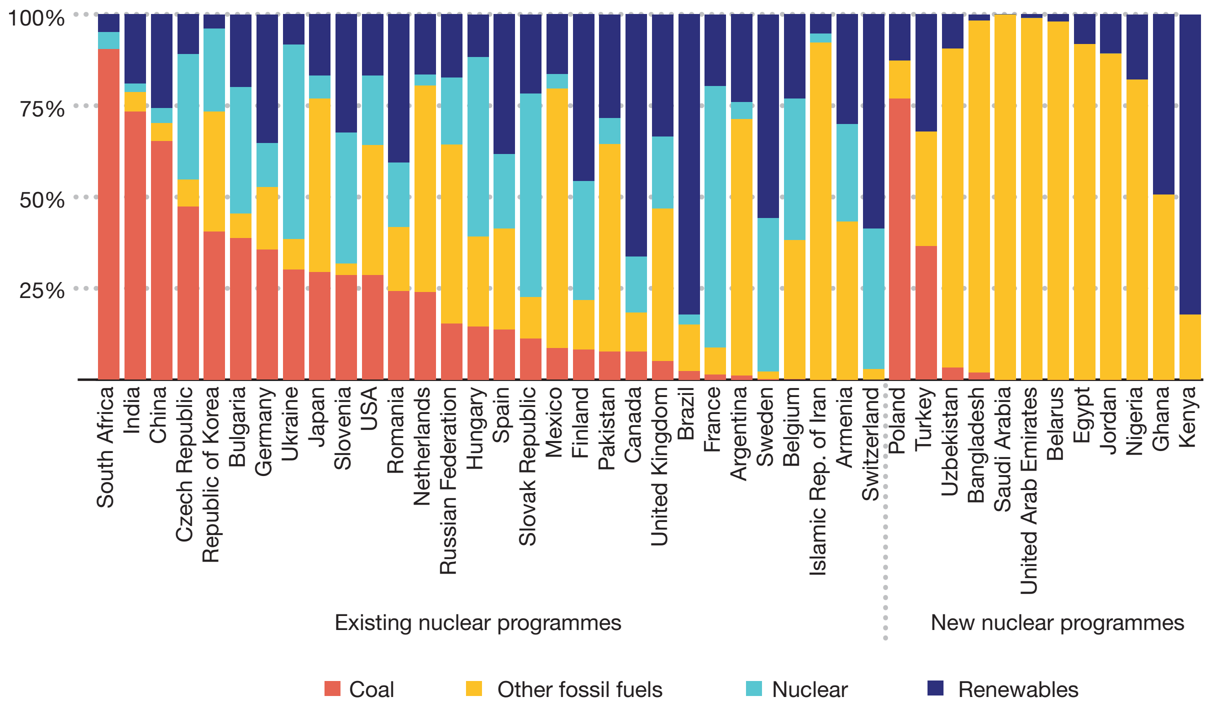


Figure 4. Electricity generation mix (2018) in countries with or planning nuclear power programmes [27].

		Plant output			Coal replacement applications	Technological and commercial maturity
		Electricity	Low temperature heat (300ºC) (district heat, industry, H_2)	High temperature heat (600-700ºC) (industry, H_2)		
Nuclear reactor design	Large water cooled	✓	✓		Multi-unit power plant	Mature; more than 300 units in operation
	SMR, water cooled	✓	✓		Single unit, power or CHP	Demonstration; pre-commercial; conventional nuclear licensing process widely applicable
	SMR, advanced (gas/sodium cooled)	✓	✓	✓	Single unit, power, CHP, industrial boiler, H_2	Design phase; demonstrated technology; pre-commercial
	SMR, advanced (salt or lead cooling; micro-reactors)	✓	✓	✓	Single unit, power, CHP, industrial boiler, H_2	Research, development and demonstration

Table 1. Categorizing selected nuclear technologies suitable for replacing coal.

Table 1 summarizes the potential applications of different nuclear reactor designs in the transition away from coal. Most currently operating nuclear power plants rely on large scale water cooled reactors. In comparison, coal fired boiler units tend to be smaller, so a single nuclear reactor could replace multiple coal units. In comparison, various SMR designs in different stages of development could be well suited to replace smaller coal fired units across a wider range of applications.

Replacing coal fired power plants with nuclear power plants

While coal fired and nuclear power plants have a number of technical similarities, nuclear power plants can be more flexible than coal (and gas) power plants — e.g. they can be quickly ramped up or down as necessary, as illustrated in Figure 5 [28] — to match demand and support the integration of variable renewable generation.

Nuclear power plants also require less space on the plant site for fuel storage and can store sufficient fuel for more than a year, compared to a few weeks for a coal fired power plant, which thus requires frequent coal deliveries via road, rail or water.

On the other hand, while both coal and nuclear power plants need to adhere to licensing frameworks for conventional steam and electricity generation, nuclear power plants need to also comply with nuclear safety standards and licensing requirements, necessitating, in particular, specialized utility staff. However, in those countries operating nuclear power plants this is already standard practice. Nuclear power plants also need to maintain a “controlled zone” and an “emergency planning zone” to ensure physical separation between the nuclear part of the plant and the rest of the site to contain radioactive material, both by working procedures and physical separation. This is an important consideration for nuclear power plants providing heat, requiring multi-stage heat exchangers for any heat transfer through the controlled zone boundary.

Decades of experience in many countries have demonstrated that these differences can be easily managed. Nuclear power plants can thus be envisaged as a cost effective solution for either entirely replacing or potentially “repowering” coal power plants on brownfield sites with the aim to maintain the generating capacity, ensure continued baseload and load following capabilities, and retain jobs on the site, while switching to low carbon electricity and heat production. While the most common form of repowering — i.e. re-utilization of coal power plant components,

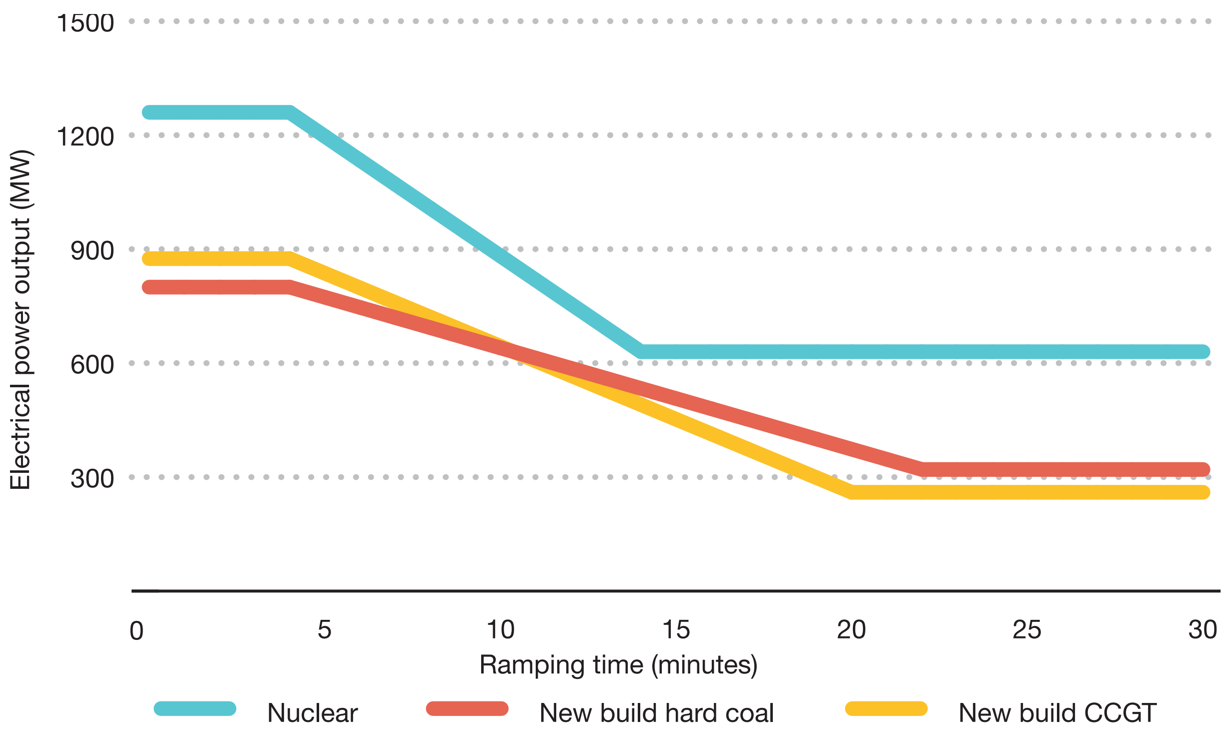


Figure 5. Ramping capabilities of nuclear, coal fired and gas fired generation [28].

typically steam generation and heat rejection systems — is converting from coal to natural gas (in the U.S. between 2011 and 2019, 86 coal fired plants were converted [29]), other options include adding a geothermal heat source, or equipping a plant with post-combustion carbon capture. In addition to repurposing the steam generation and heat rejection systems, repowering coal plants to nuclear power may also enable other elements of the existing infrastructure to be retained — such as transmission and cooling systems — resulting in significant savings and faster deployment, although this is likely to require significant modifications.

Replacing coal fired boilers by nuclear power plants to supply heat

While decarbonizing electricity generation and heat production plants, together accounting for about 40% of energy related CO_2 emissions, is a crucial step towards net zero, the remaining 60% of energy related emissions — much of it from direct combustion of fossil fuels for heat production (in industry and buildings) or transportation — also needs to be rapidly reduced, either by electrification (with low carbon electricity) or by replacing fossil fuels by other means. For instance, nuclear power reactors can replace coal fired boilers producing steam to feed district heating networks and supply certain industrial clients. Heat can be supplied either as an additional output from nuclear power plants or from reactors dedicated to heat production (see country cases for the Czech Republic and China). Various efforts are also underway to study decarbonization through nuclear district heating with advanced reactors: for instance, in Finland, which adopted an action plan to reach carbon neutrality in 2035, for the Helsinki metropolitan area [30], the development of dedicated reactors for district heating (see China country case) and modifications that allow existing reactors to supply district heating [31].

Accompanying the transition: socio-economic impacts of a “Just Transition”

While a rapid shift away from coal and other fossil fuels is critical to the goals of Paris Agreement, and there are technical options to realize this objective (including nuclear power) as elaborated above, there is a need to ensure that workers, communities and businesses reliant on existing coal power plants and mines are supported in this transition to avoid significant economic and social disruption. Nuclear power and other low carbon options can contribute to such a 'just transition'.

The concept of a just transition evolved from its use in the 1990s by trade unions seeking to establish social assistance programmes for workers losing jobs due to environmental protection policies. It is now widely used in the context of climate change mitigation and the transition to a low carbon world. In the preamble of the Paris Agreement and in the Solidarity and Just Transition Silesia Declaration, the notion of a 'just transition' is framed primarily as a workforce related issue — which is reflected in significant interest among members of the International Trade Union Confederation (ITUC) and the International Labour Organization (ILO) — but it is now increasingly being seen as extending to include broader considerations related to impacts on regional economies dependent on industries based on fossil fuels and potentially adverse effects on consumers and energy intensive industries [32].

Deep and rapid transition in advanced economies

To deliver early results during the next ten years on the pathway to a net zero world, the IEA estimates that advanced economies such as the USA and EU will need to reduce coal demand by 75–90% and institute a wave of coal fired plant retirements. Even without strong action on climate change, challenging market conditions could lead to about 275 GW of coal fired capacity (equivalent to 13% of 2019 totals) going offline by 2025, including 100 GW in the US and 75 GW in the EU [21].

These projections are consistent with the direction of policy in several countries. For instance, the EU Green Deal, a plan to make Europe climate neutral by 2050, encourages the power sector to move rapidly towards lower emissions, and 16 out of 27 EU Member States have already endorsed or begun considering the phase out of coal over the coming decades [33]. In these countries, the pressure to find solutions for a just transition in the coal sector and beyond is a pressing issue.

Figure 6 illustrates how existing structural economic and social challenges could be amplified by the phasing out of coal in the EU. A large proportion of coal power plants and mines are located in lower income regions, i.e. regions with a GDP per capita below the national average. In some extreme cases, regional incomes are less than half the national average. The coal phase out will place additional pressure on those regions with a less diverse economy and lower wages, thus making a just transition more challenging.

Country Case: Czech Republic

Reducing emissions in Ceske Budejovice with clean heat from the Temelín Nuclear Power Plant

The Temelín Nuclear Power Plant (2 units each of 1086 megawatts (MW)) located in the South Bohemian Region in the Czech Republic, will contribute towards the heating of the region's capital — Ceske Budejovice. It is one of the most important projects aimed at reducing carbon dioxide emissions in the Czech Republic.

Already in the 1980s, it was envisaged that the Temelín nuclear power plant would provide heat to Ceske Budejovice. However, for various reasons, the heat distribution system was only extended to the nearby town of Tyn nad Vltavou, where it helped to eliminate 22 medium sized coal fired heating plants and three large boiler facilities, meaning that the town now has among the cleanest air in southern Bohemia.

The current project to connect the regional capital supports the Czech Republic's climate protection goals. It will supply heat to the city's largest housing estates with approximately 30,000 inhabitants and contribute about one third of the city's total heat supply, saving about 80 kilotonnes (kt) of CO_2 each year for at least 30 years.

Construction is already underway, with 15 out of 26 km of the hot water pipeline already completed. The water will be heated with steam extracted from one of the turbines at the Temelín nuclear power plant, which even at maximum heat consumption will only reduce the electric power output of the plant in the order of a few MW. To ensure security of energy supply, backup heating capacity will be maintained in case there is a need to simultaneous shut down both units of the power plant.

CEZ Group

Country Case: China

Dedicated Reactors for Clean District Heating in Liaoyuan

The China National Nuclear Corporation (CNNC) is conducting preliminary work to build a pool type low temperature heating reactor in the city of Liaoyuan, Jilin province, in the north of China, as part of a safe, economic and environmentally friendly heating system.

Compared with conventional pressurized water reactors, heating reactors operate under atmospheric pressure and at low temperature, eliminating the need for a pressure vessel and containment. The reactor's simple design, inherent safety, high reliability and stability, technological maturity, low construction costs, convenient maintenance, and small footprint make it suitable for wide scale deployment.

A 400 MW thermal pool type heating reactor could provide clean heating for a city of 300,000, replacing 320,000 tonnes of coal or 160 million cubic metres of natural gas per year. This equates to a saving of 520 kt CO_2 (for coal) or 260 kt CO_2 (for gas) and a significant reduction in emissions of other air pollutants.

While the pool type heating reactor is more costly to construct than a conventional fossil fuel heating system, it has much lower operating costs and a service life of 40–60 years (2–4 times longer than the life of a coal fired boiler). As a result, the pool type reactor produces heat at a lower cost than gas heating, and a comparable cost to coal fired cogeneration.

After the successful deployment in Liaoyuan, CNNC plans to promote this type of heating system in other parts of northern China. This complements parallel initiatives to deliver heat from nuclear power plants — for example, the Haiyang plant started providing district heat to the surrounding area in 2020 [31].

China National Nuclear Corporation

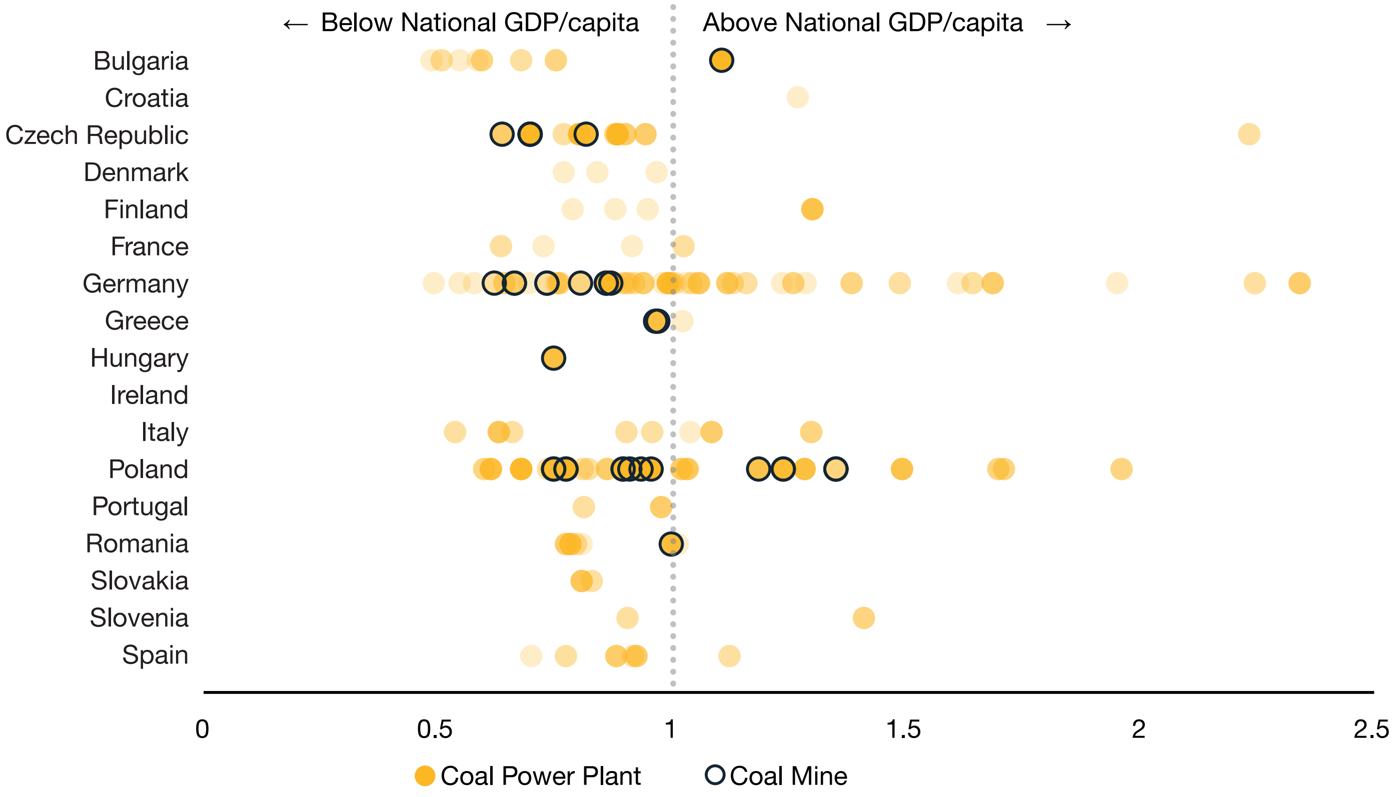


Figure 6. Relative GDP/capita in regions with coal fired generating plants and coal mines, compared to the average national GDP/capita for selected countries in 2018. Refs [34–36]. Note: Dark shades of yellow indicate a larger number of units at coal plants.

Delayed transition in emerging economies

Even with a rapid global shift towards a low carbon energy system, coal demand is projected to decline only gradually in emerging economies between 2020 and 2030, particularly in key Asian markets. Moreover, in the absence of additional measures needed to realize such a rapid shift, coal demand is likely to continue growing in India and remain fairly stable in China until 2030 before gradually declining [21].

In some emerging economies, there is resistance to a shift away from coal stemming from a desire to replicate the historical industrial development paradigm of developed countries, built around energy intensive industries. Following such an economic development path, while phasing out coal, will be a massive challenge for emerging economies seeking to eradicate poverty and increase living standards consistent with the UN Sustainable Development Goals.

New models of development and nuclear power to support a 'Just Transition'

Governmental support to affected communities and workers is considered essential to ensuring that the transition away from coal (and other fossil fuels) towards a net zero world is socially acceptable. The required level of support will vary significantly across regions, being greatest in countries with high dependence on coal production and/or consumption and few alternatives. At the same time, the capacity of governments to provide support also varies widely, with social security systems in developing countries often constrained by limited resource availability. Moreover, support via social security systems alone will not necessarily guarantee the sustainability of any success — technical, economic and social — of a coal phase out.

To be successful, countries need to align coal phase out policies with new long term development strategies. One example of such an approach is the EU's Just Transition Mechanism (JTM) which augments support provided to the most vulnerable, including in coal mining regions, with a vision to diversify economies through low carbon and climate resilient investments — at least EUR 150 billion over the period 2021–2027 [37–38].

While the EU JTM is directed towards investments other than nuclear energy, there is no one-size-fits-all model of future low carbon economic development, and in many contexts nuclear energy is well suited to supporting a new growth paradigm and a 'just transition' in several ways. Beyond energy security and climate change mitigation, nuclear power can make a significant contribution to economic development and thus maintain or even improve economic wellbeing of citizens. Moreover, compared to other energy technologies, investment in nuclear energy is estimated to produce much larger economic benefits (see Chapter 5).

At the country level, the Czech Republic and Poland [39–40] have placed nuclear energy development at the centre of the transition away from coal fired power while guaranteeing self-sufficiency in electricity supply. A similar approach is being adopted by Canadian provinces seeking to shift away from coal by factoring in nuclear technologies, with Ontario having been the first province to phase out coal completely by 2014. China is likely to increase nuclear capacity substantially to advance a low carbon transition.

The economic boost associated with nuclear energy investment will be concentrated in the regions in which plants are built and operated. Nevertheless, with favourable macroeconomic conditions, important benefits to economic development will extend far beyond the plant and surrounding region. Nuclear energy investments can stimulate economic activity and job creation across many sectors, such as construction, manufacturing and services.

Labour market effects will be at the core of the impetus for local and regional economic development and key to delivering a just transition. They include not only direct employment effects of construction and operation activities but also the indirect (supply chain) and induced (in local community outside supply chain) employment. Recent experience in IAEA Member States shows that these secondary effects of nuclear energy programmes might be several times higher than the impact on direct employment.

Apart from the direct and indirect job creation potential of specific power plants, nuclear energy also has positive implications for electricity and aggregate price stability leading to a more favourable macroeconomic context, particularly when it comes to new sources of economic growth. A number of countries recognize an important role for nuclear energy to initiate a new wave of industrialization, to drive structural transformation and to boost long term growth potential (see also Chapter 5). For example, the United Arab Emirates identifies industrialization as the key to economic diversification away from oil/gas extraction and development to be achieved through the deployment of nuclear and renewable energy projects [41]. The UK seeks to advance the ‘green industrial revolution’ through a number of low carbon technologies, including nuclear energy. Considerations around nuclear power in Ghana are based on the country’s industrialization agenda [42].

Country Case: South Africa

Nuclear Power Development in Africa

South Africa prides itself as the only country in Africa with a commercial nuclear power plant, situated at Koeberg, North of Cape Town. However, this situation is about to change significantly with many countries actively pursuing nuclear energy to fill the continent's huge 'energy gap' while protecting the environment. As a pioneering nuclear country, South Africa offers some important lessons for other African countries embarking on this development pathway.

South Africa launched its civil nuclear power programme in 1957 by signing an agreement with the USA to acquire a research reactor, SAFARI-1 at Pelindaba, West of Pretoria. The decision to adopt nuclear power — starting with the Koeberg Nuclear Power Plant (KNPP) completed in 1984 — was partly to mitigate against dependence on transmitting electric power from the coal power plants located in the North East of the country (Mpumalanga Province) over long distances of about 2,000 km to Cape Town. The idea was to follow up Koeberg by building another plant in the Eastern Cape near Jeffreys Bay but plans were abandoned following the Chernobyl accident in 1986.

More recently, a renewed interest in nuclear power generation emerged in response to concerns that baseload coal fired generation would soon be overtaken by increasing demand. In response, nearly 10 GW of nuclear capacity was included in the Department of Energy's Integrated Resource Plan (IRP) for the period 2010 to 2030. However, these plans were shelved after the Fukushima accident, and a long period of stagnant electricity demand, coupled with increasing interest in renewable energy sources, mainly wind and solar, reduced the impetus for nuclear energy. In this period, the national energy policy debate also became increasingly polarized, contributing to a lack of energy policy certainty, which was exacerbated by a high turnover of officials. Nonetheless, the latest IRP (of 2019) reaffirmed the commitment to developing nuclear by calling for 2,500 MW of new nuclear capacity as well as life extension of KNPP.

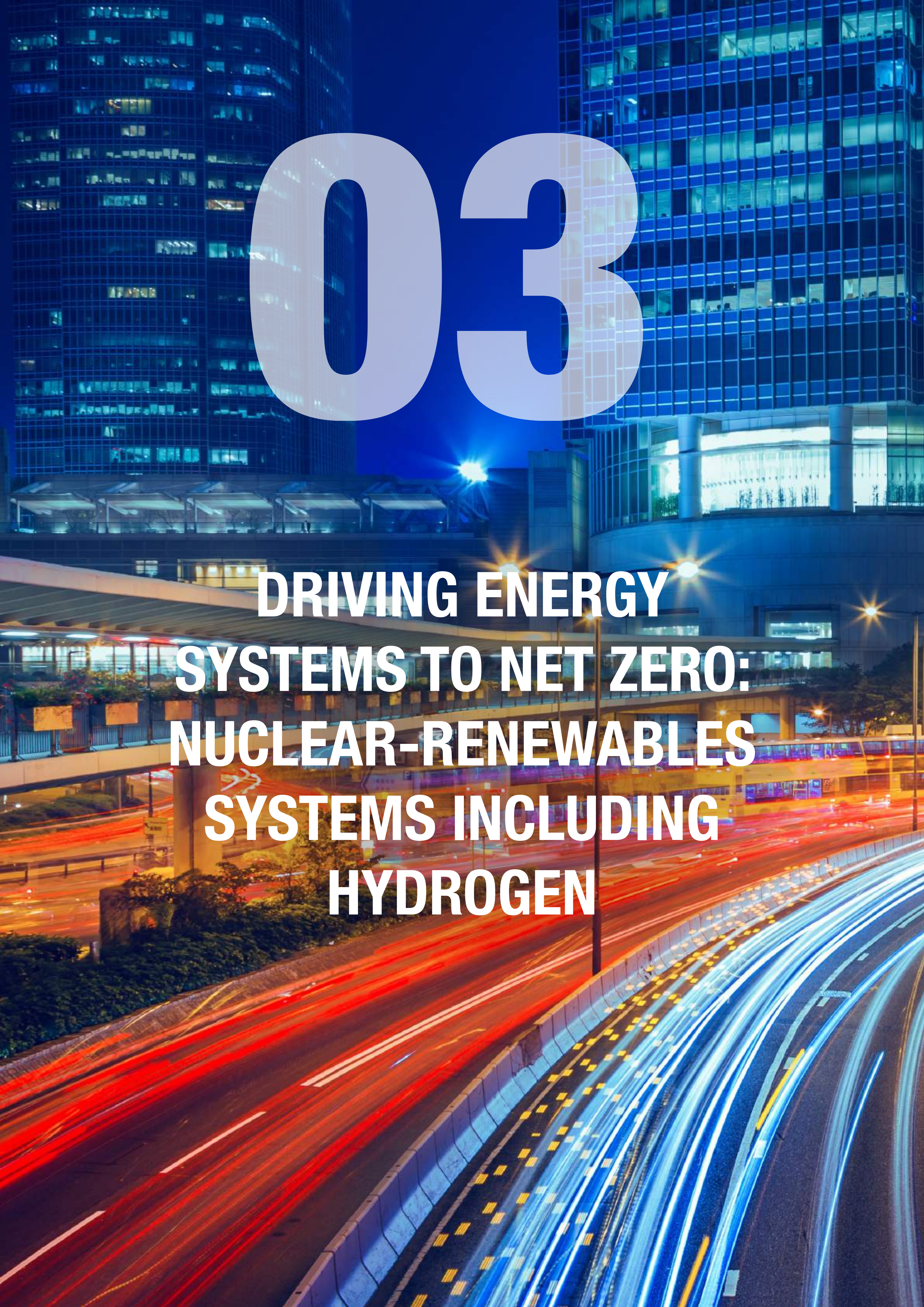
The South African experience also highlights some of the challenges in energy policy development across the continent, which needs to reflect national circumstances including the stage of economic development.

More broadly, what might be good for an advanced economy may not suit African countries which invariably have low levels of industrialization, infrastructure and electricity penetration. While it could be argued that Africa cannot afford the luxury to be selective in the choice of energy sources in the short to medium term, these challenges also draw attention to the need for international support for the adoption of clean energy sources — including capacity building, infrastructure development, technology transfer and finance, among others — to enable Africa and other emerging economies to also transition to a net zero world.

Nuclear Industry Association of South Africa

Recommended Actions:

- Phase out public support and financing for investment in fossil fuels, coupled with additional measures including carbon pricing.
- Adopt objective, technology neutral ESG (Environmental, Social and Governance) frameworks for low carbon investment.
- Accelerate nuclear innovation through Public Private Partnerships, including the demonstration of non-electric applications with conventional and advanced reactors.
- Direct clean energy investment to enable a just transition, supporting regions and communities dependent on fossil industries, retraining workers, capitalizing on existing infrastructure, and driving new industrial development.



03

DRIVING ENERGY SYSTEMS TO NET ZERO: NUCLEAR-RENEWABLES SYSTEMS INCLUDING HYDROGEN

Key Points:

- Dispatchable, low emission, flexible and reliable sources of power are needed for electricity to be the foundation of net zero emission systems.
- Nuclear power can help lower the costs of the overall electricity generating system, by providing dispatchable power and reducing the need for grid expansions and storage.
- Nuclear energy can provide low carbon heat and be used to produce hydrogen for hard-to-abate sectors via both established and emerging production processes.

Achieving a net zero energy system requires a rapid and radical transformation of how energy services are produced, provided and used worldwide. The electricity system is expected to play a critical role in this transition, with increasing electrification of transport, buildings and industry, combined with a nearly complete decarbonization of the electricity generation mix. This is reflected across long term scenario studies outlining pathways compatible with a net zero world [4], which recognize direct electrification as among the most efficient and economical ways to decarbonize several sectors of the economy, particularly light duty road transportation and many forms of heating. However, other hard to abate sectors such as steel, cement and chemical production, long distance shipping, and air transport will require the deployment of other energy carriers, including hydrogen and heat, which must also be produced with a low carbon footprint.

As the cornerstone of the low carbon transition, the power sector is expected to evolve towards a larger, more complex and integrated system, and rely on a much broader range of low carbon technologies. The use of unabated fossil fuels, which today account for about 60% of global power generation [1], must be reduced to zero in only 30 years or be limited to meeting peak demand or providing system services. The size of this task is compounded by the fact that it must occur in a much shorter timeframe than the average lifetime of power infrastructure assets. To achieve such a transformation, and thereby avoid the worst impacts of climate change, swift deployment of all low carbon generating options, while preserving existing low carbon generating capacity, will be needed, together with technologies to facilitate their integration into the energy system. It is also likely to require early retirement of significant fossil fired generating capacity. Such a radical transition will create challenges, not only from a technical or engineering perspective, but also across economic and social dimensions, that should be understood and addressed by policy makers (see Chapter 2).

The role of hydrogen in a highly decarbonized economy

In recent years there has been a renewed and significant interest in hydrogen among industry, the research community, national governments and international organizations. Governmental initiatives, plans and programmes on hydrogen have been established, including in Canada, the EU (as part of its European Green Deal), Japan, the Republic of Korea, the Russian Federation, the UK and the USA. Hydrogen is increasingly viewed as an effective and versatile energy carrier to decarbonize hard to abate sectors for which direct electrification is not possible or uneconomic. Used directly or in the form of ammonia or synthetic fuels, low carbon hydrogen can reduce the carbon footprint of long haul transport, steelmaking and chemical production as well as a variety of other heat applications. Hydrogen can also help to overcome some of the challenges of operating a low carbon power system and facilitate the integration of large shares of variable renewable energy sources by providing a form of energy storage.

Global hydrogen demand reached about 120 megatonnes (Mt) in 2019 [43], primarily in oil refining and the chemical sector, where it is used as feedstock for ammonia and methanol production. Smaller amounts are also used in steel production (5% of the total demand in 2019), transport and in the manufacturing of other materials and equipment such as other metals, glass and electronics [44]. Demand for hydrogen is expected to increase

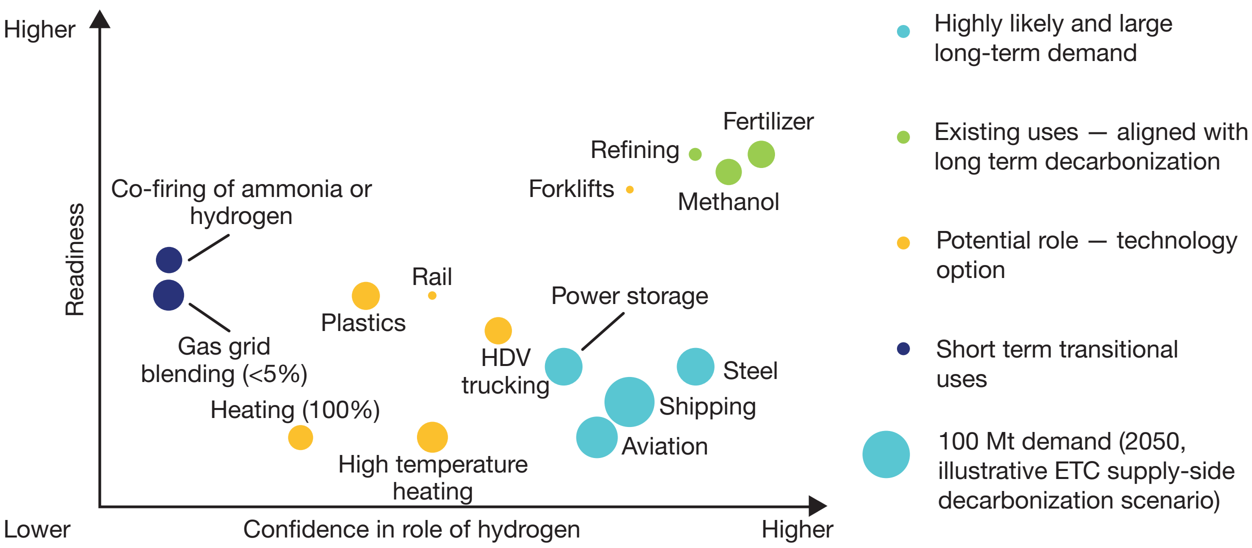


Figure 7. Potential uses of hydrogen in a low carbon economy [45].

significantly in the next 30 years as the transition towards a net zero economy advances. The Energy Transitions Commission (ETC) estimates that 500 to 800 Mt/year will be needed in 2050, a 4–6-fold increase from current demand levels [45]. The ETC has identified a range of potential long term applications for clean hydrogen (see Figure 7). Sectors with high potential in the long term include steel production, shipping, aviation and the power sector. In other sectors, such as domestic heating, high temperature heat applications, manufacture of plastics, and heavy duty transport, hydrogen is seen as a possible alternative to direct electrification or other decarbonization options. Potential short term but transitional uses of hydrogen to reduce emissions include co-firing of ammonia or hydrogen in conventional power plants or blending with natural gas.

Hydrogen is produced in various ways using different energy sources, such as natural gas, coal, biomass and electricity. Currently, almost all hydrogen is produced from fossil fuels: either through steam methane reforming of natural gas (75% of total) or coal gasification (23%). Both processes emit CO_2 (9 and 20 kg CO_2/kg H_2, for natural gas and coal respectively), and the adoption of carbon capture and storage (CCS) is so far very limited. Carbon capture technologies can reduce direct emissions from steam methane reforming by up to 90%, with an increase in production costs. However, there is a need to consider the full life cycle — in particular, the substantial residual methane emissions from upstream processes in natural gas production and distribution. The use of CCS in coal gasification processes appears technologically more challenging and less likely to be economically competitive for a stringent abatement strategy.

Hydrogen can also be produced using electrolysis to split water into its basic components, hydrogen and oxygen, using electricity and possibly heat. Currently this technology accounts only for 0.1% of total hydrogen production, but it has attracted strong interest due to the potential to generate hydrogen with a very low carbon footprint. Alkaline and proton exchange membrane (PEM) electrolysers operate at low temperature and are technologically mature. Other technologies, including solid oxide electrolysis cells use high temperature steam and have much higher electrical efficiencies. While electrolysis does not entail direct carbon emissions, the indirect carbon intensity depends on the source of electricity used in the process. Compared to unabated steam methane reforming, hydrogen production via electrolysers provides benefits in terms of carbon emissions if the carbon content of electricity is below 200 g CO_2/kW·h, a level that only few countries in the world currently achieve (see Figure 8). An even lower carbon content would be required to reduce emissions compared to steam methane reforming with CCS. Thus, a widespread use of electrolysers can provide benefits only if directly coupled to a low carbon source such as wind, solar or nuclear power, or if the power generation mix is almost fully decarbonized.

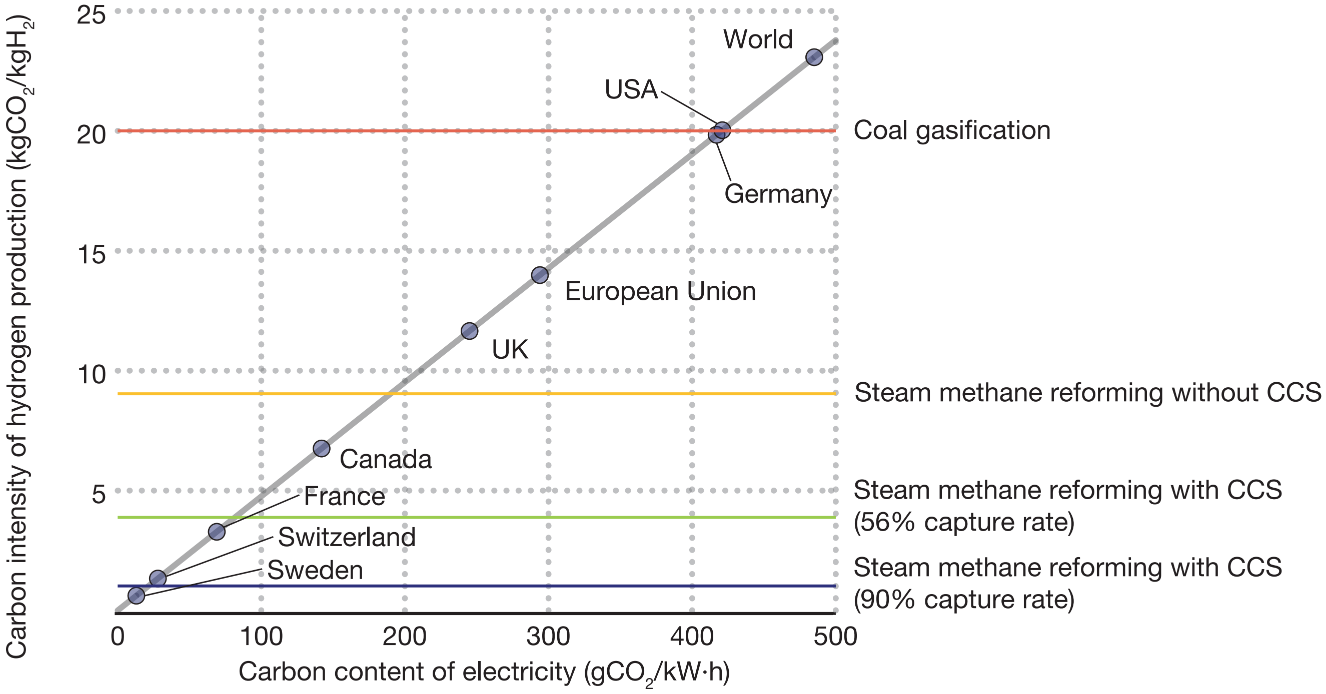


Figure 8. Carbon intensity of different hydrogen generation routes. IAEA, based on [33][1].

Hydrogen production costs from fossil fuels are mainly influenced by the price of the feedstock, natural gas or coal (which is subject to large regional variations), the technology used (with or without CCS) as well as the cost of carbon emissions, if these are priced. The current cost from steam methane reforming is US $1.0–1.6/kg H_2 for unabated production and US $1.5–2.2/kg H_2 if CCS is used [46]. The cost of hydrogen via electrolysis depends on a complex interplay of many factors: capital expenditures for the electrolyser, efficiency, annual operating hours and the price of electricity. Current cost estimates vary in a wide range between US $3 and 10/kg H_2 [45–47], indicating that substantial cost reductions are needed to be competitive with fossil fuels. However, electrolysis production costs are expected to decline significantly in the near future as the capital cost of electrolysers and electricity generation costs from low carbon technologies, mainly variable renewables, decrease from current levels.

Among different low carbon electricity sources, using nuclear power for electrolysis allows for very high and efficient utilisation of the electrolyser, minimizing the related capital costs. However, to achieve hydrogen production costs of about US $2–2.5/kg H_2, the levelized cost of electricity (LCOE) needs to be in the range of US $35–45 per megawatt-hour (MW·h), much lower than projections for new nuclear power plants in many regions of the world. However, such costs can be achieved with lifetime extensions of existing reactors and may enable existing plants to diversify their revenues as explained below.

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[1] The carbon intensity of hydrogen for individual countries has been estimated applying the average carbon content of electricity generated in 2017 (based on data from [52]) and assuming an electrolyser efficiency of 70%.

Nuclear, renewables and hydrogen in integrated low carbon energy systems

To realize a net zero energy system, electricity production must be almost fully decarbonized by 2050 and therefore rely on a combination of low carbon sources: variable renewable energy sources such as wind and solar, and dispatchable low carbon technologies such as nuclear power, fossil fuels with CCS and some hydropower plants. Interconnections, innovative storage technologies, demand side measures and energy carriers such as hydrogen are also likely to play a significant role in future low carbon power systems. Irrespective of the specific mix of technologies adopted, the transition to a low carbon power system creates new challenges, both technical and economic. However, these challenges and the associated costs for the system increase significantly with the share of variable renewable energy sources in the mix, since these sources are more volatile, unpredictable and often decoupled from daily, weekly and seasonal demand patterns [48–49].

This is one important reason why flexibility will be at the heart of future low carbon electricity systems. Short term flexibility, from milliseconds to hours, will be increasingly needed to ensure the demand–supply equilibrium in response to volatile variable renewable energy (VRE) generation. Medium term flexibility, from hours to days, will be needed to compensate for the cyclical production profile of wind and solar resources. Additional long term flexibility needs will emerge, particularly with high VRE shares, for large seasonal storage capacity given that generation from renewable sources alone could reach or exceed total demand over extended periods of time. This will coincide with the phasing out of gas and coal power plants, which are the main source of flexibility and providers of ancillary services in today's power systems.

New sources of flexibility will be needed, and existing sources will need to be scaled up from current levels, including interconnections with other networks, demand-side measures, existing and new storage technologies, and load modulation from thermal and renewable power plants. Nuclear power plants may need to respond both technically and economically to a strong increase in the requirements for load following and flexibility provision, with a corresponding decline in the achievable load factors.

The new demand for flexibility will also create new opportunities. A tighter coupling between electricity generation and the broader energy sector, supplemented with hydrogen produced from electrolysis as an energy vector, could untap a vast potential for flexibility and help address some of the challenges of achieving a low carbon system. In particular, the use of hydrogen in power systems, combined with the deployment of batteries, is essential to provide the level of flexibility over different timescales required by a large scale deployment of VRE sources.

From the power system viewpoint, an electrolyser can be seen as an additional, extremely flexible, load. Electrolysers can be operated at times of low demand or excess VRE production, thus better matching supply with demand, and can vary their power consumption rapidly to provide balancing services to the system. Hydrogen could also be used as a fuel for power generation in fuel cells or in gas turbines, in conjunction with natural gas or as a standalone fuel. In this way, hydrogen can also provide short term flexibility to the power system and replace carbon emitting peaking power plants in periods of high demand and low renewable generation, thus reducing the overall carbon emissions. Large quantities of hydrogen could potentially be stored for long periods and with limited losses in salt caverns or in depleted natural gas fields and oil reserves [51], thus potentially providing a solution for seasonal storage, addressing imbalances in production and demand typical of systems with high shares of VRE. For long term storage, hydrogen also has the potential to be more effective and economical than other storage technologies currently available such as batteries and hydroelectric reservoirs.

The widespread deployment of batteries and the use of hydrogen will thus help to improve the overall stability of the system, limit the curtailment of VRE generation and reduce the requirements for load

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[1] The carbon intensity of electricity production must decrease from a 463 g CO_2/kW·h in 2019 [15] to less than 10-20 g CO_2/kW·h in 2050.

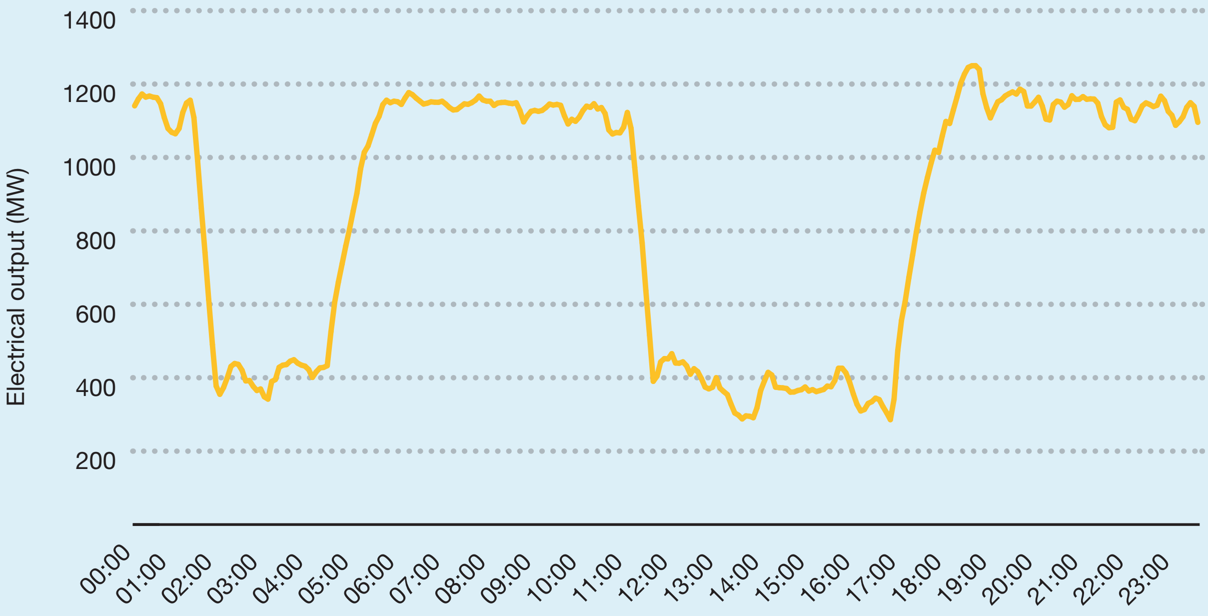
[2] It should be noted that different types of electrolysers have different degrees of flexibility and capability to vary the power demand: PEM electrolysers can be operated more flexibly than the more mature alkaline electrolysers.

Country Case: France

Flexibility of nuclear in France

Nuclear power supplies over 70% of electricity demand in France and emits only 12 g CO_2 equivalent per kW·h (median estimate) over the entire lifecycle (uranium mining and processing, fuel fabrication, plant construction, operation and decommissioning, and waste disposal) [50]. Since the 1980s nuclear power plants in France have been operated flexibly to provide ancillary services such as frequency and voltage regulation required for grid stability in a safe and cost effective way. In addition to responding to changes in demand, nuclear flexibility can be one solution for accommodating fluctuations in renewable generation, which is expected to increase significantly, without relying on gas or coal plants.

On average, each reactor in France performs 30 power variations per year. However, most of these variations are performed by a small number of units, which may perform up to 125 large load modulations per year. A typical daily profile illustrating flexible nuclear power plant operation is shown in the figure below. The plant performs two large power variations in the day, reducing the nominal power from 100% to 20% in thirty minutes, and also provides frequency (up to 7% of nominal power) and voltage regulation to the system.



Power output of a French nuclear power plant in one day (courtesy of EDF).

Électricité de France (EDF) forecasts that the flexibility provided by its nuclear fleet is sufficient to satisfy the needs of the system envisioned by 2030 and 2040. Nuclear power, together with other technologies such as hydroelectric power, batteries and hydrogen, is therefore considered essential for the integration of more renewable sources in France.

Électricité de France

modulation and for ramping up and down, as well as the number of startups and shutdowns for all dispatchable generators, including nuclear power plants. Overall, this would enable more efficient operations and increased load factors. From an economic perspective, electrolysers can help to smooth demand and thus, as a side effect, reduce price volatility, with benefits for VRE, nuclear power plants and consumers alike. A recent study focusing on the transition towards a net zero energy system in the UK [53] confirmed that a combination of nuclear power, renewable energy and hydrogen is needed to achieve rapid decarbonization, reduce the dependency on fossil fuels and minimise overall carbon emissions. Deploying a sizeable share of nuclear power alongside wind energy and solar PV would achieve such transition at a minimal cost and reduce the associated risks.

A more tightly coupled energy system will provide new opportunities for nuclear power to provide services beyond pure electricity production. Unlike most renewable energy technologies, nuclear power can provide heat and other non-electric applications to the system, and thus replace fossil fuels as described in Chapter 2. The flexibility of nuclear power plants to produce electricity in combination with another, possibly storable, energy product, such as heat, hydrogen or desalination services, is particularly suited to the needs of a sustainable system. By operating steadily at full power, while modulating output between electricity and non-electric products, nuclear power plants can achieve high load factors while providing flexibility services at very low cost and respond to market demands for each product (electricity, heat, hydrogen), thus maximizing revenues.

Country Case: China

China’s first Nuclear+ Smart Energy project in Rongcheng

China’s nuclear power industry launched the construction of a smart energy project, Guohe One+, on 13 April 2021, in Rongcheng, Weihai city. The Guohe One+ project aims to transform Weihai, on the east coast of China, into a carbon neutral demonstration city integrating nuclear and other low carbon energy technologies.

As an extension of the two state of the art pressurized water reactors in Rongcheng, the Guohe One+ project will implement a smart energy management and service platform to integrate nuclear, solar photovoltaic, offshore wind and other technologies into a clean electricity system. This low carbon, integrated and smart system will also optimize provision of heat, seawater desalination and hydrogen production using nuclear energy.

Once Guohe One+ is put into operation, it will increase the supply of clean electricity by an average of 6 gigawatt-hours (GW·h) per year (on top of the substantial quantity from the two pressurized water reactors), saving 1889 tonnes of standard coal, and reducing carbon dioxide emissions by 5167 tonnes. The total investment in the first phase is about RMB 30 million (US $4.6 million) and the internal rate of return on capital is expected to be over 8%.

Guohe One+ is highly valued by the local government, which has signed a cooperation agreement with the State Power Investment Corporation (SPIC), the developer of Guohe One+ and a major generator in China. In the future, the local government and SPIC plan to jointly develop two further integrated energy system demonstration projects which, together with Guohe One+, will provide a model for smart energy projects throughout China.

State Power Investment Corporation

Exploring the hydrogen option with nuclear energy

Interest in hydrogen production using nuclear energy is growing internationally due to the potential to deliver electricity and heat for hydrogen synthesis in a sustainable, low carbon and cost effective manner. This is reflected in an increasing number of demonstration projects and international partnerships — for example, between leading nuclear utilities Rosatom and EDF — to analyse the feasibility and business opportunities of hydrogen production, using existing light water reactors (LWRs) coupled with low temperature electrolysers (see Figure 9). These projects are often motivated by the need to improve the economics of the existing nuclear reactor fleet, especially in electricity markets with low or sometimes negative prices, by producing an additional high value product.

Research and development activities are also focused on advanced reactors and SMRs — including high temperature gas reactors (HTGRs) — for non-electric applications and, in particular, hydrogen production using high temperature steam electrolysis (HTSE) or thermochemical processes (see Spotlight 1). A range of different technologies are currently under development, including some close to market deployment (see Figure 9).

Spotlight 1:

Small modular reactors

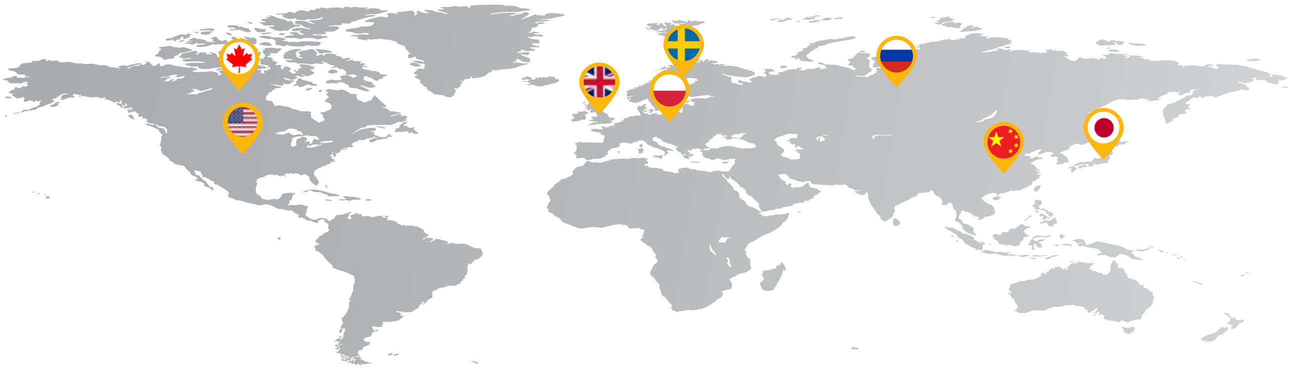
Several types of SMR are currently under development [52], with the aim of offering improved economics, higher operational flexibility, a wider range of plant sizes and the ability to provide multiple energy services to meet the emerging needs of sustainable energy systems.

Some of these reactors are designed to operate at high or very high temperatures (up to 700–950°C for gas cooled reactors) compared to current LWRs, which operate at 280–325°C. This allows for a higher electrical efficiency and creates the possibility to supply industrial processes requiring higher temperature heat. High temperature advanced reactors are expected to also generate hydrogen through more energy efficient processes such as high temperature steam electrolysis or thermochemical cycles.

Small modular reactor designs also offer some significant advantages for hydrogen production and non-electric applications. Their smaller size and easier siting are expected to be a better fit for most non-electric applications, which require an energy output in the range of 100–1000 MW thermal.

Recommended Actions:

- Improve the competitiveness of nuclear electricity generation by addressing/reducing costs, adapting to emerging energy market needs and capitalizing on synergies with other low carbon generation options.
- Ensure energy market regulatory and policy frameworks value and remunerate nuclear energy’s contribution to a reliable, low carbon energy system.
- Foster integrated clean energy and industrial clusters utilizing multiple low carbon energy carriers (electricity, heat, hydrogen, etc.) and reducing energy distribution costs.
- Support technology neutral low carbon hydrogen deployment.



Hydrogen production using existing LWRs with electrolysers

USA

- DOE H2@Scale: public-private partnerships to advance flexible operation of LWRs with integrated H_2 production.
- Davis Besse NPP pilot using a 2 MW PEM electrolyser.
- Palo Verde NPP studying the potential of a reversible PEM electrolyser, producing electricity at peak demand and H_2 during periods of low demand.
- Exelon conducting demonstration of a 1 MW PEM electrolyser for H_2 production.

UK

- EDF confirmed the technical feasibility of low carbon hydrogen production at the Heysham NPP, but the project has not advanced to the demonstration phase.
- EDF is considering large scale hydrogen production powered by its UK nuclear plants, starting with a 2 MW demonstration electrolyser supplying H_2 to decarbonize construction at the Sizewell C project.

Russian Fed.

- Rosatom is launching a pilot project to produce hydrogen at the Kola NPP using matrix-alkaline electrolysis and will also develop hydrogen liquefaction units and liquid hydrogen transport equipment.

Canada

- The utility Bruce Power is exploring the technical feasibility and business case for nuclear hydrogen production at the Bruce Nuclear Generating Station to support the goal to achieve net zero emissions on site by 2027.

Sweden

- Vattenfall has been producing hydrogen at Ringhals NPP since 1997.
- Vattenfall, together with a steel producer (SSAB) and mining company (LKAB), has launched a new initiative to decarbonize steel production using low carbon electricity and hydrogen, with plans to produce 1 million tons of fossil-free steel per year by 2026.

R&D activities focused on hydrogen production with advanced reactors and SMRs

USA

- Under the Next-Generation Nuclear Plant (NGNP) project, DOE, the Idaho National Laboratory (INL) and industry partners are investigating two HTGRs with demonstrated potential for providing heat for hydrogen production.
- An evaluation by INL shows NuScale's 250 MW_{th} SMR could economically produce almost 50 t H_2/day, avoiding 168 kt CO_2 per year compared to H_2 from natural gas. A twelve-module plant could support a mid-sized oil refinery.

UK

- The Department of Business, Energy and Industrial Strategy (BEIS) is supporting several Advanced Modular Reactor technology projects, including U-Battery, a developer of HTGRs.

Russian Fed.

- Rosatom plans to commission an HTGR to produce hydrogen via the adiabatic conversion of methane with utilization of carbon dioxide by 2030.
- Thermochemical hydrogen production from water is also envisaged in the Russian Federation.

China

- The demonstration High Temperature Reactor Prototype Module, with a design temperature of 750°C, is expected to start operating at end of 2021, after successful cold tests in 2020.

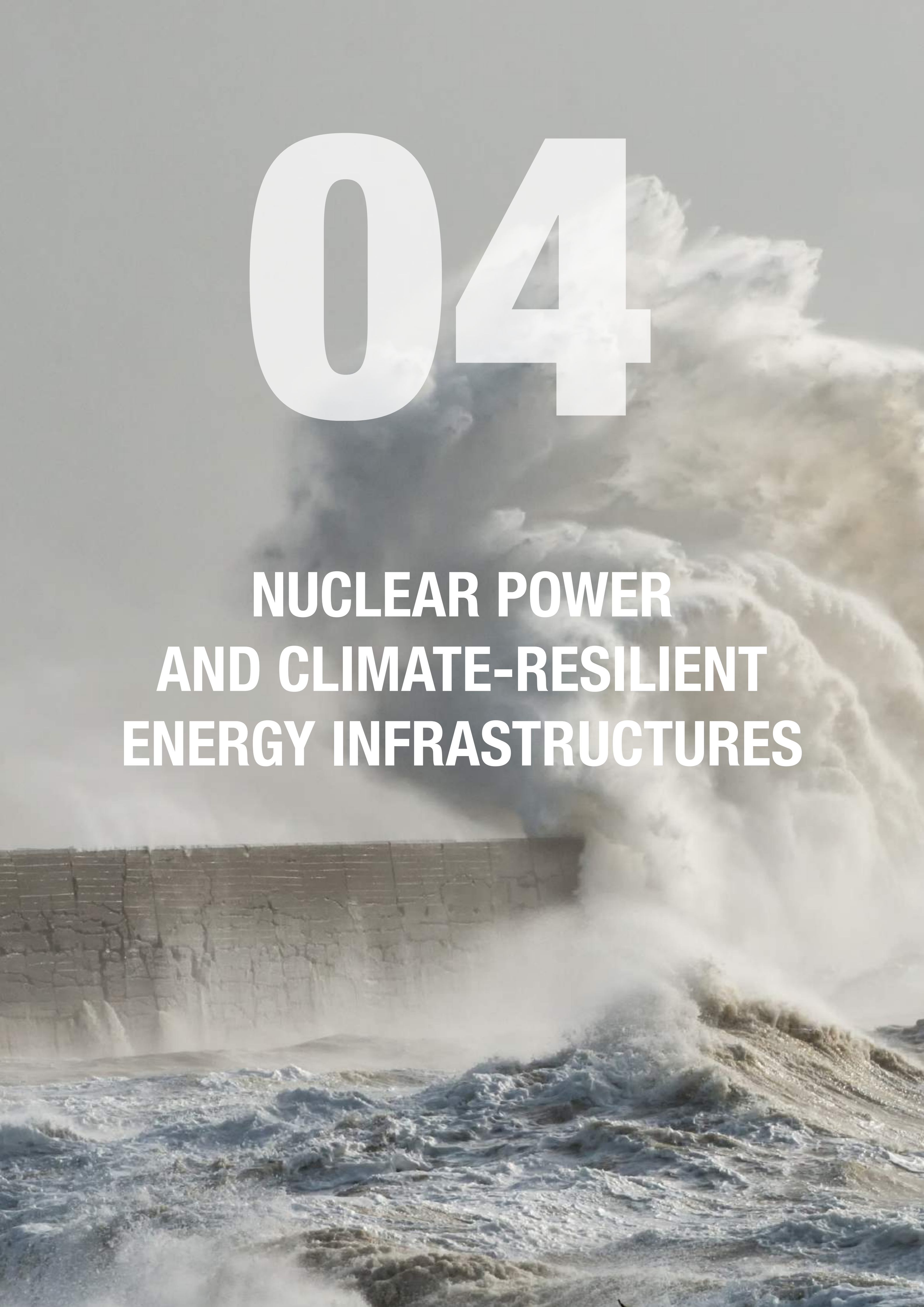
Japan

- Hydrogen production was demonstrated at the High Temperature Test Reactor using the iodine-sulphur thermochemical process in 2019.

Poland

- The Polish National Center for Nuclear Research initiated a project to develop the HTGR reactor in cooperation with Japan.

Figure 9. Map and summary of selected nuclear hydrogen demonstration projects, partnerships and R&D.



04

NUCLEAR POWER AND CLIMATE-RESILIENT ENERGY INFRASTRUCTURES

Key Points:

- The resilience of the energy system relies on the robustness of individual generation technologies, the grid infrastructure and demand side management.
- Net zero emission systems need built-in climate resiliency to guarantee the security of energy supply.
- The nuclear sector is well prepared to face the challenges posed by climate change including the risks of more frequent and more extreme weather events, and has developed specific adaptation measures to mitigate these risks.
- While the frequency of weather related outages at nuclear power plants increased over the last 30 years, total production losses were minor, with reduced losses per event over the past decade.

The path to net zero requires integrated action on both mitigation and adaptation, with climate smart investment strengthening the security of the energy supply in the face of climate impacts [54]. This need to ensure the built-in resilience of future energy systems was highlighted by the disruptions caused by the COVID-19 pandemic, and coping with a broader range of external shocks, including more variable and extreme weather patterns expected from climate change, is likely to represent a growing challenge. A resilient energy system relies on the robustness of individual generation technologies, grid infrastructure and demand side measures.

Severe weather events are already being felt regularly, sometimes with devastating economic and social consequences due to the interdependence of critical infrastructures. The catastrophic cold snap in Texas in February 2021 caused more than 200 deaths and multi-billion economic damages after the collapse of electrical supply [55–56] This reflects a troubling trend in the USA, where power failures have increased by more than 60% since 2015. And, although the recent outage in Texas focused attention on the impact of severe cold weather, of particular concern is the impact of more frequent and severe summer heatwaves, in combination with blackouts — which are more likely to occur during the summer, driven in part by high temperatures and the surge in electricity needs for air conditioners — exposing vast populations to heat exhaustion or heat stroke [57].

Changes to the climate are particularly pronounced at higher latitudes: an increase in average air and seawater temperature, increased precipitation, more frequent weather extremes as well as reduced snow and ice cover are already being observed (Figure 10). In addition, temperate regions in Western and Central Europe, as well as sub-tropical areas around the Caspian and Middle East, have also experienced sizeable changes in surface air temperatures.

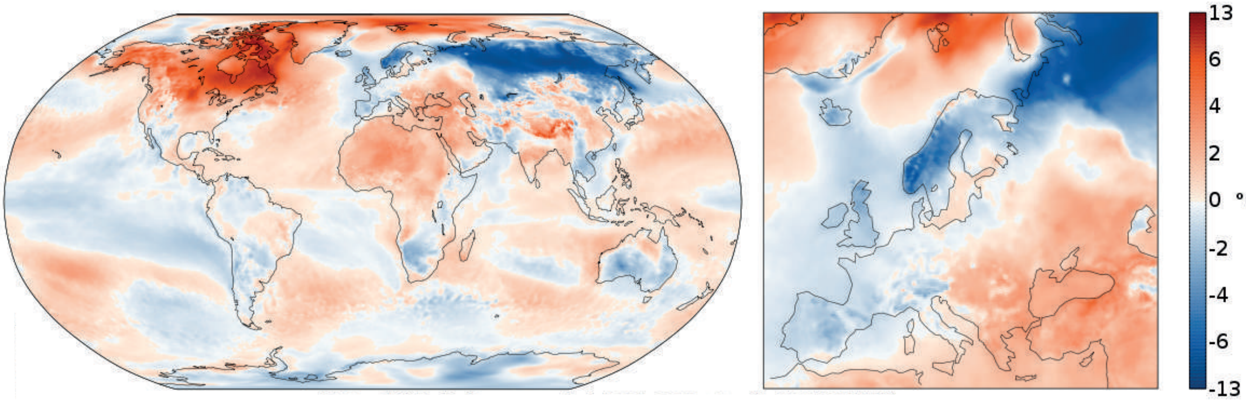


Figure 10. Surface air temperature for January, difference between 1981-2010 and 1991-2020 [58].

Nuclear power in a changing climate: rising to the challenge

Nuclear power plants are not immune to changing weather conditions. Winter storms and extreme cold remain important threats but other environmental conditions such as floods, severe winds and lightning strikes also cause occasional outages at nuclear power plants. However, the principal threat to nuclear power plant operations is extreme heat, resulting in restrictions — regulatory, physical or both — on the availability of cooling water [10].

A unique transversal illustration of the changing climate conditions faced by nuclear power plants worldwide over the past three decades is provided by the IAEA Power Reactor Information System (PRIS). This database includes reports of weather induced power outages from IAEA Member States and nuclear power plant operators worldwide, including a description of the cause, impact in terms of production loss, and precise geographical and climate information. This can be cross-referenced with information on reactor characteristics, including cooling system specifications, providing a valuable resource for both nuclear practitioners and, potentially, the wider community concerned with energy system resilience in the face of changing climate and weather patterns.

This dataset provides important insights into the frequency of weather related events. Firstly, there is strong evidence that extreme weather conditions worldwide are forcing more frequent shutdowns or partial throttling of nuclear reactors across all geographies and climatic zones (Figure 11, left panel). The cumulative number of reported weather related power outages was four times higher in 2010–2019 compared to the period 1990–1999.

Accounting for more than 40% of reported power outages, nuclear reactors located near rivers are particularly vulnerable to extreme weather conditions (Figure 11, right panel) and associated restrictions on cooling water withdrawals, many of which were adopted following the severe heatwave in Western Europe during the summer of 2003. In France, for example, reactors are forced to shut down beyond certain water temperature thresholds (28°C) and when river streams run too low, with the aim of protecting plant and animal life.

While abnormal water temperature events occur most frequently during summer months, a growing number of power outages are reported all year round (Figure 11, left panel). Understanding these seasonal patterns is especially useful to anticipate extreme weather, organize prevention measures and respond effectively to unusual events. For example, in response to the experience of the 2003 heatwave, France implemented a comprehensive plan — “Grand Chaud” (high heat) — triggering

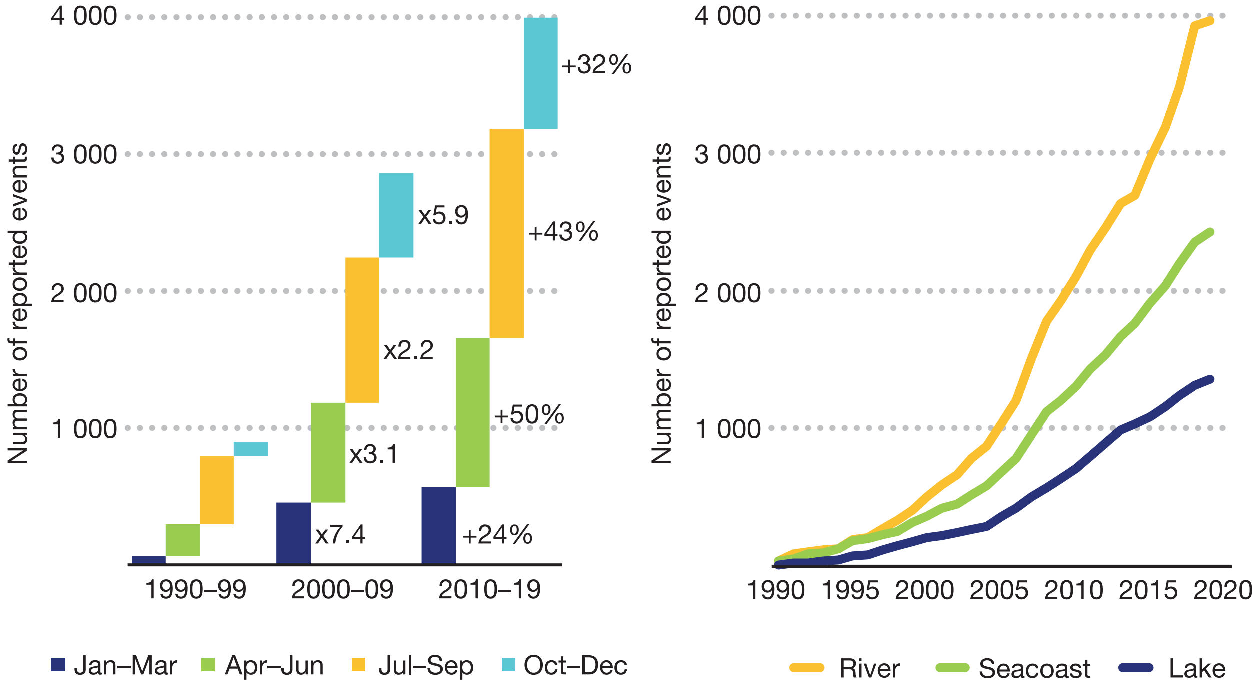


Figure 11. Quarterly breakdown of power outages due to weather events reported globally over 1990–2019 (left chart); breakdown of global power outages by plant location (right chart).

the systemic review of the nuclear reactor fleet and the adoption of a variety of measures to maintain safe operations in the face of high air and water temperatures.

Finally, the increasing reporting of events (Figure 12) indicates that more and more countries are concerned by weather induced power outages, suggesting a rising awareness among nuclear power operators and regulators of such threats to production and service reliability. It is noteworthy that the last two decades saw a growing number of countries identifying and reporting critical weather conditions as the single cause of production disruptions. However, it is likely that many additional unscheduled outages can also be partly attributed to weather related events, including events related to grid unavailability.

A closer look at the severity of reported events, measured in terms of production losses, provides a more nuanced perspective on the actual vulnerability of nuclear power plants vis-à-vis extreme weather events:

- The production foregone since 1990 due to isolated and identified extreme weather conditions remained fairly stable despite the increasing frequency of events (Figure 13). Overall, the cumulative production losses over three decades reached almost 50 TW·h (or 1.55 TW·h per year on average), i.e. less than 0.07% of nuclear electricity generated over the same period.
- In the most recent decade, a better comprehension and anticipation of risks, adaptive operational practices and new regulatory measures largely reduced the impact of extreme weather conditions (Figure 14). While total production losses increased sharply during the 2000–09 period relative to the prior decade, reported losses decreased appreciably from 2010 in most countries.
- A majority of countries report average production losses per event below 5 GW·h — the equivalent of five hours of production for a 1 GW nuclear power plant operating at full capacity (Figure 15). Nuclear power plants located in colder climates, including in Finland, the Russian Federation and Canada reported higher losses per event, which may indicate an increased vulnerability coinciding with the increase in water temperatures in these regions beyond historical thresholds.

Together, these various trends confirm the strong reliability of nuclear power plants in the face of extreme weather conditions, with limited forced outages owing in particular to robust facility design and limited reliance on vulnerable fuel supply chains [59]. It is also important to recognize that the regular adaptation upgrades of nuclear power plants contribute to the overall climate resilience of energy infrastructure, and thus these plants can be a critical building block in climate proof decarbonized energy systems.

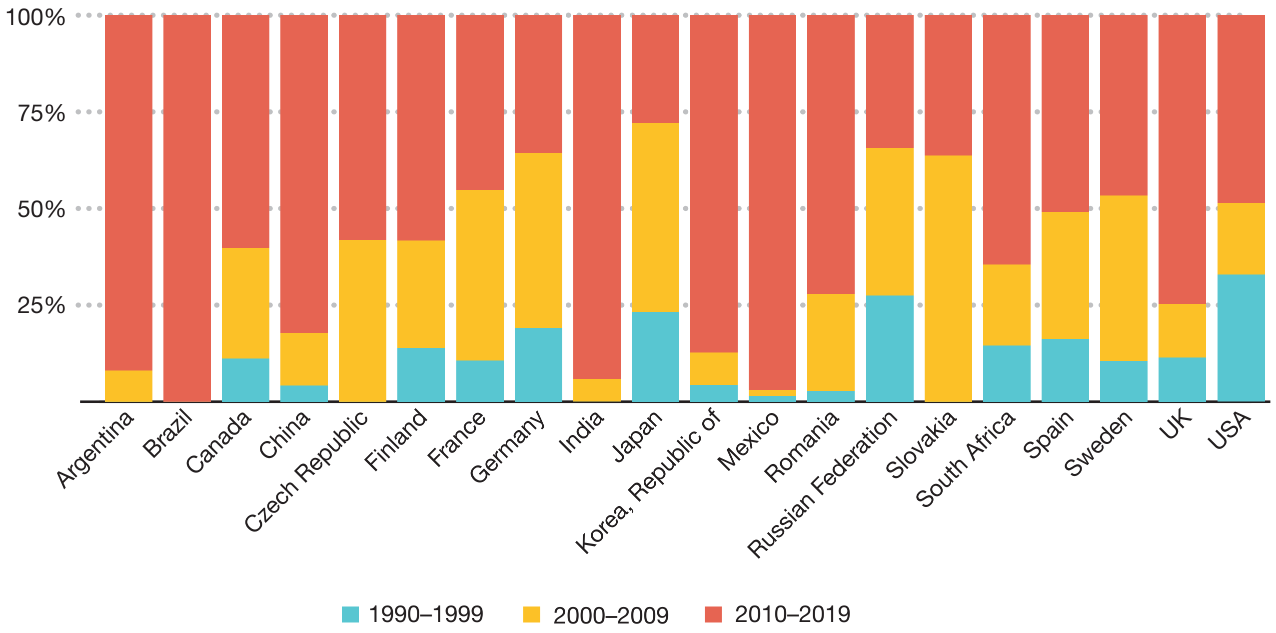


Figure 12. Decadal breakdown of power outages due to weather events by country, 1990–2019.

Future climate resilient energy infrastructure

The recent trends described previously foreshadow some of the challenges facing energy infrastructure in the future, illustrated in national, regional and global climate change assessments. In its Special Report on Global Warming of 1.5°C, the IPCC concludes with high confidence that an increase in the frequency and intensity of periods of extreme warm temperatures is to be expected in many regions [2].The frequency and intensity of extreme precipitation events and flooding is also very likely to increase in several regions, while an increase in the intensity and frequency of droughts and water stress is anticipated in others, with ongoing consequences for the integrity and performance of energy infrastructure [10].

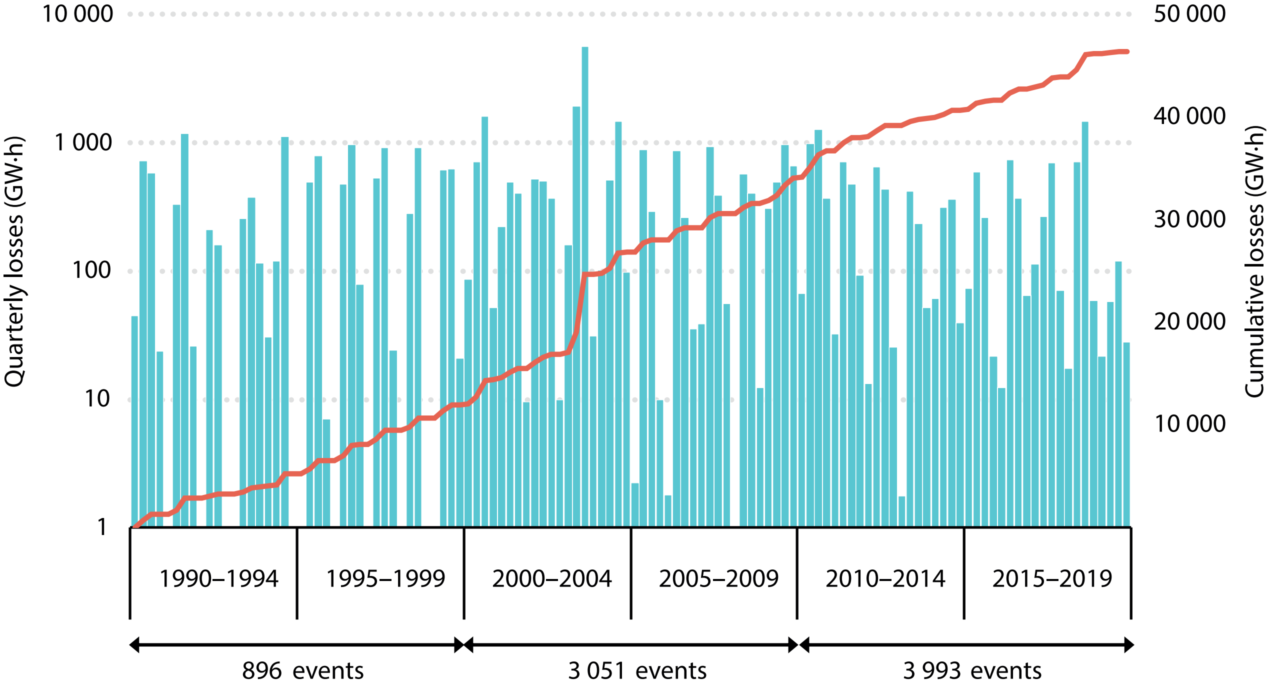


Figure 13. Quarterly production losses due to extreme weather events over 1990–2019 (Left axis); Cumulative losses (Right axis).

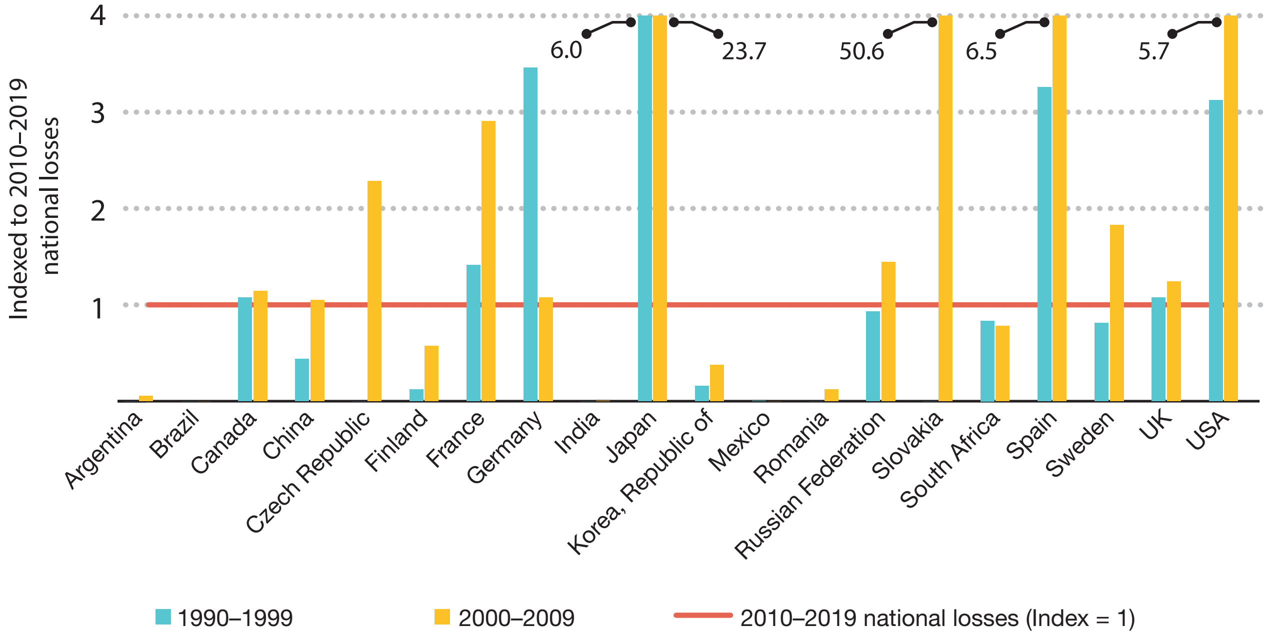


Figure 14. Decadal production losses due to extreme weather events relative to period 2010–2019. Note: Limited data reported for some countries.

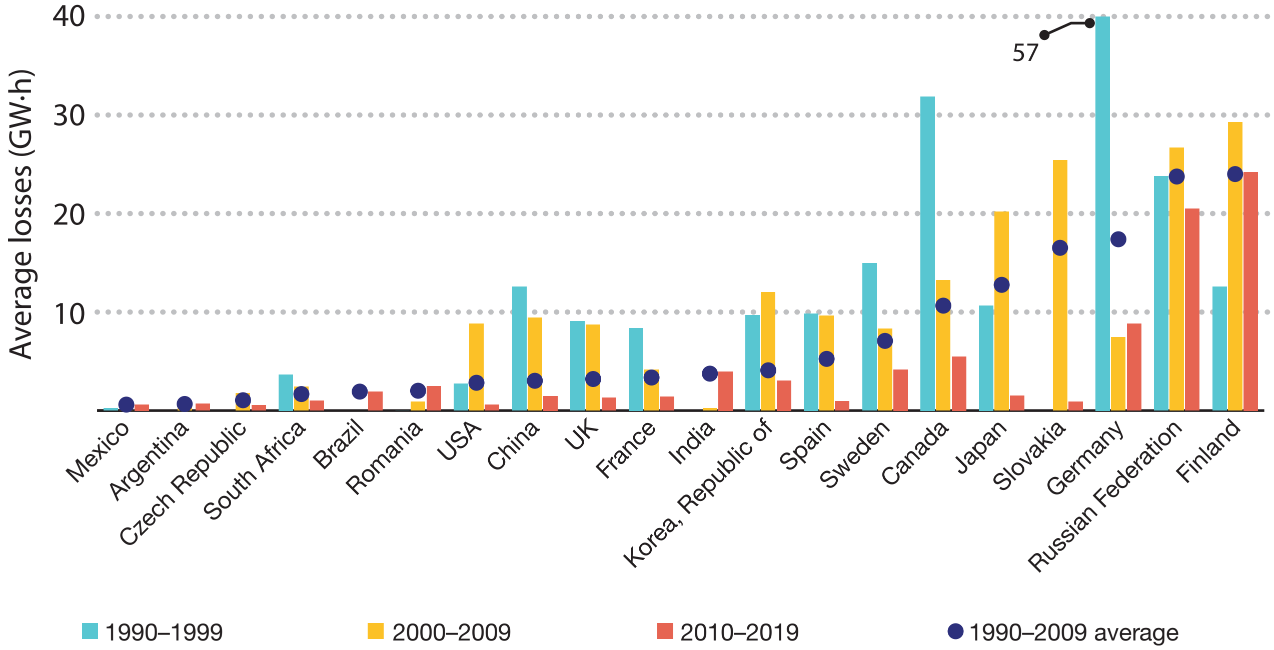


Figure 15. Average production losses per event per year by country, 1990-2019.

Building future proof, climate resilient infrastructure is therefore of utmost importance in order to reduce future risk exposure and associated economic losses. In addition to contributing to climate change mitigation, nuclear power plants also serve to render energy systems more resilient to the climate impacts expected in the future. This is also illustrated in assessments of local risks — for example, Nordic countries, which are particularly exposed to changing weather patterns, recently released a system level assessment concluding that nuclear power plants are well equipped to face current conditions. However, future risk exposure and overall energy system resilience will depend on the magnitude of climate changes (see Sweden country case).

With these challenges in mind, priority should be given to resilience focused investments which benefit customers and society on the path to net zero. Innovative approaches to resilience valuation, drawing notably on the people's perceptions and experiences of micro- and macro-level impacts of long duration power outages, can help inform investment decisions by providing estimates of the value of resilient energy services [60].

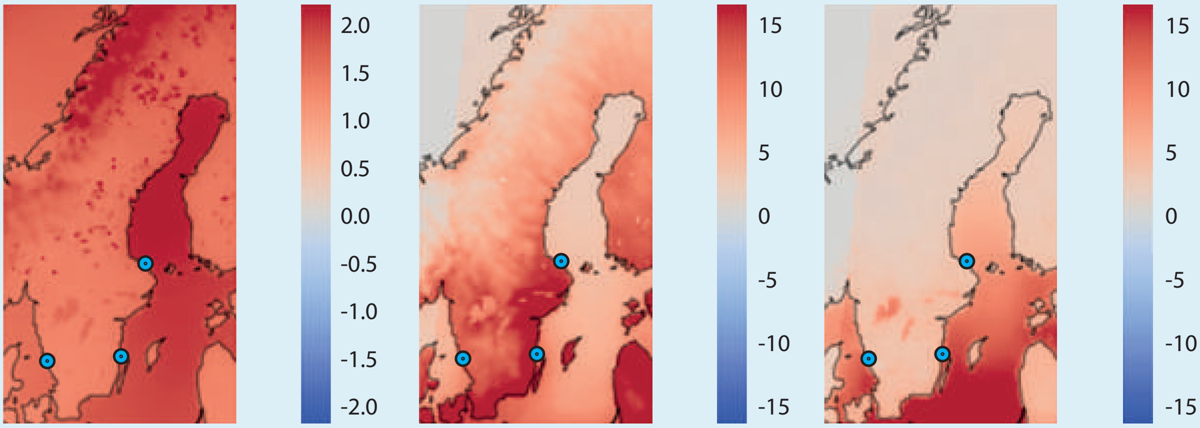
Recommended Actions:

- Maintain and improve good practices and adaptation measures by nuclear operators in response to specific and local weather and climate risks anticipated in the future.
- Adapt resilience by design and regulatory frameworks to increased climate variability, thereby affecting the site selection, facility design and plant operation phases.
- Identify external, system level sources of potential climate vulnerabilities, including impacts of severe weather of grid networks.
- Improve the representation of extreme weather risks in energy planning, including the development of sophisticated risk assessment tools and innovative data processing techniques, drawing on climate science, meteorology and operational experience.
- Apply a coordinated approach to the climate vulnerability of energy systems and access to financing mechanisms for the implementation of adaptation measures.
- Promote diversified electricity systems to mitigate climate risks to energy infrastructure, ensuring the continuity and quality of electricity services.

Country Case: Sweden

Nuclear power plants in Nordic countries: well prepared for the impacts of climate change

Nuclear power plants in Sweden and Finland are well prepared for a changing climate, over the coming decades and well beyond 2050 [61]. Actions initiated in the aftermath of the Fukushima accident and the overall high level of safety in the nuclear sector ensure a robustness to meet extreme events in general, including extreme weather events. Recent investments in independent core cooling in plants in Sweden have further strengthened durability.



Projected changes in climate indices of relevance for high sea water temperatures at +2°C global warming compared to pre-industrial conditions; blue dots denote operational nuclear power plants. From left to right changes in: maximum temperature (°C), consecutive warm days in June–August (days), and tropical nights (i.e. days when nighttime temperatures remain above 20°C).

Nonetheless, climate and weather related events with the potential to affect the operation of nuclear power plants have occurred historically and are expected to increase in frequency and severity in the future. For instance, all Nordic nuclear power plants are situated by the sea, making them potentially vulnerable to rising sea levels, although this effect is partly offset by land uplift at most of the nuclear sites. It is estimated that current safety margins can accommodate the impact of sea level rise caused by climate change and extreme weather conditions for several decades to come — for example, plants in Sweden can cope with a sea level rise of up to 3 metres above the current normal level.

A number of other climate or weather related events may also potentially affect the operation of nuclear power plants in Nordic countries. These include, for example, lightning strikes that may impact the electricity grid at the plant site and externally. Another example is higher seawater temperature, which in extreme cases may lead to power reduction or even require a temporary shutdown. In the summer of 2018, the production in both the Ringhals and Loviisa nuclear power plants was impacted by high cooling water temperatures.

A warmer sea also increases the risk of marine organisms obstructing cooling water intakes, as evidenced by jellyfish intrusions at the Oskarshamn nuclear power plant in 2005 and 2013. Furthermore, frazil ice, a phenomenon that may occur in subcooled moving water, led to the clogging of the cooling water inlet at the Olkiluoto nuclear power plant in 2008.

The potential impacts of climate change outlined above are not considered threats to plant safety, at least for a foreseeable future, and hence are more relevant for plant economics and electricity supply security. Mitigating actions are thus a matter of finding a balance between costs and benefits. The effect of high seawater temperatures can be mitigated by increasing the capacity of the heat exchangers or installing a deep water inlet, which can also reduce potential disturbances from frazil ice and jellyfish, albeit at a high cost. Measures can also be implemented to monitor for, screen and clear marine organisms. To protect the facilities from lightning strikes several different types of protections have been installed, both in the plants and in the grid.

Energiforsk

05

NUCLEAR ENERGY INVESTMENT FOR A SUSTAINABLE POST-COVID WORLD

Key Points:

- Investment in nuclear power is among the most effective actions for a sustainable post-COVID economic recovery, as well as the transition to a resilient net zero energy system.
- Mobilizing investments in sustainable energy requires a consistent, technology neutral policy framework, including objective criteria for climate investments, to address barriers and enable access to financing for countries wishing to invest in nuclear power programmes.

The COVID-19 crisis has been a wakeup call for humanity, coming at a critical juncture for multiple environmental and development challenges. How the global community responds and emerges from the shadow of the pandemic will have a substantial bearing on whether a sustainable net zero world can be realized.

In response to the economic and social impacts of the COVID-19 crisis, national governments and international organizations are developing and implementing investment led recovery plans to sustain, stimulate and restart economic activity. Many are increasingly recognizing the need for these investments to deliver a sustainable recovery (Figure 16) that brings the world closer to net zero greenhouse gas emissions.

Investment in nuclear energy is well matched to respond to these multiple urgent needs by boosting economic activity and job creation in the short term — for example with “shovel ready” projects to extend the operating lifetimes of nuclear power plants — and enhancing sustainable growth, development and industrialization over the longer term while ensuring resilience to future challenges, including climate change (as outlined in Chapter 4), and delivering affordable low carbon electricity.

Boosting economic activity and employment from a proven base

Nuclear power plants already generate direct employment and economic activity throughout their lifetimes, including in construction, operation, decommissioning and waste management. The International Energy Agency (IEA) estimates that “[n]uclear power provides over 800 000 jobs” despite only accounting for around 10% of global electricity generation [64]. As outlined in Chapter 2, in addition to direct employment and economic benefits, nuclear power plants also generate indirect

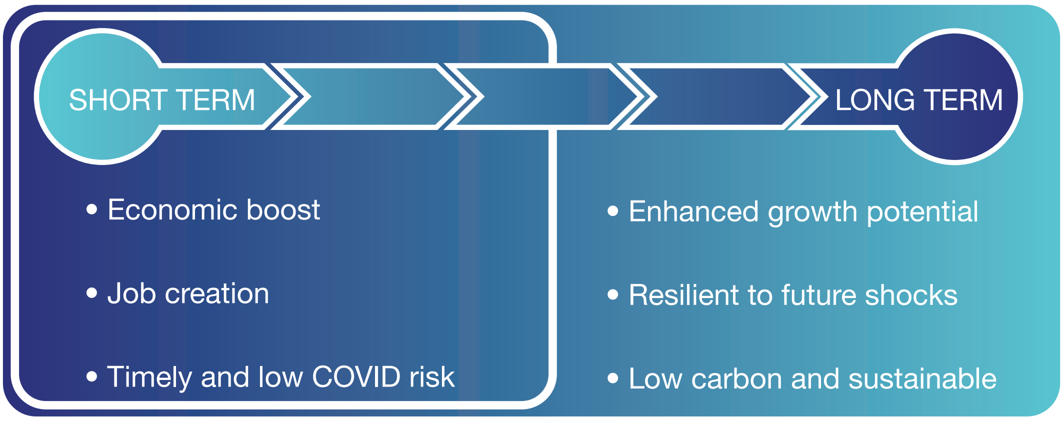


Figure 16. Key elements of a sustainable recovery. Based on [62–63].

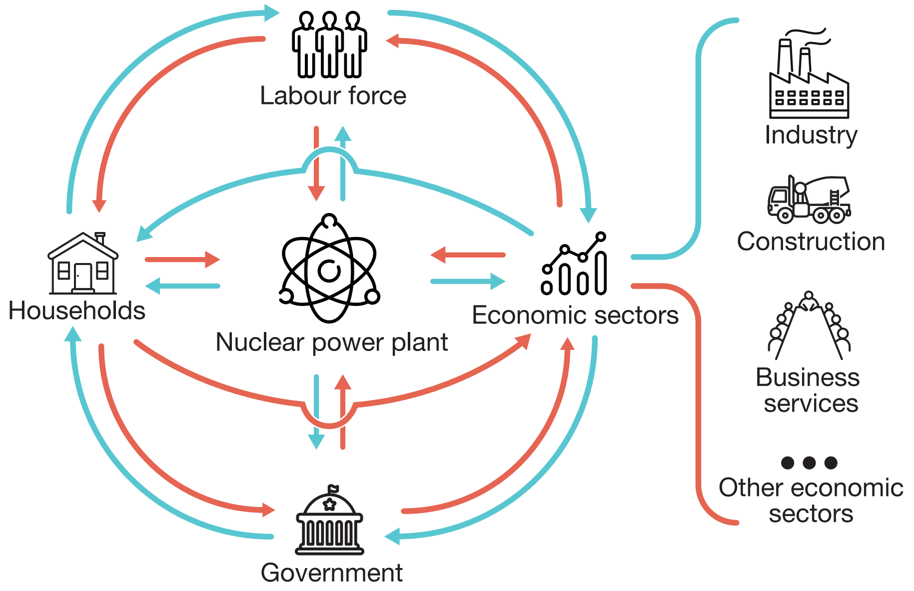
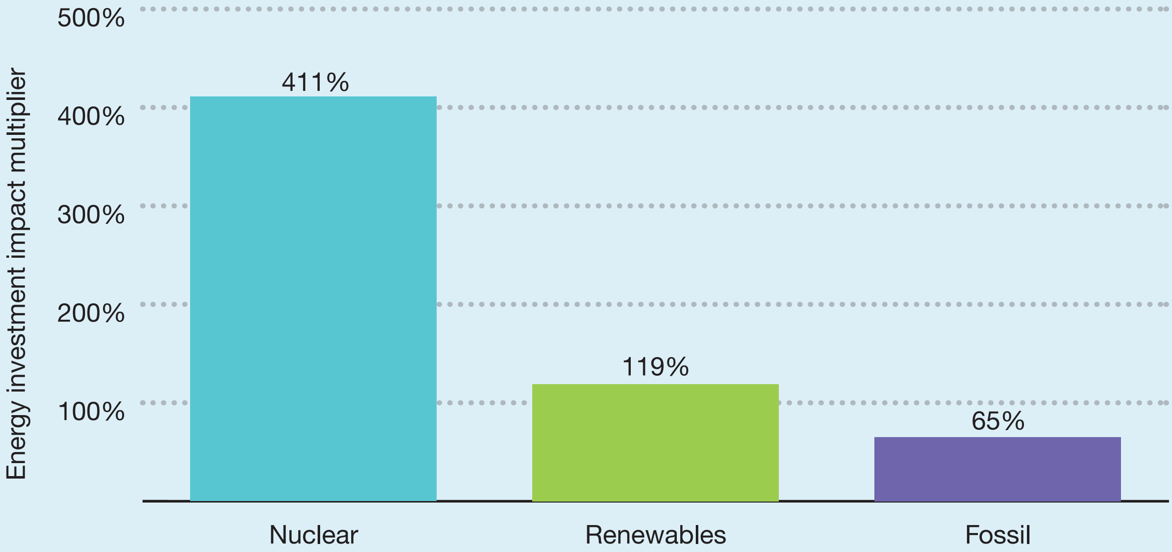


Figure 17. Nuclear power plants can stimulate activity across the economy to support a sustainable post-COVID recovery [66].

effects along their supply chains, while spending by workers employed at the plant and in the supply chain induces further economic and employment activity — for example, it is estimated for France that these indirect effects provide 285,000 jobs in addition to the 125,000 direct jobs in the nuclear sector [65]. This means that investment in nuclear power projects can stimulate economic activity and employment across many sectors, including construction, manufacturing, services and agriculture, to support the post-COVID recovery (see Figure 17). Moreover, a recent study carried out by the International Monetary Fund (IMF) estimates that investment in nuclear power generates a larger economic impact than investment in other forms of energy (see Spotlight 2).

Spotlight 2:

Green multipliers: nuclear and other clean energy investment



Energy investment impact multipliers (i.e. change in GDP per unit of investment spending) [67].

(continued overleaf)

Spotlight 2 (continued)

To inform the design of stimulus measures for a sustainable post-COVID-19 recovery, the International Monetary Fund recently estimated so called spending multipliers for investment in low emission energy [50]. The spending multiplier — i.e. the change in economic activity (GDP) divided by the change in investment spending — for nuclear energy is estimated to be around six times larger than for fossil energy and around three times larger than the multiplier for renewable energy over the short term, delivering a much more rapid economic boost. Spending on nuclear energy is also estimated to stimulate (or 'crowd in') more investment in other parts of the economy and lead to "larger employment of both high- and lower-skilled resources" per unit of spending compared to other low emission energy sources.

Investment in nuclear lifetime extension: rapid, competitive and low carbon

To capitalize on these strengths of nuclear power in the near term, investment in projects to extend the operation of existing nuclear power plants can be implemented rapidly and at scale, providing a substantial boost to economic activity and employment as the world emerges from the COVID crisis, while delivering competitive, low carbon electricity [44].

In quantitative terms, extending the life of nuclear power plants from 40 to 60 years would retain 95 gigawatts (GW) of low carbon generation by 2025 and an additional 90 GW by 2030 [4, 64]. At an estimated investment cost of US $650 per kilowatt for extension projects in much of Europe and the USA, this would be realized with a global investment of around US $120 billion over the next decade and create up to 370,000 jobs [22, 44, 64, 68].

The potential economic boost from lifetime extensions varies considerably across countries using nuclear power. In absolute terms, the largest potential is in the USA where 87 of the 93

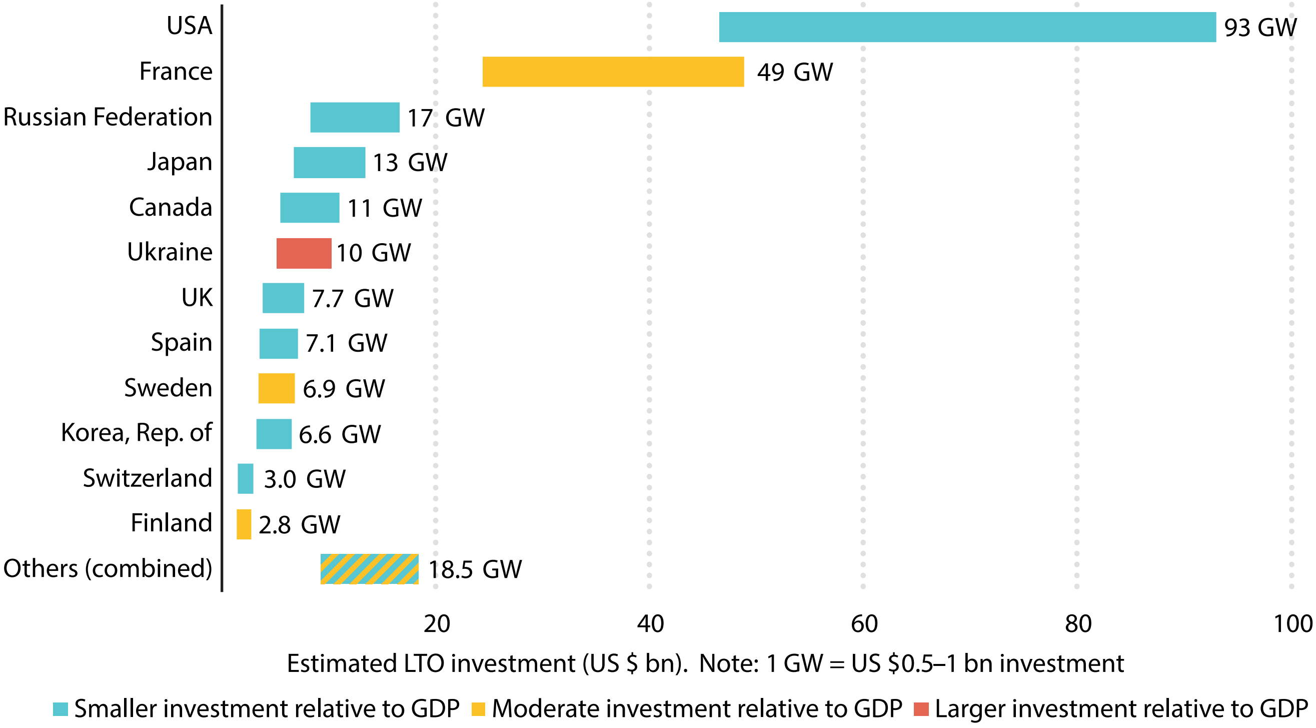


Figure 18. Nuclear power plant lifetime extension investment potential (2021–2030) [11, 68–69].

operating reactors have already received licence extensions up to a total lifetime of 60 years, with some extended up to 80 years [12–14]. However, relative to economic output, a number of other countries — mainly in Europe — could receive a larger economic boost from lifetime extensions (see Figure 18 and example in Spotlight 3). Moreover, there are few, if any, technical barriers to realizing these potentials. Programmes to extend the original lifetime of nuclear power plants have been successfully implemented in several countries and considerable technical experience has been gained so far with more than 90 reactors (representing 70 GW) already in lifetime extension [68].

In addition to supporting recovery in the shorter term by boosting local economies and employment, lifetime extensions are considered "crucial to getting the energy transition back on track" [11]. This reflects the scale of low carbon electricity generation that can be delivered through lifetime extensions, reaching around 1800 TW·h annually by 2030, or around 10% of all clean electricity under the IEA's Sustainable Development Scenario [21]. The relatively modest investment required translates into a low levelized generation cost of US $30–40/MW·h [44, 68].

Enhancing human, physical and institutional capital over the long term

While lifetime extensions can provide an immediate boost to economies, new build nuclear power programmes can provide even greater and more enduring support to sustainable development over the long term by building human, physical, knowledge and institutional capital; in addition to providing reliable, affordable and clean energy, and ensuring a resilient backbone to low carbon energy systems [72].

Nuclear power programmes rely on a diversified and skilled workforce across fields such as engineering, project management, safety and security. Building this human capital and the associated education system — for example, see Spotlight 4 — can profoundly enhance long term social and economic development.

In addition, developing the broader physical, industrial and institutional infrastructure underpinning nuclear power — ranging from roads, ports and electricity grids through advanced manufacturing and supply chains to regulatory and legal frameworks — further augments long term growth potential (see also Chapter 2). Finally, investment in nuclear energy R&D can enhance growth both directly and indirectly via spillovers to other applications; moreover, given that not all technologies needed to achieve a net zero energy system are mature, such investment is needed to accelerate innovation in clean technologies, such as advanced reactors [17].

Spotlight 3:

Long term operation in France: Grand Carénage

EDF in France is implementing a large investment programme including support for long term operation of its nuclear power fleet over 2014–2025, with an overall budget of around €50 billion for capital expenditure, maintenance and enhancing safety standards [70–71]. Apart from maintaining substantial low carbon generation capacity — France has around 61 GW of installed nuclear power plants [68] — and sustaining many of the 400,000 direct and indirect jobs supported by nuclear energy [65], the investment in long term operation is expected to deliver positive returns and ensure competitive electricity prices.

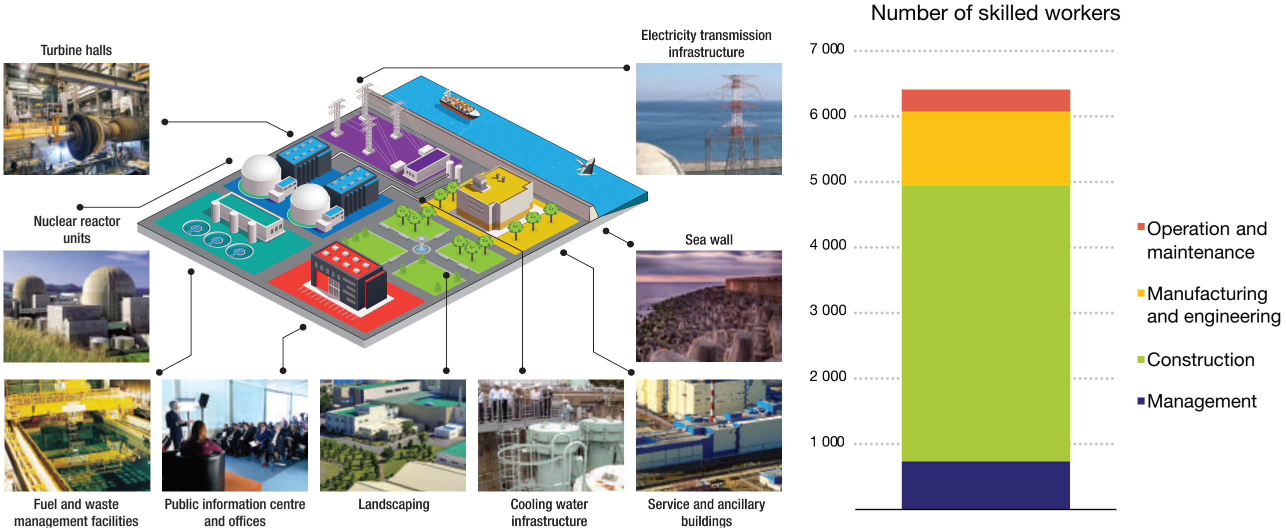


Figure 19. Physical capital (facilities, equipment, materials) and workforce for new nuclear power plants [4].

Spotlight 4:

Building an education system for the low carbon transition in the United Arab Emirates

In 2020, the United Arab Emirates began connecting its first nuclear power plant — Barakah — to the grid. The plant will supply up to 25% of the nation's electricity and reduce annual CO_2 emissions by 21 million tonnes (around 6–7% of expected 2030 emissions) [73–74]. Like many of the 30 or so countries currently implementing or considering nuclear power programmes, the UAE undertook a series of systematic actions to develop the supporting human, physical and institutional infrastructure [75]. The UAE paid particular attention to building up the technical and vocational education systems to train the skilled professional workforce for nuclear power and other clean energy technologies to ultimately support national priorities for sustainable development, economic diversification, reliable energy and climate change mitigation [41, 74]. This enhanced education infrastructure provides a basis for broader social and economic development.

Along with these systemic benefits to growth potential, investment in new nuclear power plants directly builds physical capital, stimulates supply chains and employs thousands of workers (see Figure 19).

The scale of the economic impact of such investment can be substantial, particularly for smaller economies. For instance, although the largest current and planned new build programme is in China, projects in countries such as Belarus, Finland, Hungary, Poland and the United Arab Emirates have the potential to generate larger impacts relative to the size of their economies (see Figure 20), particularly with measures to support the localization of supply chains.

Investment for a sustainable post-COVID world

According to the 2020 IEA World Energy Outlook, realizing a sustainable recovery that puts the world on track towards the Paris Agreement goals will require a 60% increase in annual energy sector investment to around US $3 trillion by 2025–2030 directed predominantly at low emission energy and electricity networks [21]. This includes an 80% increase in annual nuclear energy investment to US $50 billion — although, as illustrated for lifetime extensions, this relatively modest amount can have an outsized impact on economic activity, jobs and decarbonization (see Figure 21).

To date, however, many national government responses to COVID-19 continue support for the production and consumption of fossil fuels. For instance, among G20 countries almost half of the US $650 billion in public finance committed to energy investment in pandemic recovery packages is allocated to fossil energy [76], jeopardizing the goals of the Paris Agreement. In comparison, around US $2.5 billion has been committed to nuclear energy investment — mainly in the USA [77], UK [78], France [79] and Canada [80] — although a number of countries announced longer term plans for new nuclear power plants during the pandemic (e.g. see Spotlight 5) [39, 81–82] and, by July 2021, 19 countries (accounting for around 65% of global CO_2 emissions) had included nuclear power in their Paris Agreement commitments for 2030 (i.e. in their 'nationally determined contributions') [83].

Over the longer term to 2040, the IEA estimates that almost US $30 trillion of cumulative investment will be needed in the electricity sector, including around US $1.2 trillion in nuclear power — primarily in the Asia Pacific (esp. China) and Europe — to transition the global energy system onto a sustainable pathway more compatible with a net zero world (see Figure 22) [21]. Notably, many longer term national growth strategies (e.g. Japan's Green Growth Strategy [85]) and around half of the low emission development strategies submitted under the Paris Agreement also identify an important role for nuclear power [86]. Nonetheless, despite some positive developments [87], recent trends indicate that the current market and policy environment may be unable to mobilize the required investment in this technology, from either public or private sources.

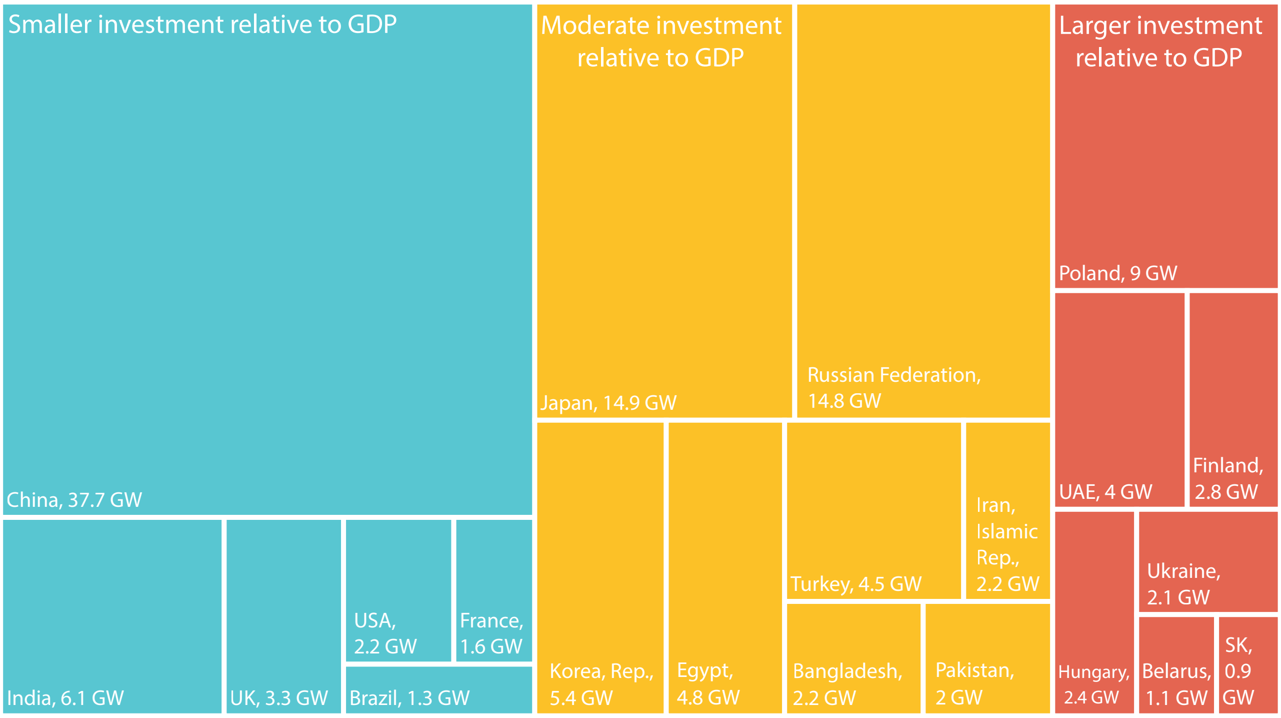


Figure 20. New nuclear power plants under construction or planned for construction, 31 Dec. 2020 (colours indicate size of new build programme relative to economic output — see Figure 18). Note: each GW of new build is estimated to require US $2–7 billion of investment; Argentina not shown (0.025 GW); SK — Slovak Republic [39, 44, 68–69, 84].

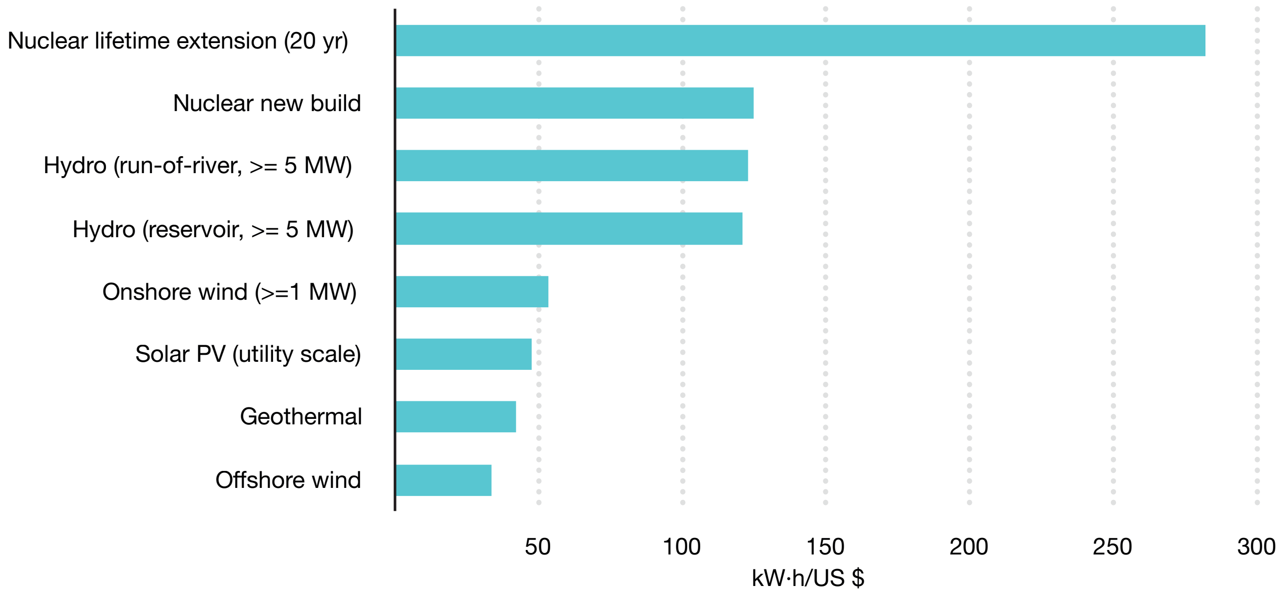


Figure 21. Low carbon electricity generation per unit of investment (median estimates, undiscounted) [44].

Ensuring timely investment to address both the immediate needs of the pandemic recovery and the long term goals of climate change requires a consistent and multi-pronged policy approach. In the near term, publicly financed recovery packages should be better aligned with long term climate change and sustainability goals. However, it is also critical to leverage private investments (and promote public–private partnerships) by providing policy signals to mobilize a reallocation of resources toward clean energy projects in both the short and longer terms [88]. This requires coherent policy design including suitable "regulatory frameworks, infrastructure planning, market design and fiscal incentives" [21].

Spotlight 5:

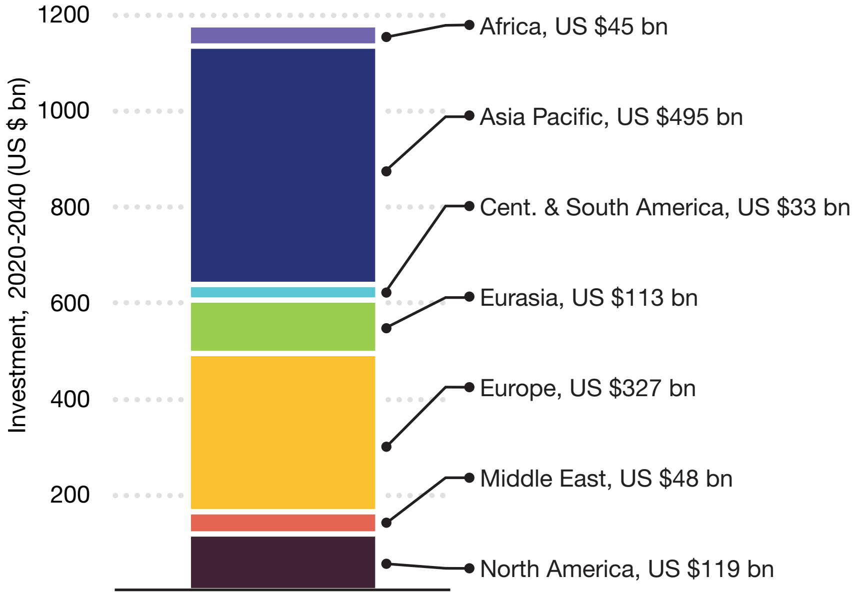
New nuclear investment and financing in Poland

The 2021 energy policy of Poland anticipates investment of US $410 billion (PLN 1600 billion) in the energy transition over 2021–2040 and includes construction of 6–9 GW of nuclear generation capacity to meet increasing electricity demands while achieving climate goals and maintaining stable prices [39]. Macroeconomic analysis estimates that this scale of investment in nuclear power — around US $40 billion — will generate significant economic activity and employment, creating 10–20,000 fulltime jobs (for 6 GW), largely in construction and the manufacture of machinery and electrotechnical equipment, but also in wholesale and retail trade and agriculture through induced and indirect spending [89]. The greatest macroeconomic boost can be realized with a supportive financing model that minimizes the need for tax increases or reallocation of resources — for example via low cost public borrowing or financing from external private or public sources.

For investment in nuclear power, coherent policy can help address (or avoid) several specific barriers including insufficient carbon prices and the absence of mechanisms to value and remunerate the system services provided by nuclear power plants (including flexibility and reliability), together with investment challenges created by suboptimal energy market design and distortionary subsidies. In addition, investors in nuclear power projects face risks associated with long time horizons, complex regulatory processes and political uncertainty over the future role of nuclear power in some countries [21]. Policy makers can facilitate investment through measures to manage and share these risks, including direct public financing, guarantees to debt and equity providers and schemes to share revenue and pricing risks, such as contracts for difference or power purchase agreements [4, 47, 90]. As part of an integrated policy package — see Spotlight 6 for an example — such measures can serve to unlock investment for the transition to net zero.

Policy makers should also reduce arbitrary barriers to the eligibility of nuclear energy projects to access public finances, particularly resources from development and green banks as well as infrastructure and clean energy funds [21] — this can represent a significant barrier in developing economies reliant on development finance institutions such as the World Bank [4, 91].

More broadly, such barriers should similarly be avoided in the definition of environmental, social and governance criteria aimed at directing public and private investment towards low carbon options [92], such as the EU's "taxonomy" of sustainable activities [93] (see also Chapter 6) and in "Green New Deals" under development in many countries. By adopting objective and transparent technology neutral criteria, as part of an overarching coherent policy framework, investment can be mobilized and guided to maximize the likelihood of realizing a sustainable net zero world after the COVID crisis.



Global energy investment needs (2020–2040)

- Total electricity, fuels & end use US $67.8 trillion
- Electricity sector US $29.3 trillion (43% of total)
- Nuclear sector US $1.18 trillion (1.7% of total)

Figure 22. Nuclear power investment needs, 2020–2040 (IEA Sustainable Development Scenario) [21]. Note: clean energy investments in electricity (including networks and storage), fuels and end use account for almost US $55 trillion (or 80%) of total investments; nuclear power investments account for just over 2% of total clean energy investments.

Spotlight 6:

Integrated investment and recovery policies for a low carbon transition — United Kingdom

The UK has implemented a package of measures to support investment in nuclear and other low carbon options [94–97] including:

- **contracts for difference** to stabilize revenues for investors in low carbon electricity projects
- a **final investment** decision process to accelerate energy investment
- a **capacity market** for dispatchable generation to ensure reliable and affordable electricity supplies
- a loan **guarantees scheme** to support infrastructure project finance and investment

Also under consideration, particularly for nuclear investment, is government financing during project construction and **regulated asset base** models that provide a regulated return to investors. These measures are complemented by a **comprehensive strategy for the nuclear industry** [98].

Moreover, the UK has explicitly targeted nuclear energy among the recovery measures in its *Ten Point Plan for a Green Industrial Revolution* providing over UK £400 million for small modular reactors (and mobilizing private funding), research and development of advanced modular reactors, developing regulatory frameworks and supporting supply chains [78].

Recommended Actions:

- Boost public investment and support for private investment in nuclear power, including lifetime extensions, as part of (and as a complement to) “Green Deals” and recovery packages.
- Ensure coherent policy, embracing regulatory frameworks, market design, infrastructure planning and fiscal incentives (including in taxonomy and ESG criteria to include nuclear energy).

06

NUCLEAR TECHNOLOGY AND SUSTAINABLE DEVELOPMENT

Key Points:

- Nuclear technology supports many SDGs, and nuclear power in particular contributes to SDGs on energy, economic growth and climate action.

Despite the scientific consensus on the urgent need to address climate change, the unprecedented scale of the transition to low carbon technologies, and the noted importance of nuclear power to meeting that goal, support for the technology has been lacklustre. Critics of nuclear power often question its long term sustainability — "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [99]. While it is helpful to define sustainability, there are different frameworks for achieving the so called, 'sustainable future', each with different perspectives on whether nuclear energy constitutes a sustainable technology.

One particularly noteworthy framework for achieving a sustainable future is the UN's Agenda 2030 Sustainable Development Goals (SDGs), comprising 17 interlinked global goals intended to create a more sustainable world by 2030. The SDGs are generally technology neutral, with no preference for one technology over another except for their effectiveness in achieving the goals. Notably, all of the objectives are mutually reinforcing, which means that ignoring the potential of nuclear power as a sustainable energy source has cascading consequences, for climate change and beyond. If the exclusion of nuclear makes it more difficult to achieve SDGs related to climate change, there could be follow on consequences in not achieving or delaying the achievement of other goals [100]. Figure 23 shows linkages between nuclear technologies and each of the SDGs, and Table 2 gives examples of nuclear technology benefits for the connected SDGs. In meeting the goals, it is imperative to recognize that climate change, the economy, migration, and conflict are interconnected and are a function of larger global challenges [101].

Another framework for achieving a sustainable future is the EU Taxonomy for Sustainable Activities, a classification system that establishes a list of environmentally sustainable economic activities for channelling financial investment (as mentioned in Chapter 5). The EU Joint Research Centre (JRC) recently published a study of the potential for nuclear energy to be included as a "sustainable technology" within the Taxonomy.

The analysis concluded that nuclear energy does no more harm to human health or the environment than other electricity production technologies already included in the Taxonomy [102]. The impacts of nuclear energy on the human health and the environment are mostly comparable to hydropower and other renewable energy sources. Notably, the latest commercial nuclear reactors ('Generation III') evaluated had the lowest fatality rate of all electricity generating technologies [102].

Furthermore, the report concluded that all potentially harmful impacts of the various nuclear energy lifecycle phases on human health and the environment can be duly prevented or avoided. Nuclear energy based electricity production and associated activities over the nuclear fuel cycle (e.g. uranium mining, nuclear fuel fabrication, etc.) do not represent significant harm to any of the objectives evaluated in the JRC study, provided that all specific industrial activities involved fulfil an established set of comprehensive technical screening criteria [102].

Together, these two frameworks illustrate the value of nuclear energy and nuclear technologies to achieving a sustainable future.

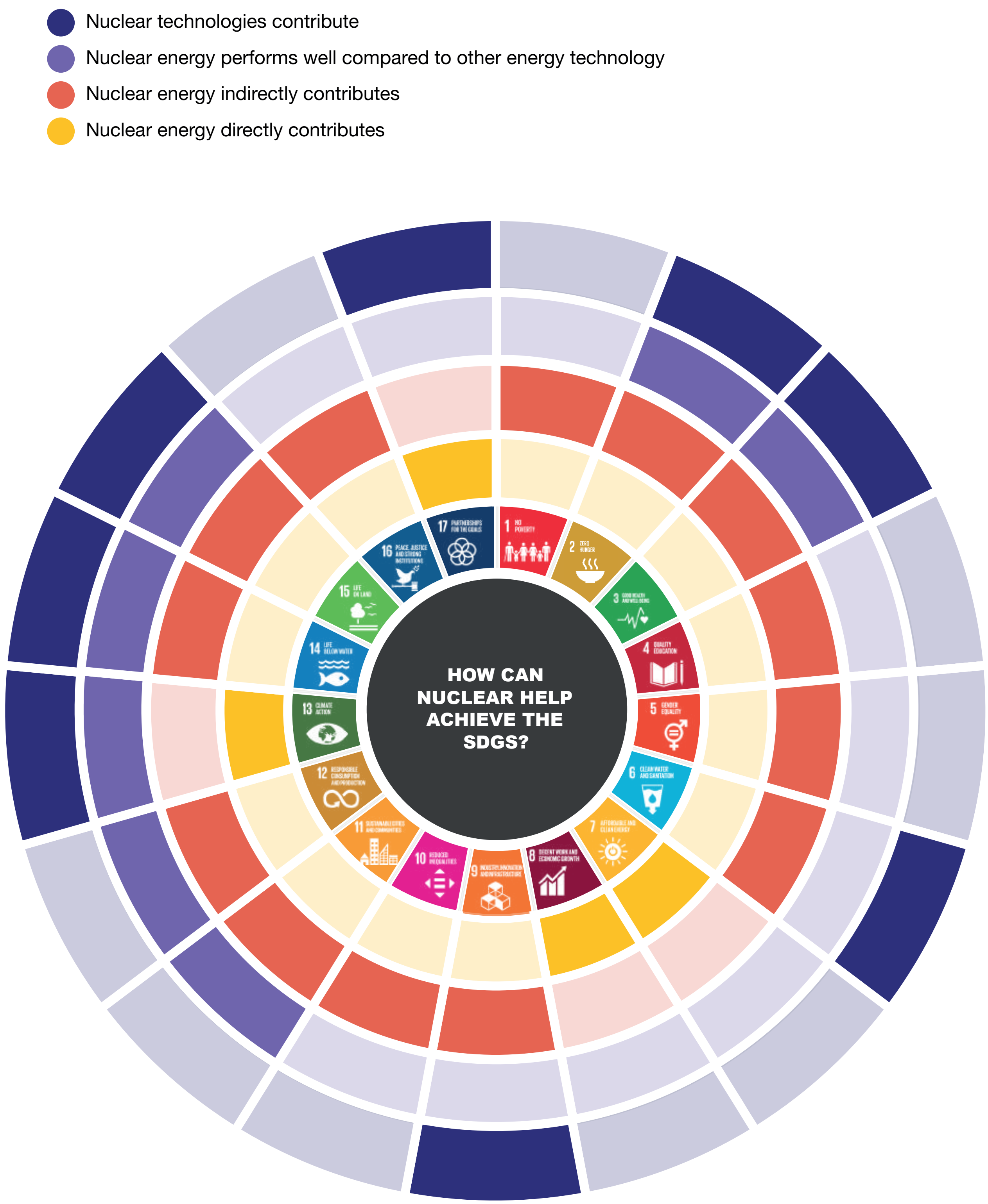


Figure 23. Sustainable Development Goal linkages with nuclear energy and other nuclear technologies. Note: dark colours indicate linkages; light colours indicate no linkages.

Table 2. Examples of nuclear technology and energy benefits for selected SDGs. NOTE: NE Direct — Direct benefit of nuclear energy; NE Indirect — Indirect benefit of nuclear energy; NE Comparable — Nuclear energy performs well compared to other energy technologies; NT Direct — Direct benefit of nuclear technologies other than nuclear energy. Reference [113] illustrates, for example, the direct contribution of nuclear technologies and energy to nine SDGs: 2, 3, 6, 7, 9, 13, 14, 15 and 17. Reference 115 explains in detail how nuclear energy (power) contributes directly to SDG7 and indirectly to many interlinked SDGs.

<table>
<tr><td>SDG 1</td><td>No poverty [103–105, 115]</td></tr>
<tr><td colspan="2">NE Indirect: There is no way to escape poverty without a large increase in energy consumption. Nuclear power can provide reliable large scale low carbon electricity that encourages economic growth.</td></tr>
<tr><td>SDG 2</td><td>Zero hunger [106–109, 113]</td></tr>
<tr><td colspan="2">NE Indirect: Modern energy supply can greatly improve agricultural productivity.
NE Comparable: Nuclear energy requires much less land than other generating technologies, leaving more space for agriculture use.
NT Direct: The production of radioisotopes by nuclear reactors and other nuclear installations are being used for pest control, fertilizer improvement, increased crop yields, increased livestock health and productivity, and food preservation and safety. Irradiation techniques create crop varieties that are more resistant to diseases and abiotic and biotic stresses and grow better in poor soils and under various climatic conditions.</td></tr>
<tr><td>SDG 3</td><td>Good health and well-being [104, 110–111, 113]</td></tr>
<tr><td colspan="2">NE Indirect: Health services are enhanced by clean energy for lighting, refrigeration and modern equipment.
NE Comparable: Nuclear energy is safer than nearly any other energy generating technology when considering health impacts, including fatalities, per unit of electricity generated.
NT Direct: Modern health services make regular use of safe radiation and radioisotopes, in particular for cancer treatment, and radioisotopes, produced in research reactors and other nuclear installations.</td></tr>
<tr><td>SDG 4</td><td>Quality Education [115]</td></tr>
<tr><td colspan="2">NE Indirect: A reliable energy supply is essential for education. Likewise, an effective nuclear programme requires a highly educated workforce.</td></tr>
<tr><td>SDG 5</td><td>Gender Equity [112, 115]</td></tr>
<tr><td colspan="2">NE Indirect: Due to the gendered nature of energy poverty, access to modern, sustainable energy can enhance female empowerment by reducing time and labour burdens, improving health, and providing opportunities for enterprise and capacity building.</td></tr>
<tr><td>SDG 6</td><td>Clean water and sanitation [113–114]</td></tr>
<tr><td colspan="2">NE Indirect: Nuclear power can generate electricity to support large scale water sanitation activities and can be cooled using wastewater. Nuclear power can support desalination to produce drinking water as populations grow and economies expand.
NT Direct: Isotopic techniques can be used to map areas of ground water supplies, determine aquifer replenishment rates, surface water budgets, assess water resources pollution, and identify suitable underground reservoirs for steam supply to geothermal plants.</td></tr>
<tr><td>SDG 7</td><td>Affordable and clean energy [2, 4, 27, 113, 115]</td></tr>
<tr><td colspan="2">NE Direct: Nuclear power represented nearly 40% of global low carbon electricity over the period 1971–2018. Moreover, nuclear has proven to be a useful heat source as well, for district and industrial heating.</td></tr>
<tr><td>SDG 8</td><td>Decent work and economic growth [18, 115]</td></tr>
<tr><td colspan="2">NE Direct: Nuclear power provides access to affordable and reliable electricity, contributing to economic growth and job creation. The power plant itself also supports both direct, indirect and induced employment.</td></tr>
</table>

SDG 9 Industry, innovation and infrastructure [18, 113]

NE Indirect: Nuclear energy stimulates economic activity for industry and other energy-dependent infrastructures — for example, with innovations like virtual reality and robotics technology in the nuclear energy industry.

NT Direct: Radioisotope and radiation technology is being used for industrial, applications such as non-destructive testing, electron beam and gamma irradiators for sterilization, materials processing, and preservation of cultural heritage artefacts.

SDG 10 Reduced inequalities [100, 115]

NE Indirect: Poverty indicators are highly correlated with lack of access to electricity, suggesting that income and energy inequality can be jointly addressed.

SDG 11 Sustainable cities and communities [115–117]

NE Indirect: Modern and sustainable cities will require significant quantities of clean energy.

NE Comparable: The UN predicts that 68% of the world’s population will live in cities in 2050. Nuclear power occupies a very small footprint of land and can supply large urban areas and megacities with electricity and heating and cooling.

SDG 12 Responsible consumption and production [102, 115]

NE Indirect: Clean energy helps reduce waste and promote resource efficiency.

NE Comparable: Nuclear power has low resource requirements and responsibly manages waste.

SDG 13 Climate action [2, 4, 113, 115]

NE Direct: Nuclear energy can support a climate resilient energy system and economy.

NE Comparable: From a climate mitigation perspective, nuclear power is among the lowest carbon producing energy technologies.

NT Direct: Nuclear isotope technologies can play a significant role in both climate change adaptation and GHG monitoring.

SDG 14 Life below water [102, 113, 118]

NE Indirect: Nuclear power can replace fossil fuels and eliminate the need for ocean extraction and transport.

NE Comparable: Nuclear has a low impact on marine ecotoxicity compared to other energy technologies.

NT Direct: Isotopic techniques can support and monitor ocean health and marine phenomena such as ocean acidification and harmful algal blooms and support the control of pollution or radioactivity in the marine and coastal environments, including plastic pollution.

SDG 15 Life on land [102, 113, 119–120]

NE Indirect: Nuclear power has been recommended for inclusion in the EU Taxonomy as a sustainable energy option, with relatively low impact on ecosystems and biodiversity.

NE Comparable: Nuclear energy is capable of replacing fossil fuels while requiring less space than other low carbon electricity sources and keeping the air clean.

NT Direct: Nuclear techniques are used to track and stop contaminants from harming the environment, assess soil quality and study how crops take up nutrients, as well as how soil moves. This can also be used to combat desertification.

SDG 16 Peace, justice and strong institutions [115]

NE Indirect: Increasing the availability of energy encourages peace and justice.

SDG 17 Partnerships to achieve the goals [113]

NE Direct: Nuclear power encourages strong international partnerships, a key instrument for peace and dialogue.

NT Direct: Nuclear technologies encourage strong international partnerships, a key instrument for peace and dialogue.

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