Climate Change and Nuclear Power 2022

Securing Clean Energy for Climate Resilience

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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Foreword

The climate emergency is one of the greatest challenges facing humanity today. The latest scientific findings outlined in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) paint a stark picture. They reaffirm the importance of reaching net zero greenhouse gas emissions in the coming decades to avoid global warming of more than 1.5 degrees Celsius (°C). We are already seeing how climate change is affecting every region of the world, with disastrous impacts falling disproportionately upon the most vulnerable. The IPCC tells us to urgently reduce fossil fuel use and switch to low carbon energy. At the same time, there is the important task of our communities, economies, agricultural systems and infrastructure — including our energy infrastructure — adapting so as to be able to deal with the challenges posed by the increasing occurrences of extreme climate events.

Against this backdrop, the international community committed to urgent action in the Glasgow Climate Pact adopted at the 26th United Nations Climate Change Conference (COP26) late last year. The IAEA organized several key events at COP26 to facilitate an informed debate on the benefits and challenges associated with nuclear power and applications. Countries, international organizations, scientific experts and other members of civil society are more unequivocal than ever about the key role nuclear energy must play in responding to climate change, and the level of public acceptance and advocacy continues to rise. Nuclear now has a firm seat at the table, where it will again be represented by the IAEA at COP27 in Egypt in 2022.

The science on nuclear power's contribution is clear. 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) — equivalent to the emissions from the entire global power sector in the five years between 2015 and 2019 — and continues to avoid more than 1 Gt CO_2 annually. It is a welcome development to see policy better reflecting such evidence, with the inclusion of nuclear energy in many sustainable finance 'taxonomies' being developed around the world to drive investment in the clean energy transition.

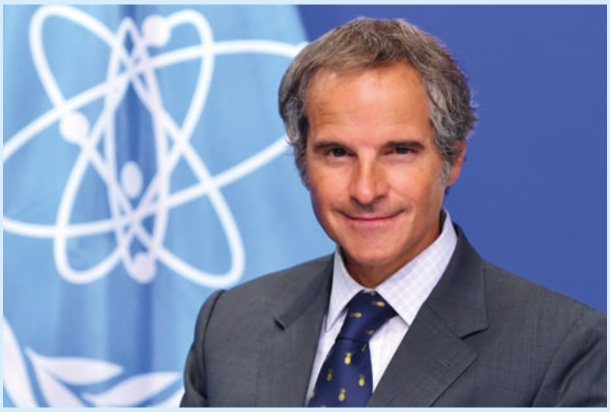
Nuclear energy, when working together with renewables such as hydropower, solar and wind, can enable countries to move away from fossil fuels and achieve their net zero targets, including through the use of low carbon hydrogen and heat. We are seeing an example unfold in the United Arab Emirates as the new Barakah nuclear power plant and large scale solar plants enter into service. Nuclear energy, moreover, reinforces climate resilience in energy systems. It can also ensure an affordable, secure and reliable energy supply, addressing challenges highlighted by the energy crisis of the past year and exacerbated by the war in Ukraine. As this publication shows in the case of Africa, nuclear energy is an option that can provide developing countries with reliable electricity to support socioeconomic development and industrialization, and to help meet their economic, social and climate goals. This is exemplified by the recent start in construction of Egypt's first nuclear power plant at El Dabaa — also the first to be built on the continent in around 40 years.

The contribution of nuclear energy to both climate change and energy security explains in part why countries are now scaling up their plans. The IAEA's latest high case projection for 2050, based on a country-by-country assessment, sees a 120% increase in nuclear electricity production capacity from current levels, an upward revision of 80 gigawatts (equivalent to 50 large reactors) compared to last year's projection. This revision reflects decisions supporting the long term operation of existing reactors, new construction of generation III/III+ designs, and the development and deployment of small modular reactors. Such an increase will be needed if we are to reach our net zero climate goals, according to experts at the International Energy Agency (IEA) and the IPCC. This will require significant investment in nuclear energy. The IEA reminded us in June 2022 that without nuclear energy, realizing sustainable and clean energy systems will be "harder, riskier and more expensive".

This latest edition of Climate Change and Nuclear Power continues the IAEA's contribution over more than 20 years to the analysis of nuclear energy's role in responding to climate change. It complements other IAEA initiatives on energy and climate, including the fifth International Ministerial Conference on Nuclear Power in the 21st Century, to be held in Washington, D.C., USA, from 26 to 28 October 2022. The conference will provide a forum for high level dialogue on the role of nuclear energy in the transition to clean energy sources and its contribution to sustainable development and climate change mitigation. It builds on efforts such as the IAEA's engagement with the G20 Energy Transition Working Group under the presidency of Indonesia.

As we head next towards the 27th UN Climate Change Conference (COP27) in Sharm El-Sheikh, Egypt in November, we are reminded by global events that the priorities of adapting to the impacts of climate change, mobilizing climate finance and scaling up emission reductions must be pursued in parallel with efforts to address current and long term economic, development and security challenges. Nuclear energy, science and technology — which can contribute across many of these dimensions — is thus essential to realizing a sustainable, resilient and clean energy future.

Rafael Mariano Grossi
Director General, IAEA



Key datapoints

26%

global gross low carbon electricity provided by nuclear energy in 2021.

33+

countries that include nuclear energy in their sustainable finance taxonomies or roadmaps, accounting for close to half of global energy emissions.

>2x

increase in annual electricity sector investment needed between 2023 and 2030 to achieve net zero emissions by 2050, including a projected US $100 billion for nuclear investment annually.

55

nuclear reactors in nine countries provided **district heat** in 2021.

25%

electricity needs in the United Arab Emirates met by the Barakah nuclear power plant, nearly halving power sector carbon emissions in the Emirate of Abu Dhabi by 2025.

10%

total energy consumption supplied by electricity in sub-Saharan Africa, compared to an average of **20% globally** in 2020.

32%

global nuclear generation from emerging markets and developing economies in 2021.

3%

total electricity needs in the Middle East met by clean sources, similar to levels seen a decade ago despite a substantial increase in total power production.

14%

of the world's operating nuclear fleet produced **28 petajoules of heat** for non-electric applications in 2021, equivalent to 2.3 terawatt hours of electricity or **<1%** of the output of these reactors.

85%

less metals and minerals required for nuclear power compared to solar photovoltaic technologies, and **45% less** than wind technologies on an average life cycle basis.

23%

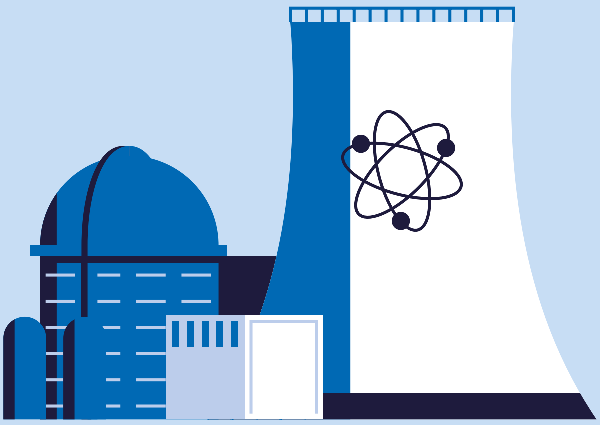
projected decrease in power costs in France by 2050 with nuclear new build compared to a case without new nuclear power plants.

<0.1%

nuclear electricity production lost between 1990 and 2020 due to weather events.

5.1-6.4

grams greenhouse gases emitted per kilowatt hour of nuclear electricity generation over the full life cycle, **>100 times lower** than coal fired electricity and around half the average of wind and solar generation.



Executive summary

To achieve carbon neutrality and limit global warming to 1.5°C, energy sector investment must be scaled up and directed towards cleaner and more sustainable technologies that support climate change mitigation and adaptation. At the same time, the world is confronted with the need to reinvigorate and rebalance energy sector investment to address energy security vulnerabilities and broader sustainability challenges. Investment in nuclear power can help address these challenges.

Including case studies and contributions from 15 international organizations and Member State government, private sector and scientific experts, the 2022 edition of this publication outlines the potential role of nuclear technology in the transition to a low carbon future. The report begins by outlining key opportunities and challenges for nuclear energy in a dual role that both enables a decarbonized, secure power supply and enhances climate benefits by serving non-electric markets. It contains novel analysis of climate, weather and water risks that may affect nuclear sites in the future and summarizes actions that IAEA Member States are already taking to mitigate them. The publication also includes a regional focus on the Middle East and the African continent, where nuclear energy can represent an opportunity to support both sustainable and economic development. It concludes with a discussion on how policies can shape markets, help allocate and share financial risk associated with nuclear projects and empower partnerships. In light of recent political scrutiny, it also describes the latest scientific findings on the environmental impact of nuclear energy.

The role of nuclear energy in creating decarbonized and reliable energy systems

The power sector — responsible for roughly 40% of global energy related emissions — will require a complete transformation on the path to net zero. The phase-out of unabated fossil fuel use and the integration of large shares of variable renewable technologies will pose major technical, economic, societal and political challenges. Considerable investment is needed to ensure a global fleet of low carbon generation, grid infrastructure, energy storage and adequate flexibility measures. The availability and reliability of energy infrastructure will become increasingly important as power demand develops over the coming decades – International Energy Agency (IEA) Net Zero Emissions by 2050 Scenario (NZE) modelling shows that demand for power could more than double by 2050.

With one of the lowest carbon footprints among energy technologies, 24/7 availability and the ability to operate flexibly, nuclear power can make an important contribution to the stability and security of a fully decarbonized power system and act as a good complement to renewable energy sources. A 2021 study by the French transmission system operator modelled the future flexibility needs of the French electric grid at European scale and found that the larger the share of nuclear energy in the power mix, the lower the requirements for additional flexible capacity and the lower the overall costs of the electric system. In sum, a more diverse energy mix can achieve decarbonization with a relatively larger share of renewables and at a lower cost to end users.

The transport, industry and building sectors make up about 55% of global energy related emissions today, and according to the IEA NZE, will represent nearly all of the energy sector's released emissions after 2040. Fossil fuel use is deeply embedded in existing heat applications today. Using nuclear energy to produce hydrogen can create a low carbon alternative energy product, which can, together with the electrification of the transport, industry and building sectors, provide a large scale, reliable means to decarbonize.

Twenty-seven of the world’s nuclear power plants in eleven different IAEA Member States produced 2.3 terawatt hours of electrical equivalent heat for desalination, district heating and process heat in 2021. This thermal output accounted for less than one percent of the nuclear reactors’ total electrical generation, indicating a huge potential to utilize more nuclear capacity for heat applications in future decarbonization efforts. An expanded use of the non-electric applications of nuclear power, such as desalination, district heating and hydrogen production, can be used to reduce emissions and increase the security of supply of the global energy system.

Opportunities and risks for nuclear power in building economic growth and climate resilience

Adverse weather conditions are increasingly prevalent around the world, with implications for energy infrastructure across technologies. Despite a quintupling of adverse weather conditions between 1990 and 2019, nuclear power losses due to weather events decreased over the same period. Nuclear plant designs have been adapted to mitigate the risk of production loss, employing a variety of engineering and plant management solutions, including the timing of refuelling outages to avoid periods of elevated energy demand due to climate-related events. Climate related hazards are an increasing threat to all energy infrastructures, including all types of nuclear installations worldwide. Windstorms, tropical cyclones and the rise in sea levelscan have a considerable impact on coastal power supply and grid infrastructure. The climate modelling of the Intergovernmental Panel on Climate Change (IPCC) overlaid with nuclear site locations show that nuclear plant sites located on the eastern coast of the United States are most likely to be exposed to sea level rise and severe cyclones with maximum wind speeds and heavy precipitation, whereas nuclear plant sites in eastern China, the Korean Peninsula and the Japanese Archipelago may face relatively fewer extreme storms in the future. Extreme heat conditions, heavy precipitation, coastal and river floods and tropical cyclones will make the design and the implementation of climate resilience plans even more complex, but all the more necessary. Many individual climate risks can be mitigated, provided that nuclear owners and operators alike undertake the necessary adaptation steps to help face these changing conditions. Increasingly frequent and severe climate hazards, including the risk of simultaneous concurrent weather events, must be included in infrastructure and energy supply planning. Against this backdrop, the IAEA has initiated a technical project that draws on the most recent experience of Member States in the application of climate predictive methods for the assessment of site hazards and safety issues related to existing and new nuclear sites.

The African continent and the Middle East are where some of the most severe and damaging manifestations of climate changes are expected to accelerate, putting the environment and populations at risk. Both regions are experiencing an evolution in clean electricity generation and demonstrating a growing interest in developing nuclear power. The United Arab Emirates has begun work on the region's first nuclear project, which is expected to supply a quarter of the country's electricity needs and halve Abu Dhabi's greenhouse gas emissions from the power sector. Countries across the African continent are also showing increasing interest in developing nuclear power plants – more than 26% of IAEA missions to assess the potential for nuclear power since 2009 have been requested by African countries. Both regions will have to face systemic challenges to achieve emission reductions and meet climate goals, while satisfying fast growing energy demand to support economic development and urbanization. Across the Middle East and North Africa, the rise in large scale clean energy development is a promising start to reducing the regional economy's reliance on fossil fuel exports. Yet the deployment of clean energy projects has not kept up with massive growth in the region's electricity consumption. IEA data show that despite a 43% increase in the region's power production over the past decade, clean sources meet a mere 3% of total electricity needs. As a result, lower carbon power systems – potentially fuelled in large part by nuclear power – will be indispensable to achieve climate goals in the region. Across the African continent, the availability of clean electricity is increasing but still meets only a tenth of total energy consumption. Unreliable and prohibitively expensive electricity supply represents a lost economic opportunity, requiring government dedication to long term energy strategy reforms. The deployment of nuclear energy could help meet the dual goals of decarbonization and expansion of reliable energy supply. However, some countries with high debt levels and limited borrowing capacity could struggle to finance such a capital intensive technology. In these cases, a strong policy push and directed investments are needed. Case studies focusing on Ghana, Kenya and South Africa highlight ways in which nuclear energy can aid in meeting climate objectives and furthering economic development.

How policy and markets can guide a sustainable future

Climate change mitigation, economic development and energy security goals are most effective when governing bodies and private finance work together. Effective policymaking can attract private sector investment as well as ensure an equitable and just energy transition. Despite an increasing recognition of the role of nuclear energy in meeting national climate commitments, the current market may be unable to mobilize the scale of nuclear investment needed to achieve net zero goals. For both climate and energy security goals, public sector financing and development of infrastructure will be necessary to fully unlock the potential of financial markets. Private sector frameworks to measure environmental, social and corporate governance can serve as one measurement of sustainable activities, but these frameworks vary by company and are difficult to compare. The use of 'green bonds' has recently gained traction as a financial instrument used to fund projects that have a measurable environmental or climate benefit. The market is huge for clean investments – new sustainable debt financial products issued in 2021 broke the US $1 trillion threshold. The volume of capital available for green financing initiatives has created an opportunity for governments, which often seek private sector investment during and beyond the construction phase of a nuclear project's lifetime.

To effectively manage financial risk, the public sector can help guide private investment by establishing coherent, transparent guidance on which activities are compatible with long term climate and sustainability goals. Financial frameworks such as country or regional sustainable taxonomies can mobilize finance towards investments that address energy security as a pillar of any sustainable energy system. Taxonomies provide investment guidance, and neither mandates nor prohibits investment, lending only a clear definition of sustainability to project developers and financiers. Sustainable taxonomies that either explicitly or implicitly include nuclear have been adopted or are under development in more than 33 countries, and notably in the European Union.

Taxonomies and other green finance initiatives only partly address barriers to energy investment. Complementary policy measures are required to provide additional incentives and manage various project and market risks. Carbon pricing can provide a market based solution to mitigate climate change, while energy offtake contracts, such as power purchasing agreements, or contracts for difference and the regulated asset base model in the United Kingdom, can effectively share risk between nuclear project developers and electricity consumers. Consistent policy and regulation, both over time and across countries, are especially important given the relatively long lifetime and high upfront cost of nuclear compared to other energy technologies.

Faced with important decisions on how to mitigate climate change and increase security of energy supply, policymakers have increased scrutiny of the sustainability of various energy technologies. Nuclear technologies, including those supporting medicine, agriculture, clean water and environmental monitoring and protection, in addition to energy, can help countries meet the United Nations Sustainable Development Goals. An analysis of the entire nuclear life cycle shows that the environmental impact of nuclear energy is among the lowest of all electricity generation technologies. A case study by the United Nations Economic Commission for Europe outlines the results of its annual life cycle analysis of the environmental impacts of electricity generation technologies, measuring greenhouse gas emissions, freshwater eutrophication, radiation and human toxicity, as well as land, water and resource use. The 2022 study found that, considering all of the above environmental factors, the life cycle environmental impacts of nuclear power generation are 16% to 70% lower than solar photovoltaic technologies and 26% to 35% lower than wind generation technologies.

Climate change mitigation and security of energy supply are two of the foremost global challenges in 2022, likely requiring a complete reimagining of the world's energy systems. This publication provides guidance on how nuclear energy can work alongside other technologies to achieve a decarbonized global economy. Nuclear energy deployment across the power, industry, building and transport sectors can help to alleviate reliance on fossil fuels and provide flexibility services to increase the reliability of energy systems with a large share of renewables. Noting the risks that all infrastructure will face in an increasingly volatile climate, this report outlines some of the key mitigation measures already employed by nuclear operators and provides a roadmap for countries that seek to drive sustainable development for their growing populations. Policy and financial markets are vital to ensuring success in meeting the climate and energy challenge.

01

Introduction

Recent disruptions to the global energy system threaten the urgent action needed to address the climate emergency. An already volatile global energy mix, resulting from increased demand for fossil fuels and growing shares of variable renewable output, has been further aggravated by the conflict in Ukraine. These cumulative factors have given rise to an important choice concerning the future of energy sector investment: between either more fossil fired power plants in the name of stopgap measures and security of supply, or in favour of a renewed push towards building the foundations needed to meet low carbon energy targets. More than ever, nuclear has the potential to link these pathways in a global way, offering energy security through firm low carbon energy along with the ability to flexibly dispatch that energy, ultimately enabling an integrated pairing with the growing shares of variable renewable energy (VRE).

Market instability threatens climate action

Economic recovery following the first waves of the COVID-19 pandemic increased global energy demand by more than 8% in 2021, compared to 2020 (IEA, 2021a). As a result, average natural gas prices rose 126% globally in 2021, and coal prices more than doubled compared to 2020 (World Bank, 2022a). Efforts by some countries to avoid energy supplies from the Russian Federation, the world's second largest producer of natural gas and a top three supplier of oil (IEA, 2022b), as well as the broader disruption of global supply chains due to the crisis in Ukraine, have further exacerbated the global energy supply crunch. The conflict has caused already high energy and food prices — particularly in low income countries and emerging markets — to soar (IMF, 2022).

Rising natural gas prices are calling into question a basic tenet of the modern energy system — namely, that natural gas could act as a 'bridge fuel' to usher in a sustainable future. Natural gas currently provides about a quarter of the world's electricity, while also fuelling various global industrial processes and energy needs (IEA, 2021a). Short term concerns over energy security, particularly in the European Union (EU), will reshape the entire global energy landscape. Given the volatility of fossil fuel prices, new countries and regions could emerge as reliable trading partners, shifting attention to regions with abundant low carbon energy resources, such as nuclear power. The European Commission's plans to reduce dependence on fossil fuels from the Russian Federation includes a strong role for nuclear power and for the deployment of clean hydrogen as a substitute for natural gas (European Commission, 2022a). This potential reduction in fossil fuel use is significant for a region that meets more than a quarter of its power mix with gas and nearly a third with oil, with the Russian Federation supplying 45% of total gas imports and 34% of oil imports to the EU in 2021 (IEA, 2022c).

The uranium market has also been affected by the conflict in Ukraine, but to a lesser extent in the short term relative to other commodities. Unlike oil and natural gas, uranium resources benefit from a wide geographical distribution, and from larger stockpiles. For example, Australia, Canada and Kazakhstan are home to more than 6.5 times the amount of the Russian Federation's recoverable uranium (OECD NEA, 2020). Additionally, uranium inventories kept by utilities in Europe and the United States amounted to more than 80 000 tonnes of uranium equivalent at the end of 2020 (ESA, 2021; EIA, 2021).

Record setting growth of renewable energy over the past decade has created additional pressure for global energy security. Global renewable capacity grew at an 8.8% compound annual rate over the past five years, more than three times higher than the growth rate of natural gas capacity over the same period (Ember, 2022; IRENA, 2022). As VRE makes up a greater portion of the global energy mix, policymakers are facing new challenges. Policies and market mechanisms to balance the variability of renewable output must be deployed in parallel with plans to secure a sustainable supply of the critical minerals needed for deployment of many low carbon options (IEA, 2021b). A lack of effective action could potentially mean a delay in, or risk to, a successful and equitable energy transition.

From Paris and Glasgow to Sharm El-Sheikh and beyond

A major discrepancy exists between national climate targets and the level of urgency and ambition required to meet the 1.5°C commitment agreed upon in the 21st United Nations Conference of Parties (COP) Paris Agreement. The updated nationally determined contributions (NDCs) submitted in the lead up to COP26 in Glasgow in November 2021 — if achieved — represent a projected long term temperature increase of ~2.7°C (UNFCCC, 2021a). There is global consensus that fossil fuel use creates a dangerous cycle, contributing to already rising levels of emissions. The United Nations Secretary General Antonio Guterres framed the urgency to reduce fossil fuel use in this way: “We know what we need – global emissions must decrease by 45% by 2030, starting now. Or rather yesterday. We cannot overstate the urgency of our task.” (UN, 2022a). Increasingly frequent extreme weather events will only continue to exacerbate the need for reliable and decarbonized energy sources.

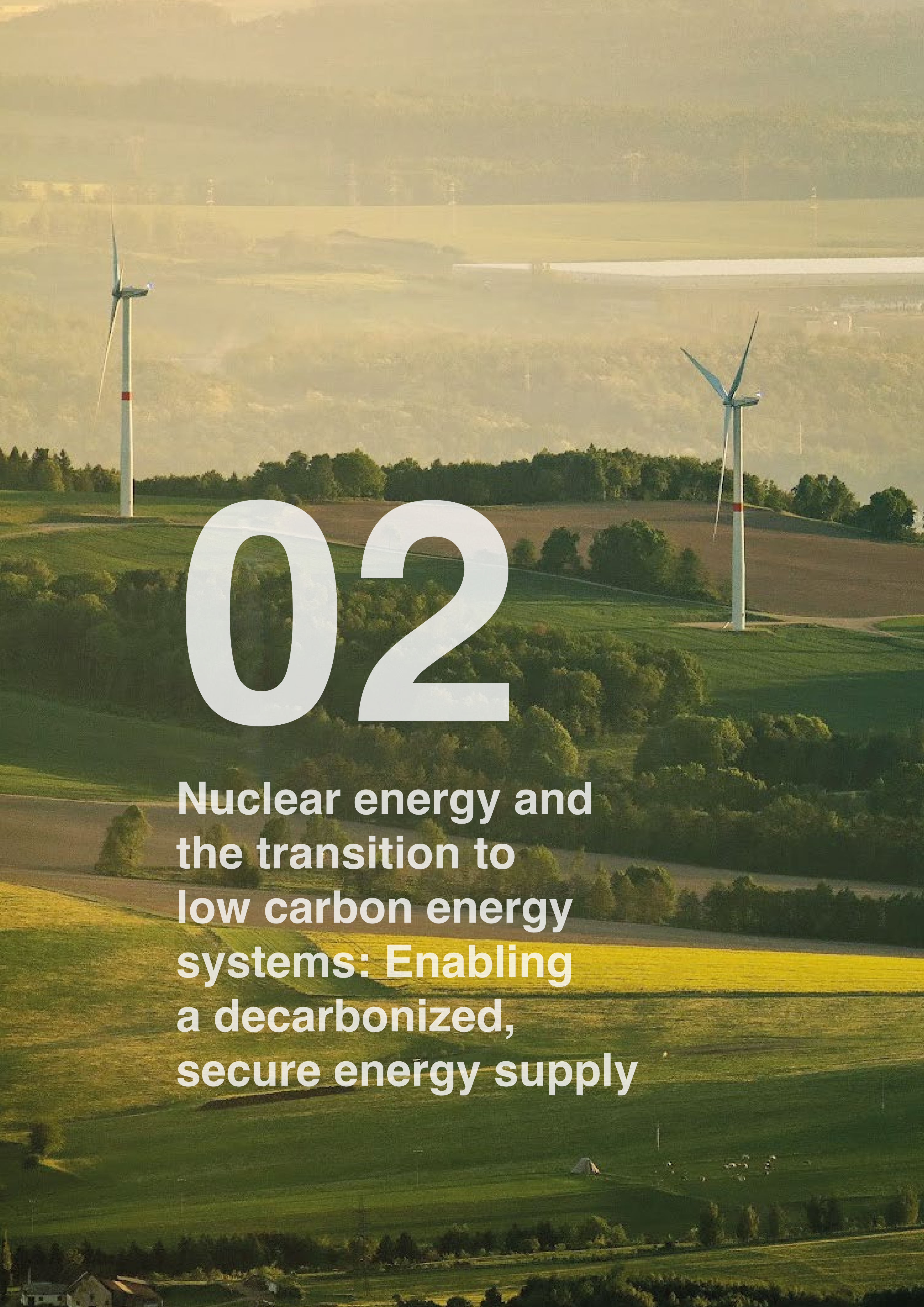
The COP26 Glasgow Climate Pact calls upon nations to increase deployment of clean power generation while accelerating efforts to phase down coal power — one of the dirtiest sources of electricity (UNFCCC, 2021b). Multilateral development banks, national governments and the private sector are being urged to at least double climate financing so as to mobilize US $200 billion per year globally. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) cites nuclear among other technologies as a low carbon energy source available to reduce emissions over the coming decades, primarily by replacing existing fossil fuel use (IPCC, 2022a). The inclusion of nuclear energy in emerging classification systems (or ‘taxonomies’) developed by governments, or in environmental, social and corporate governance (ESG) criteria in the private sector — both of which aim to guide investment towards global sustainable development — is a further indication of the evolving energy landscape.

Today, a renewed focus is being placed on technologies that can deliver significant volumes of decarbonized energy while improving energy security, meeting flexibility requirements and strengthening system resilience. Nuclear is one such technology, with additional climate benefits in terms of pollution and biodiversity, and with the capacity to meet environmental and social challenges. Public opinion surrounding the use of nuclear energy is at historic highs, reflecting a global push to move away from polluting fossil fuels amid an energy security crisis (Finnish Energy, 2021; Bisconti Research, 2022; Japan Times, 2022; The Korea Herald, 2022; RTL Deutschland, 2022). As global energy demand grows, so too does the importance of building a sufficiently abundant, secure, diverse and decarbonized energy system.

A path forward

Climate Change and Nuclear Power 2022: Securing Clean Energy for Climate Resilience outlines how nuclear energy can be mobilized to help respond to climate change challenges while providing solutions to the many pressing environmental, economic, social and security challenges confronting the world today.

Nuclear energy can accelerate a global shift away from fossil fuels by supporting the integration of large shares of renewable generation in the power sector and displacing fossil use cases in hard-to-abate sectors, such as steel, cement and chemical production, as well as long distance shipping and air transport. The mobilization of large scale, reliable, low emissions nuclear production to ensure energy security, while supporting the integration of large shares of renewable generation to respond to the climate emergency, is discussed in-depth in Chapter 2. The potential of nuclear energy to multiply climate benefits as a source for low carbon desalination, district heating and hydrogen production is assessed in Chapter 3. Chapter 4 covers nuclear energy’s contribution to climate resilience, ensuring a secure and clean supply of energy in the face of increasing climate impacts over the coming decades. In this context, and with COP27 and COP28 being hosted in Africa and the Middle East, respectively, Chapter 5 focuses on the needs and circumstances facing countries in these regions, where growing interest in nuclear energy extends beyond the technology’s low carbon footprint to include its potential to support multiple development objectives. Supported by a coherent policy and regulatory framework to mobilize investment, discussed in detail in Chapter 6, nuclear energy’s potential to contribute to many aspects of sustainable development is explored in Chapter 7.



02

Nuclear energy and the transition to low carbon energy systems: Enabling a decarbonized, secure energy supply

Key messages:

- **A cost effective energy transition can be achieved with a combination of nuclear and renewable energy.**

- **Nuclear, as a scalable, dispatchable and low carbon source of electricity, contributes significantly to the security of energy supply, and can do even more in a decarbonized system.**

- **Sizeable deployment of nuclear power increases the chances of achieving a net zero future.**

The transformation of the energy system to reach net zero emissions, with the necessary integration of large shares of variable renewable technologies in the power system, will pose major technical, economic, societal and political challenges. Considerable investments will be needed for all low carbon generation, as well as for the storage and flexibility technologies required for the energy transition. Appropriate policies are also essential, not only to attract investments, but also to address the social and distributional problems associated with the energy transition. The steep rise in energy costs in 2021 and the conflict in Ukraine in 2022 have also placed the question of security of energy supply at the centre of the energy debate. The consequences in terms of countries' capabilities to achieve net zero goals remain to be analysed.

The transition towards net zero emissions by the middle of this century requires the complete abandonment of unabated fossil fuel use. These fuels have been the engine of economic growth for the last two centuries and today still provide about 80% of energy supply and more than 60% of power production at the global level (IEA, 2021a). It is unquestionably an immense and unprecedented challenge for all countries and governments to abandon fossil fuel use, as it requires a complete reconfiguration of the transport, industrial and building sectors and a radical transformation of how energy services are produced, provided and consumed worldwide. The enormity of such a task is compounded by the fact that radical changes must occur in the next 30 years, a much shorter time frame than the average lifetime of power and energy assets.

In this context, many countries are increasingly recognizing that nuclear energy is a proven, cost effective and viable option for decarbonizing the power sector. Its 24/7 availability, dispatchability and capability to provide flexibility and other system services makes nuclear power an important contributor to the stability and security of a fully decarbonized power system, and a good complement to renewable sources. Nuclear power is also increasingly considered as an effective option for generating hydrogen and providing heat, desalination and other non-electric applications — all of which will be needed to decarbonize the entire energy sector (for more details on the non-electric applications of nuclear power, see Chapter 3).

Pathways compatible with a low carbon target

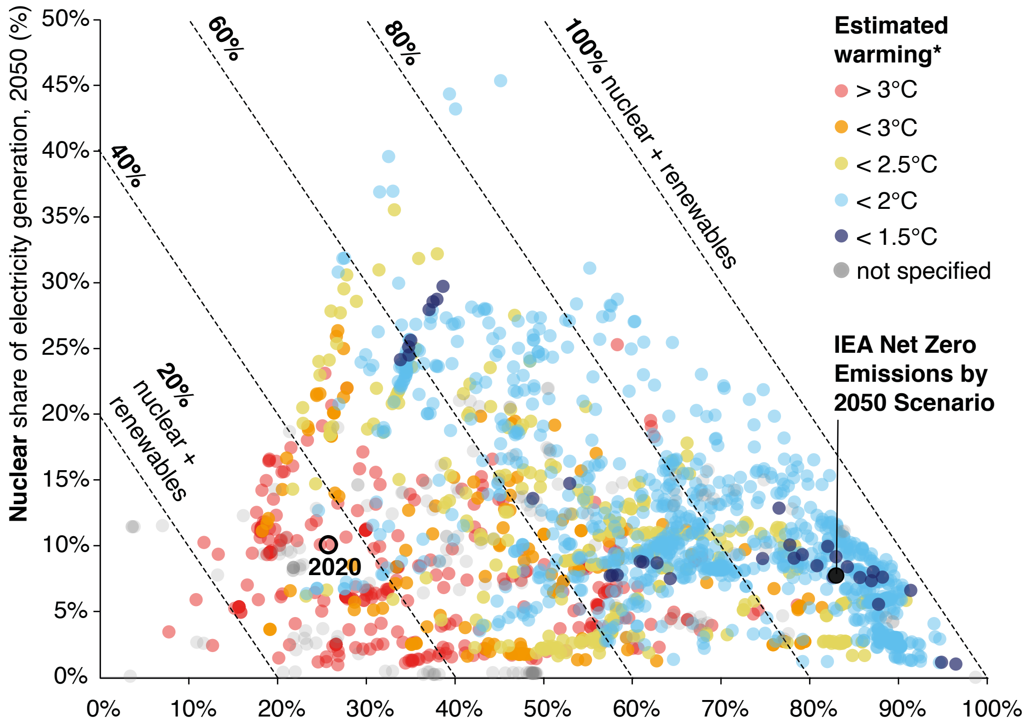
Many of the pathways assessed by the IPCC in the AR6 can achieve the goal of limiting the temperature increase to 2°C compared with preindustrial levels, with no or limited overshoot (see Figure 1). However, the likelihood of limiting the temperature increase to 1.5°C has decreased since the Global Warming of 1.5°C IPCC Special Report (IPCC, 2018), reflecting the increase in greenhouse gas (GHG) emissions since 2017. While there are multiple pathways towards carbon neutrality and large differences across individual scenarios, most of the scenarios that are compatible with a 1.5°C target identify some key pillars for decarbonization of the energy sector:

- Total energy demand is stabilized or decreases compared to current levels as a result of improvements in energy efficiency in all sectors.

- Electricity demand increases substantially as electricity substitutes for fossil fuels in the industry, transport and building sectors.

- Decarbonization of electricity generation is almost complete, with large deployment of renewable sources in combination with other dispatchable low carbon technologies. Wind and solar photovoltaic (PV) technologies dominate electricity generation in virtually all scenarios.

Figure 1: Shares of nuclear and renewable energy in the electricity generation mix and corresponding climate warming across IPCC AR6 scenarios.



Source: *IIASA (2022) and IPCC (2022a).*

Each dot represents an individual scenario coloured according to the estimated temperature increase.

Increasing shares of both renewable and nuclear electricity generation are necessary to limit warming.

* relative to pre-industrial temperature, with > 50% probability, MAGICCv7.5.3.

IEA Net Zero Emissions by 2050 Scenario is indicated.

** Renewables excluding biomass.

– Rapid deployment of other energy carriers is ensured, and will include heat, hydrogen, ammonia and synthetic fuels to decarbonize hard-to-abate sectors, such as steel, cement and chemical production, as well as long distance shipping and air transport.

In the International Energy Agency (IEA) Net Zero Emissions by 2050 Scenario (NZE), for example, global energy supply falls in 2050 by 7% from 2020 levels to 550 exajoules (EJ), despite a strong increase in population and economic activity. Energy intensity decreases by more than 3% per year between 2020 and 2050, much more than what has been achieved in the last decades. Electricity demand more than doubles between 2020 and 2050, reaching about half of total energy consumption. Renewables generate almost 90% of electricity, while the nuclear share is reduced to 8%, despite a doubling of the existing capacity. The global use of hydrogen expands 6-fold in 2050, from 90 megatonnes (Mt) in 2020 to more than 500 Mt in 2050, with more than 90% of hydrogen produced from low carbon sources, compared to only a few per cent today.

Flexibility at the cornerstone of a net zero system

Integrating large shares of VRE in a power system represents a major technological challenge and has far reaching technical and economic consequences. This is essentially due to the variable, unpredictable and non-dispatchable nature of wind and solar PV electricity generation. VRE output varies depending on the presence of wind and sunshine, is difficult to predict in advance and may not always be available when needed.[1] At the present low shares, this does not pose a major challenge for power systems since the variability of VRE output is absorbed by the overall variability of demand. However, as the share of VRE in the energy mix grows, VRE becomes the main driver of variability, leading to a significant increase in flexibility requirements.

[1] Electricity production from VRE is also likely to be increasingly affected by climate change in future, potentially exacerbating the phenomena described here. Nuclear is not immune, but so far has proven to be less susceptible, as shown in Texas during February 2021, and in other recent severe weather events (additional information is provided in Chapter 4.)

Box 1: Contributed by Central Research Institute of Electric Power Industry

Decarbonizing Japan's energy sector: Potential contributions of nuclear and renewables

In October 2020, Japan announced that the country planned to achieve carbon neutrality by 2050, strengthening its previous target of an 80% reduction in GHG emissions. A new energy policy plan was published in 2021 to reflect this new target. The plan calls for "all-out efforts in all sectors of society" to realize carbon neutrality, without specific mention of targets for individual energy sources. With regards to nuclear, it simply states that a "necessary amount" will continuously be utilized while ensuring safety and public trust, but it does not include plans for construction or replacement of reactors.

One of the challenges to realizing carbon neutrality is to electrify the non-power sector through decarbonized power sources. With an increasingly electrified, growing economy, various organizations estimate electricity consumption will reach more than 1300 TW·h in 2050 (METI, 2021c), an increase of more than 40% from the current consumption level. The Japanese government plans to ensure that renewable energy is a major power source by 2050. However, the rapid introduction of renewables in the last decade has started to take a toll, with land conflicts occurring in many places. A landslide incident in the Shizuoka Prefecture in 2021 brought growing attention to construction work related to solar PV and has given rise to calls to re-evaluate solar development regulations. The Japanese energy sector is placing considerable expectation on offshore wind energy given the country's geographic location, but fishery rights, marine traffic and seascape concerns constrain available areas for development.

Focusing on the sustainable installation of renewables, the Central Research Institute of Electric Power Industry (CRIEPI) used a geographic information system to analyse possible locations for the installation of solar PV and wind energy, considering both land use restrictions and zoning standards. The analysis shows that a total of 350 GW of solar PV and wind energy, which can provide approximately 500 TW·h per year, can be installed in suitable areas for sustainable development (Obane et al., 2020; Obane et al., 2021). Combining this amount with other renewables (hydropower, geothermal and biomass) would give Japan the potential to supply a total of 650 TW·h per year, less than half of the expected electricity demand in 2050 (Asano et al., 2020).

The Japanese Government anticipates an additional zero emission supply from innovation in thermal power generation, for example from hydrogen and ammonia fired power generation. However, these fuels would need to be imported, which will mean relying on other countries to produce abundant clean energy and on the establishment of a new supply chain for fuels. Carbon capture and storage (CCS) provides a valuable option but storing large amounts of carbon dioxide (CO_2) in an earthquake prone country is likely to engender social conflicts. A CRIEPI study shows that if only 16.8 gigawatts (GW) of nuclear reactors are available (reflecting the capacity that has applied for review under new regulatory requirements), 30 Mt of CO_2 would need to be stored per year to achieve an 80% reduction in emissions by 2050 (Hamataga et al., 2019). Achieving carbon neutrality will require an even larger amount of CO_2 to be stored.

If current nuclear capacity in Japan restarts with a lifespan of 60 years, and the three reactors currently under construction come online, Japan will have 23.7 GW of nuclear capacity in 2050, which would provide 166 TW·h per year at an assumed utilization rate of 80% (METI, 2022). This will significantly contribute to decarbonizing the power sector, although it will still not be enough to meet the expected growth in electricity demand. For Japan to decarbonize the power sector and achieve carbon neutrality in 2050, while pursuing social acceptance to expand renewables, new construction or replacement of nuclear power plants would need to be put on the national energy policy's agenda. With less than 30 years remaining until 2050, a concrete policy for nuclear development with a clear outlook is required to make certain that Japan will have the 'necessary amount' of nuclear power in time to achieve carbon neutrality.

Flexibility is needed over very different time scales to compensate for variability, unpredictability and the seasonality of wind and solar electricity production. Short term flexible resources, are needed to ensure the demand/supply balance from milliseconds to hours in response to unpredictable VRE generation and to ensure the stability of the system. Medium term flexibility, from hours to weeks, is required to compensate for the cyclical production of VRE resources. Finally, large needs for long term storage capacity will emerge with high shares of VRE to balance the seasonality of renewable production. As the VRE generation share grows, finding sufficient flexibility resources to maintain the reliability and stability of the electricity grid will pose major technical challenges to the grid operator and will have a significant impact on the total costs of the system. These difficulties are compounded by the fact that rapid VRE deployment will take place in parallel to the phase out of gas and coal power plants, which are the main sources of flexibility and system services in today's system.

All levers of flexibility will need to be developed or significantly scaled up from current levels, as none can provide sufficient flexibility in isolation. These levers will include: (i) the development of interconnections between countries whenever possible, reinforcement and digitalization of transmission and distribution networks; (ii) strong deployment of batteries, new storage technologies and, where possible, of hydroelectric storage capacities; (iii) additional flexibility requirements from thermal and renewable plants; and (iv) robust development of demand flexibility. Deployment of hydrogen or other energy carriers could also provide additional flexibility to the system by acting as additional electricity demand or by being used as a low carbon fuel in thermal plants.

The flexibility needs of a net zero energy system will be massive, whatever the path and mix of technologies chosen. However, flexibility needs will depend greatly on the relative proportion of VRE and dispatchable capacity, i.e. hydroelectric power, nuclear and fossil fuel plants with carbon capture and storage (CCS).[2] Flexibility requirements increase fourfold in the NZE compared with current levels (IEA, 2021c).

A comprehensive study by the French grid operator, Réseau de Transport d'Électricité (RTE), entitled Energy Pathways to 2050, examines the transition to net zero and underlines that between 30 and 70 GW of new flexibility resources are needed in France by 2050 to ensure the stability of the system (RTE, 2021), (see also Spotlight 1). These flexibility requirements are nearly equal to the average power demand in France today (57 GW of average load and 83 GW of peak demand in 2020). The larger the share of nuclear energy in the mix, the lower the requirements for flexible capacity, and the lower the costs of the overall system. The amount of estimated new flexibility requirements is limited to between 28 and 35 GW if there is sustained construction of new nuclear plants, with nuclear energy reaching a share of 50% and 36% of the electricity produced, respectively. The RTE estimates that flexibility needs will roughly double to about 55 GW if there is no new nuclear construction, and thus the nuclear share will decrease to 13% of France's generation mix. A system based only on renewable sources and with no nuclear power would require over 70 GW of flexible capacity.

Scaling flexibility requirements to the level needed for a system dominated by renewable energy will be technically, economically and socially challenging. An IEA study undertaken in close cooperation with the RTE concluded that integrating large shares of renewables in France is possible in principle, but would require substantial research, innovation and technological developments in the next decades (IEA, 2021d). The additional flexibility requirements in systems with less dispatchable capacity have a direct and significant impact on the total cost of energy. The cost of flexibility services is estimated at about €3 billion per year, or about 5% of the total system cost in a system with a 50% nuclear generation share. These costs increase fivefold to €16 billion per year in a system dominated by VRE, representing about 20% of total energy costs (see Figure 4).

Finally, developing flexibility resources, in terms of infrastructure (e.g. grids, pipelines, storage facilities, new power plants) and adapting consumption behaviours will require a strong degree of social acceptance. It should be noted

[2] It should be noted that fossil fuelled plants equipped with CCS will still emit GHG directly during operations due to the inefficiencies in CO_2 capture and sequestration processes, and indirectly as a result of fugitive methane emissions in upstream processes.

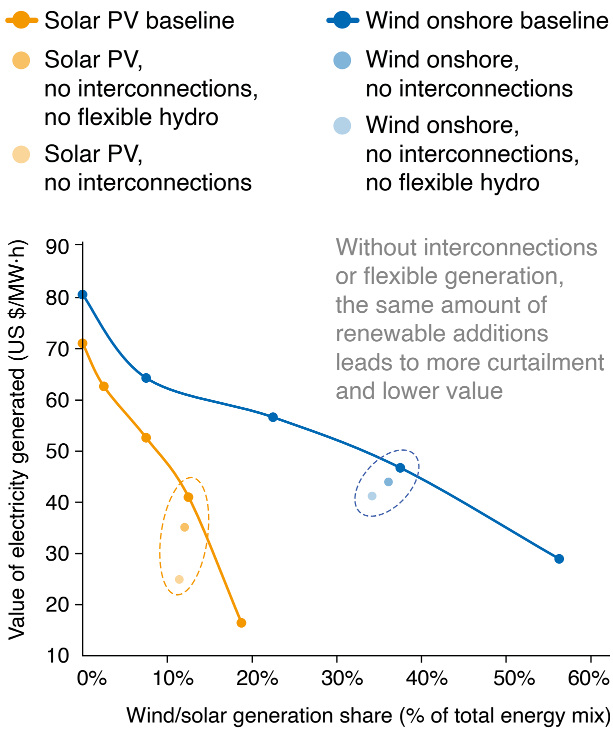
that these conclusions apply to a large, well interconnected system with abundant hydropower resources, as is the case of France; VRE integration could prove even more challenging and more costly in the case of isolated and less flexible systems.

Nuclear power, as a dispatchable low carbon technology, currently provides a vast array of system services in many Member States. These services include load modulation, balancing, inertia and voltage control, as well as management of seasonal imbalances via the optimization of planned outages (EDF, 2019; NICE, 2020). All new nuclear power plants have significant capability for flexible operations, which puts them on par with some coal plants. Technical solutions are also available to make existing plants operate flexibly, as proven in some Member States (OECD NEA, 2011; IAEA, 2018a). From a technical viewpoint, there is therefore an opportunity for nuclear to provide part of the flexibility required by a new low carbon system. The provision of flexibility services, however, comes inevitably with an economic penalty in terms of the reduction of achievable load factors, which could significantly affect the economics of power plants with high investment and fixed costs, and low variable costs, as in the case of nuclear power and renewables. The question will therefore be to what extent the flexibility provided by nuclear will be competitive with other sources of flexibility in future systems. In contrast, coupling nuclear plants with an additional storable output, such as hydrogen or other storable products, could significantly reduce the opportunity cost of operating flexibly, and thus increase the attractiveness of nuclear power as a provider of flexibility. The largest contribution of nuclear to flexibility comes, however, in an indirect way: having nuclear and other dispatchable low carbon technologies in a system significantly reduces the needs, and thus the costs, of flexibility.

Economic dimension: The cost of energy

The generation cost of renewable technologies, and notably of solar PV and wind, has decreased significantly in the last decades and in some regions is already lower today than the cost of dispatchable technologies (NEA/IEA, 2015; NEA/IEA, 2020, Lazard, 2021). Further cost reductions in VRE are expected in the coming years, albeit at a slower pace than what has been experienced until now. There is broad consensus that by mid-century generation costs from wind and solar PV plants will fall significantly below those of other low carbon technologies. Similarly, sizeable cost reductions are expected in less mature technologies, such as batteries or electrolysers, which will play an important role in the energy transition.

Figure 2: Value of wind and solar PV production as a function of their generation share.

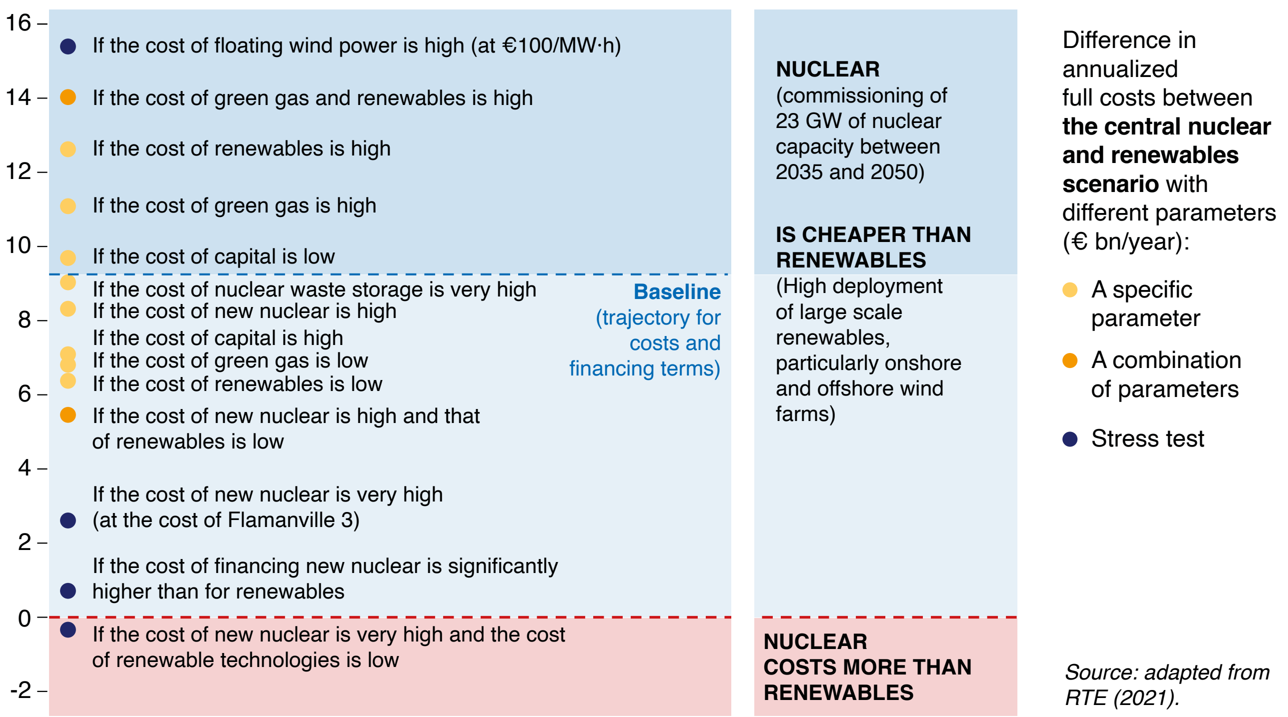


Source: adapted from OECD NEA (2019).

Deploying a sizeable amount of VRE in the energy mix makes economic sense and will be instrumental to achieving the energy transition at the lowest possible cost. However, beyond a certain level of VRE penetration, further increases in VRE generation do not produce economic benefits. The value that VRE provides to the system declines significantly and non-linearly with its share in the generation mix (see Figure 2) because the output of renewables of the same technology is strongly correlated (i.e. when the sun is shining in a region, all solar plants present in that region are likely producing electricity, and are thus depressing the value of the electricity generated). This phenomenon is more pronounced for solar PV than for wind since the former's output is more concentrated over a period of a few hours in the daytime. Geographical diversification, even at a continental scale, can only mitigate this effect. The extent of the loss in value of VRE depends strongly on the specific system, and particularly on the existing flexibility resources, as well as on the cost of adding new flexibility. A more interconnected system with sizeable storage resources will experience a lower decline of VRE value than a more isolated system with less storage capability, and thus the more flexible system will be able to accommodate a larger share of VRE in an economical manner.

A balanced generation mix, where renewables operate in conjunction with a sizeable share of dispatchable low carbon technologies, such as nuclear and fossil fuels with CCS, is key to achieving decarbonization at the lowest cost. Numerous studies conclude that having a sizeable share of nuclear energy is instrumental in minimizing the cost of the energy transition. For most systems, increasing the share of nuclear from today's levels would provide significant economic benefits. A study from the United Kingdom (UK) government concludes that deploying all low carbon technologies, including renewables, nuclear and CCS, minimizes the cost of the transition, especially if attempting to achieve a very low emissions intensity of power (UK Government, 2020a). The IEA warns that achieving sustainability with lower than expected production would significantly increase the investment needs in networks and other low carbon generation capacity, and thus significantly raise the cost of the energy transition (IEA, 2019c). In the NZE 'low nuclear case' without accelerated nuclear construction or lifetime extensions of operating nuclear plants, solar, wind, energy storage and fossil fuel plants with carbon capture technology would be needed to replace nuclear power. This case results in US $500 billion more investment and raising consumer electricity bills on average by US $20 billion each year to 2050 compared to the recommended NZE (IEA, 2022d). Several other comprehensive studies share the same conclusions (Aurora Energy Research, 2021; Compass LexEcon, 2021; RTE, 2022), see Spotlight 1. A very important outcome of the RTE study is not only its demonstration that nuclear based scenarios are significantly cheaper than those without new nuclear construction, but that this competitiveness also persists over a wide range of economic assumptions and 'stress test' scenarios (see Figure 3). Investment in nuclear energy can be seen as a 'no-regret' option for achieving the energy transition. Several Member States, including France, the Netherlands, Poland and the UK, have recently either reaffirmed the role of nuclear in achieving net zero emissions or of their intentions to step up their ambitions.

Figure 3: Nuclear energy competitiveness under a range of economic assumptions



Source: adapted from RTE (2021).

The transition to a net zero system will require immense investments in low carbon technologies and infrastructure, and will undoubtedly be costly, although estimates vary widely in this respect. While there is no doubt that addressing climate change is a priority since the energy transition will deliver substantial net economic benefits, such a transition must nevertheless be achieved at the lowest possible cost.

Since the cost structure of all low carbon technologies is characterized by high investment and fixed costs, a low carbon energy mix will be very capital intensive no matter the mix of technologies chosen. The cost of energy in a low carbon system is thus very sensitive to the cost of capital for investment in low carbon technologies. Achieving the energy transition in an effective way will require adequate energy policies that: (i) reduce the risk of investing in the energy sector, both for power plants and the associated infrastructure, thus minimizing the cost of capital; and (ii) create a level playing field across low carbon technologies to achieve the most efficient energy mix (see Chapter 6 for further details).

Decarbonizing energy beyond electricity: An opportunity for nuclear power

More tightly coupled energy systems and the replacement of fossil fuels in most energy uses will open up new opportunities for nuclear power. Unlike many renewable technologies, which generate electricity directly, nuclear power produces heat that is subsequently converted into electricity, as do all thermal plants, and in the case of nuclear with an efficiency of roughly 33%. The heat produced in a nuclear plant can therefore be directly used for space heating or in industrial processes, or it can improve the overall efficiency when providing other energy services, such as desalination or hydrogen production. A description of the status of different non-electric services provided by nuclear power is provided in Box 2, while a more comprehensive analysis of current non-electric nuclear projects is the subject of Chapter 3.

The possibility of combining the production of electricity with that of another, perhaps storable, energy product could provide significant services for a low carbon energy system, and thus boost the economic competitiveness of nuclear energy.

Spotlight 1:

A study by the French electric transmission network operator, Energy Pathways to 2050

At the request of the French Government, France’s electricity transmission network operator, RTE, launched a wide ranging study in 2019 on the evolution of the French power system in its efforts to achieve net zero emissions by 2050. The study compares, on an economic, environmental and societal basis, different energy strategies to reach carbon neutrality in France, with the objective of providing factual material to inform the public debate on energy and the climate. The study also identifies the technical challenges and technological advances required for each strategy and assesses some of the risks associated with the energy transition.

An unprecedented consultation effort underpinned the study, with the involvement of experts from over 100 different bodies to define the scenarios and the main hypothesis of the study, as well as the participation of thousands of entities and individuals. The study thoroughly analyses six main scenarios of electricity generation (three without new nuclear construction, and three considering nuclear new build) combined with three different scenarios for energy demand evolution. It also includes several sensitivity analyses and stress tests. No scenario includes electricity generation using fossil fuels with CCS, for reasons related to technical maturity, availability and social acceptance.

The study concludes that it is possible to develop a power system adapted to carbon neutrality by 2050, while keeping costs under control. Key requisites are to reduce total energy consumption via energy efficiency, quickly electrify energy uses, invest in the grid infrastructure to rapidly adapt to the changing generation mix, develop renewable resources as swiftly as possible and extend the lifetime of existing nuclear reactors. The latter two requisites are also essential for reaching the -55% GHG reduction target set in European Climate Law.

While all scenarios can reach the net zero targets set by France, they impose different costs and constraints to society and are characterized by different risks. Given that solar PV, onshore and offshore wind have become economically competitive, a significant development of renewables is essential to addressing French climate ambitions. However, the scenarios featuring new nuclear construction, and in particular those with a significant addition of nuclear capacity, have considerably lower costs than those based exclusively on the construction of new renewables (see Figure 4 below). Under the central economic assumptions of the study, the cost difference between a renewable based scenario and a nuclear based scenario (M23 and N2 in Figure 4, respectively) is about €10 billion per year. The sizeable requirements for flexibility resources and transmission infrastructure associated with the broad deployment of renewables outweighs the larger costs of generation in the nuclear based scenarios (N1, N2, N03).

The robust conclusion of this analysis highlights the economic advantages of building substantial new nuclear capacity and shows that this advantage persists across a wide range of variations in the main economic parameters and key assumptions (stress tests). Nuclear energy would therefore represent a 'no regret option' in the perspective of reaching net zero in France.

The study underlines the risks of the energy transition when relying on high shares of renewables: very high growth rates in VRE deployment are required, which exceed what currently has been achieved in EU countries, leading to potential tensions around the supply of critical materials, and concerns about land use and public support. Similarly, the scenario relying on the extension of the lifetime of nuclear reactors beyond 60 years (N03) implies a risk of not meeting several technical prerequisites in the short term.

Whichever solution is adopted, the study concludes that the achievement of carbon neutrality requires a doubling in the pace of investment in new generation capacity and the transmission and distribution (T&D) infrastructure compared to current levels. No renewable or nuclear capacity additions could be developed at the scale required by relying only on market revenues without public support. Strong governmental action, in the form of direct investment or long term contracts, will be needed to attract the required capital and to keep the cost of financing, and hence the cost of energy, at publicly acceptable levels.

Figure 4: Annualized full cost of the six main RTE scenarios in 2060.

Scenarios:

M0 100% renewables in 2050

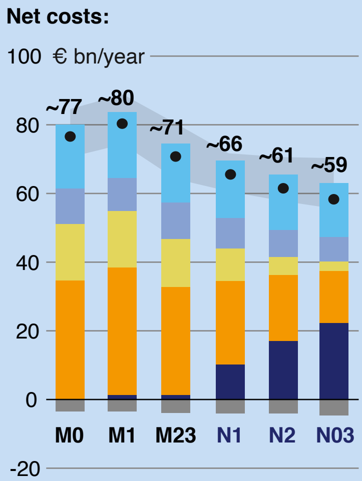
M1 High deployment of renewable generation, particularly solar

M23 High deployment of large scale renewables, particularly onshore and offshore wind farms

N1 Two new nuclear reactors built every five years from 2035–2050

N2 40 GW of new and existing nuclear capacity, resulting in a 36% share of nuclear electricity in 2050.

N03 50 GW of new and existing nuclear capacity, resulting in a 50/50 split between renewables and nuclear energy in 2050.



- Cost of distribution network, including connection infrastructure
- Cost of transmission network, including connection infrastructure and interconnections
- Cost of flexibilities,* including renewable generation used to produce hydrogen
- Cost of renewable generation, excluding production intended for storage/discharge and excluding connection infrastructure
- Cost of nuclear, including back end costs (waste processing and storage) and provisions for dismantlement
- Income from exports

*Electrolysis and related hydrogen storage logistics, on-demand flexibility, batteries and hydropower storage

Source: adapted from RTE (2021).

Box 2: Contributed by Electric Power Research Institute

The evolving role of nuclear energy in a net zero emission system

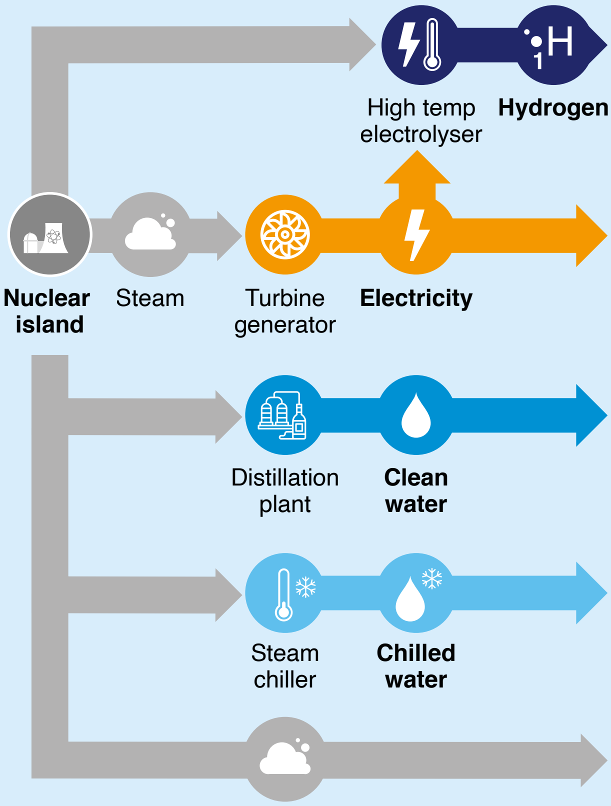
A growing amount of literature is examining the energy systems that will be necessary to reach net zero CO_2 emissions across the whole economy (Bistline J., 2021). Decarbonizing electricity plays a central role in these systems — both from direct emission reductions in the electric sector and from use of low emitting electricity to displace fossil fuel use via direct electrification and electricity derived fuels (DeAngelo et al., 2021). The twin challenge is to decarbonize electricity supply while meeting growing global electricity demand resulting from electrification and increasing access to energy in emerging economies.

The transition to a low carbon energy system shifts investments away from fossil fuels towards renewables and nuclear. There is considerable variation in the shares of nuclear energy relative to current levels, depending on the model structure, policy assumptions and other input assumptions, such as technology costs (Bistline et al., 2022). However, many studies underline the need to have low emitting, firm technologies together with renewables when decarbonizing both electricity and broader energy systems. Firm resources are "technologies that can be counted on to meet demand when needed in all seasons and over long durations (e.g., weeks or longer)" (Sepulveda et al., 2018). Clean, firm resources such as nuclear could thus play an important functional role, filling in weekly and monthly gaps when wind and solar output are low. Use of such technologies can lower the costs of decarbonization, with nuclear energy tending towards a larger role under deeper decarbonization scenarios (Baik et al., 2021; Bistline & Blanford, 2021; Duan et al., 2022; Jenkins et al., 2018). In the medium term, extending the lifetime of existing nuclear plants is critical for meeting 2030 emission reduction targets (EPRI, 2021a).

Net zero emission systems are very likely to exhibit greater integration and interconnectedness relative to today (DeAngelo et al., 2021). Nuclear energy is also likely to provide a much broader array of services and products, and its planning and operations will be increasingly linked with those of other energy carriers. In economic terms, this means that non-electric value streams could become more important under economy wide deep decarbonization, including through the direct sale of heat for industrial purposes or the sale of hydrogen, synthetic liquid fuels, direct air capture and potable water produced from high temperature heat (Sowder & Moneghan, 2021).

In a future low carbon system, nuclear energy will play an increasingly important role in maintaining the stability of the grid and in providing other services to the system. Thus, nuclear power generating stations would have to modulate their output to match renewable generation, which would result in a lower capacity factor of the facility. This lower capacity factor could reduce the economic value of the nuclear asset, depending on the value that the electricity market places on nuclear as a dispatchable resource. One solution to this challenge would be to pair nuclear capacity with a means of thermal energy storage, such as molten

Figure 5: Potential products from nuclear energy.



Source: adapted from EPRI.

salt tanks. Such an approach would allow the nuclear capacity to continue running at 100% output while the thermal storage tanks charge and discharge using a steam turbine generator to meet grid demands. Another approach could be to utilize nuclear energy in other ways at times when nuclear output is not required to generate electricity. Nuclear energy has the capability to generate other products, including hydrogen, clean water, chilled water and heat (see Figure 5). These energy products can be applied in various ways to support the following industries:

- **hydrogen;**
- **district energy;**
- **process industry;**
- **data centers;**
- **water.**

Nuclear capacity coupled with high temperature electrolysis could, for example, directly generate electricity, or use the steam together with the electricity to produce hydrogen. In this way, generation could be modulated back and forth between multiple products so as to maintain reactor output at 100% and maximize the economic value of the final output. One potential challenge lies in the ability to meet the demand profiles of each individual product. Energy or water storage can be used to mitigate this challenge, but the size of the storage capacity must be carefully considered to ensure that all of the energy demands are met under bounding conditions.

When looking to the future towards a decarbonized energy system, it is evident that nuclear energy has the capability to complement renewables in electricity generation and to provide overall stability to the system through its capability to generate additional products.

Nuclear energy has the capability to complement renewables in electricity generation.

Modulating output between electricity and a non-electric product would allow for steady operations at full power and would maximize nuclear profits by taking advantage of very volatile electricity prices. This mode of operation could also open up the possibility of providing the flexibility and other system services required in a low carbon system in a much more efficient manner than a nuclear power plant operated solely as an electricity provider, minimizing cycling needs and costs and maximizing the load factor.

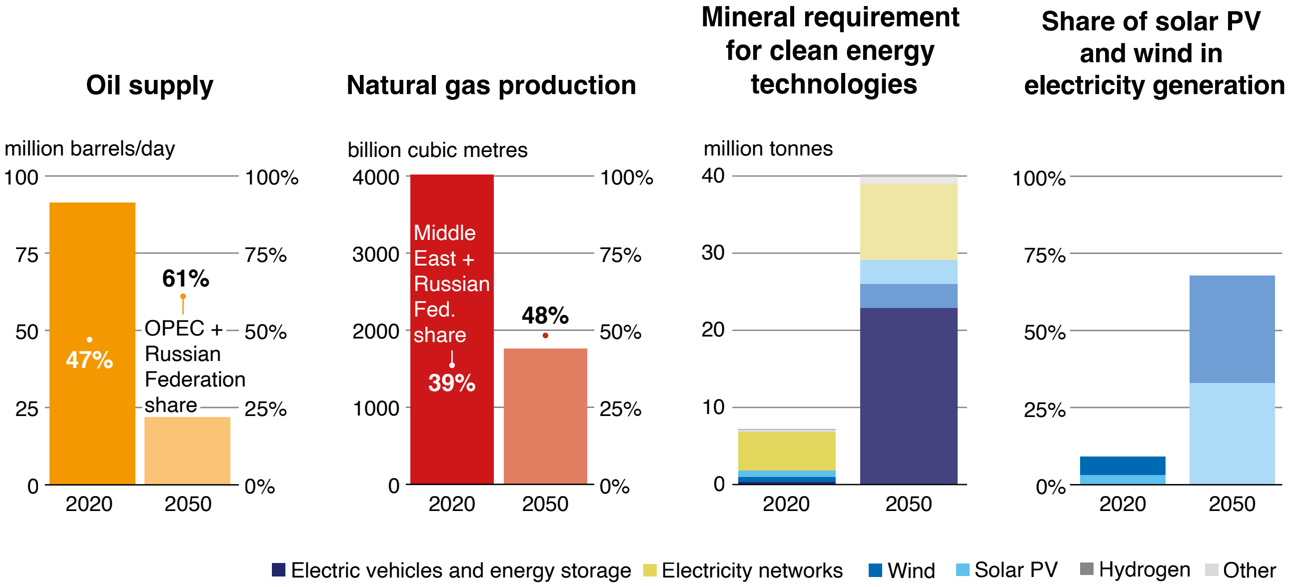
Energy security: From fossil fuel supply to critical materials and grid reliability

The transition towards a low carbon energy system will also have far reaching impacts on energy security: risks associated with the supply of oil and natural gas will be reduced in the long term, while new risks will likely arise in relation to the availability of critical materials, and the reliability and stability of power systems (see Figure 6).

In the long term, an energy system based on low carbon technologies, such as nuclear and renewables, will be inherently less vulnerable to tensions in demand–supply and the consequent price changes of fossil fuels. However, the risks associated with fossil fuel supply will not disappear. The IEA warns that the export of fossil fuels will shift to a small number of low cost producing countries and will become more concentrated in 2050 than today. For instance, the share of the oil supply of the Organization of the Petroleum Exporting Countries (OPEC) is expected to reach 52% in 2050, a level last seen during the oil crisis of the 1970s and 15% higher than today (IEA, 2021c). Risks in relation to oil and gas security may indeed increase in the medium term as demand for some fossil fuels, for example liquefied natural gas (LNG), peak without attracting investments in the related infrastructure.

Rapid deployment of low carbon technologies will trigger a huge demand for the minerals and critical materials — such as aluminium, cobalt, copper, graphite, lithium, nickel, silver and rare earth elements — that are required for the construction of these technologies and the associated infrastructure. Mineral demand for electric vehicles and battery storage is expected to increase by more than 50 times by 2050, while expansions in T&D

Figure 6: Global energy security indicators in the IEA Net Zero Emissions by 2050 Scenario



Source: adapted from IEA (2021a; 2021c).

infrastructure will double the demand for copper in the power sector. Globally, demand for critical metals increases sixfold in the Net Zero Scenario, with strong demand growth for lithium, cobalt and nickel (IEA, 2021a). Adapting the supply chain for these materials will be challenging and may pose energy security issues. Higher and more volatile prices of critical minerals could have far reaching consequences on the cost of the energy transition, and hence on its public acceptance. In 2021, higher commodity prices raised the investment cost of renewable technologies by 5–15% compared to 2020 (IEA, 2021a; IEA, 2021c). Another potential source of concern is that the production of some of these materials and their processing operations are much more concentrated than those of fossil fuels. For instance, the top three producing nations control over 75% of the global output of lithium, cobalt and some rare earths (IEA, 2021c).

The rapid electrification of energy uses, combined with reliance on low carbon technologies for power production, will bring the stability and long term reliability of power systems to the centre of energy security. The transition to low carbon systems will have both positive and negative consequences for energy security. Most of the value chain of low carbon technologies can be domestically sourced, thus increasing the self-reliance of energy-importing countries. Moreover, once built, most low carbon generation technologies ensure low, stable and predictable electricity generation costs, which are independent of fossil fuel price fluctuations. On the other hand, a larger, more complex and interconnected power system will be inherently more fragile and vulnerable to a failure of any of the system's components and to extreme weather events. As electricity becomes more important, electricity supply disruptions will have broader impacts. Another concern will be ensuring the stability of a power system dominated by intermittent renewables that have a limited capability to provide inertia and other services to the system. An IEA study in close cooperation with RTE concludes that balancing supply and demand, and guaranteeing the stability of a system with high shares of VRE, poses a major technical challenge with broad economic, political and organizational impacts. Potential technical solutions nonetheless exist even if significant research and development (R&D) is required to bring them to maturity (IEA, 2021d; RTE, 2022).

As a scalable, fully dispatchable and largely domestic source of energy, nuclear power has made significant contributions to improving the energy supply in many countries around the world (OECD NEA, 2010). Operational costs of nuclear power are stable, predictable over time and relatively insensitive to the price of uranium.

Uranium resources are abundant and well diversified across a variety of countries and have been deemed adequate to support high nuclear development scenarios (IAEA, 2020). In addition, because of the high energy content of uranium, a large amount of energy can be easily stored on-site, thus protecting the utilities from potential fuel supply disruptions.

Several characteristics of nuclear energy may further strengthen its contribution to the security of supply in a fully decarbonized energy system: (i) its role in minimizing the cost of the energy transition; (ii) the lower requirement of critical minerals compared to other low carbon technologies; and (iii) its contribution to power system reliability. Once all system costs are included, nuclear power is economically competitive with other low carbon generation technologies, and a sizeable deployment of nuclear energy is key to minimizing energy costs. Nuclear power also contributes to significantly reducing the volatility of electricity prices in a decarbonized system (OECD NEA, 2019). Together with hydroelectricity, nuclear power has the lowest mineral requirements of all low carbon technologies, with the most used minerals in nuclear power — copper, chromium and nickel — having a large market size and low market concentration (IEA, 2021b; UNECE, 2022). The RTE study points out that scenarios with nuclear power significantly decrease the reliance and need for critical materials compared to those based on renewables alone, particularly for copper, aluminium, silicon, rare earths, steel and concrete (RTE, 2022). Finally, nuclear power greatly contributes to the stability and long term security of a low carbon power system. As a fully dispatchable energy source, nuclear can provide inertia, reserves and other services to the electricity grid. The most important contribution of nuclear power to the security of supply, however, lies in the fact that a system with nuclear requires much less flexibility resources and is more stable than a system based entirely on renewables.

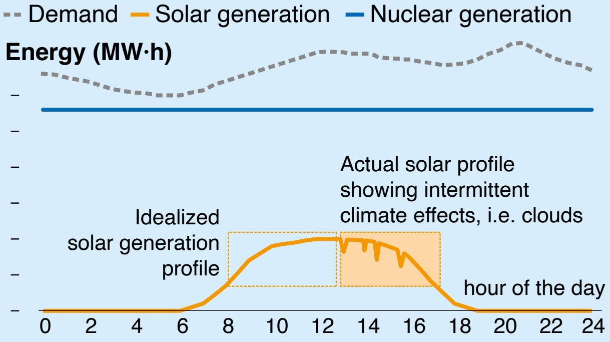
Box 3: Contributed by Emirates Water and Electricity Company

Challenges of integrating clean energy sources into the power grid: A perspective from the United Arab Emirates

From rising sea levels to shifting weather patterns, the climate is changing at an unprecedented rate, threatening humanity and life on our planet. The United Arab Emirates (UAE) is particularly vulnerable to the impacts of climate change. With nearly 1300 kilometres (km) of coastline, most of the population and infrastructure of the UAE are located within a few metres of sea level in low lying coastal areas. Studies undertaken by the Abu Dhabi Environment Agency have shown that these areas are considered at risk and that the UAE could lose up to 6% of its developed coastline by the end of the century because of rising sea levels. In order to address such climate threats, 196 parties, including the UAE, adopted the Paris Climate Agreement in 2015 with the objective of reducing GHG emissions and reaching net zero emissions in the second half of the 21st century. In 2021, the UAE adopted the Net Zero by 2050 Strategic Initiative, making it the first Middle Eastern and North African nation to implement such a strategy. The deployment and use of renewable and clean energy solutions is one of the main pillars of the UAE model for addressing climate change and reducing GHG emissions. To do so, the UAE began financing innovative renewable and clean energy projects more than 15 years ago and has invested over US $40 billion in the sector to date. Current trends predict that the capacity of these energy projects, including solar and nuclear energy, will reach 11 GW in the Emirate of Abu Dhabi by 2030, up from around 100 megawatts (MW) in 2015 and 2.4 GW in 2020.

In 2022, the power capacity in the Emirate of Abu Dhabi is comprised of 70% combined cycle power units (CCGT), 4% open cycle power units (OCGT), 22% nuclear power units, and 4% solar power units. By 2025, the generation mix is projected to be comprised of 48.5% CCGT, 1% OCGT, 43% nuclear and 7.5% solar. This change showcases the significant progress made by the UAE Government to meet its commitment to net zero by 2050. While integrating renewable and clean energy sources into Abu Dhabi's power portfolio is instrumental in reducing GHG emissions, it also presents some challenges to the system operator, the Emirates Water and Electricity Company (EWEC). EWEC is the sole planner, procurer and system operator of water and electricity in the Emirate of Abu Dhabi and beyond, with the mission to deliver a secure power and water supply at the lowest possible cost. In order to better understand the challenges associated with integrating solar and nuclear power into the grid, the typical generation profile for each type of energy must be examined. A solar PV power plant (the type best suited for operation in UAE conditions), consists of a large number of photovoltaic modules which convert light to electricity. Generation from a PV power plant is limited to daytime hours, and is directly dependent on climatic conditions, as shown in Figure 7. On the other hand, a nuclear power plant consists of single or multiple nuclear power units that convert thermal energy from a nuclear fission reaction to mechanical energy, which is in turn used to generate electricity. The majority of nuclear power units are designed as baseload units, and run steadily at their rated capacity throughout the operation cycle, as shown in Figure 7.

Figure 7: Typical daily generation profiles for solar PV and nuclear power units.



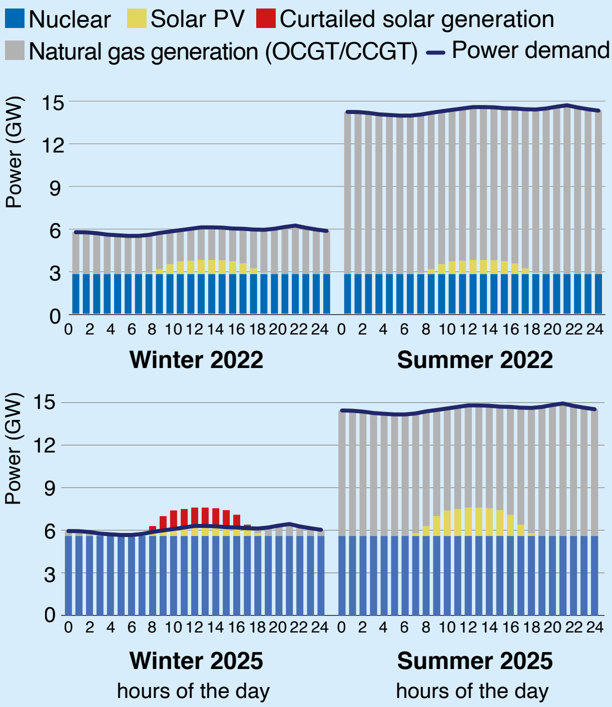
Source: adapted from EWEC (2022).

The intermittent nature of PV production presents a challenge to stable system operations because of its variable and uncertain output. This requires control systems that are able to ensure a fast response from other units in order to compensate for this variability in generation output, which can be as large as hundreds of megawatts over very short periods. The situation becomes even more complex during winter months, when electricity demand is much lower than in summer. Once all of the Barakah nuclear power plant units are in operation, over 86% of the minimum winter power demand could theoretically be supplied by nuclear units that are not designed to respond to such variations. Grid stability services that have previously been provided by flexible gas units (CCGT and OCGT) will thus need to be replaced by alternative sources, for instance battery energy storage systems or static compensators used in combination and coordination with operational measures, such as planning nuclear refuelling outages during periods of lowest demand rather than in the summer.

As of May 2022, two of the four units at the Barakah nuclear power plant are in commercial operation, producing 2.8 GW in total. In addition, solar PV power plants provide about 1.2 GW to the grid. This combined nuclear and PV generation accounts for about 25% of the summer demand and about 60% of winter demand, as shown in Figure 8. This significant power production by nuclear and solar PV, coupled with the difference in power demands between summer and winter, limits the operation margin where cogeneration units can be used efficiently to secure the water demand. By 2025, it is expected that 5.6 GW of nuclear capacity will be operational at Barakah nuclear power plant. If no other market action is taken, the additional nuclear generation will outpace expected growth in power demand, resulting in a curtailment of solar generation.

EWEC identified this challenge at an early stage through its annual assessment of future capacity requirements, and it has initiated several mitigation actions accordingly. In the short term, the operational solution is to increase power demand through exports and trading, combined with optimizing the refuelling schedule of nuclear units and the curtailment of solar output when necessary. EWEC has been working closely with the Emirates Nuclear Energy Company and the Nawah Energy Company to manage the operational schedule of the nuclear units with a view to aligning the refuelling outages over the winter period. In addition, EWEC has engaged with the cogeneration units to optimize the physical configurations at the different units to enable the production of fresh water via bypass operations, where gas turbines directly connect with the distiller units, bypassing steam turbines.

Figure 8: Example generation mix in the UAE during winter (left) and summer (right), today and in 2025, assuming no corrective measures are taken to balance the generation mix ('what-if scenario').



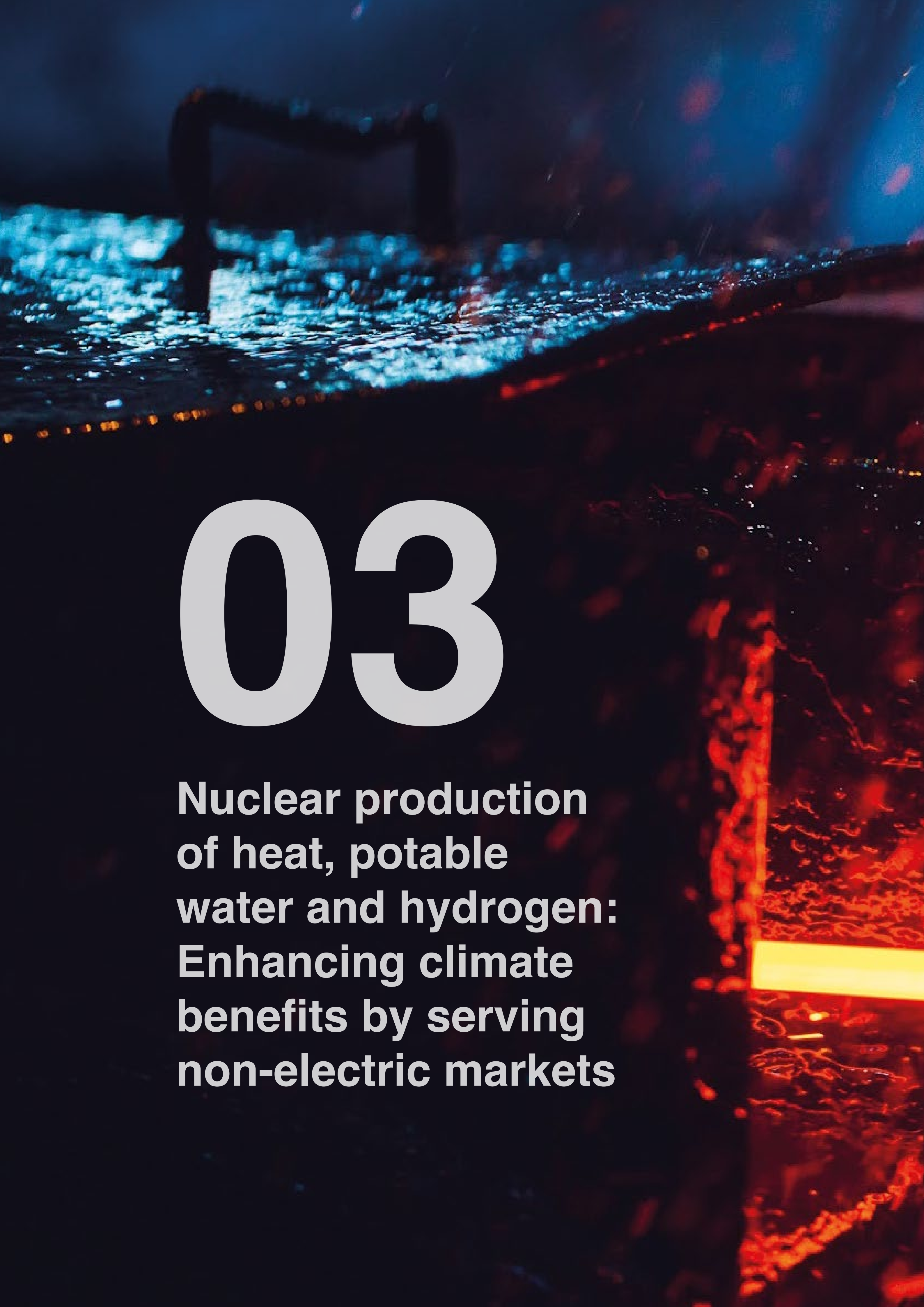
Source: adapted from EWEC (2022).

The longer term solution is to decouple power and water production through the adoption of stand alone, membrane based desalination plants. This offers benefits in terms of the lower cost of production and increased system flexibility, thereby increasing security of supply. It would also mean a reduction in the carbon intensity of water from around 12 kg/ m^3 to less than 2 kg/m^3. Consequently, between 2020 and 2030, EWEC expects to increase the proportion of water produced by membrane based desalination from 15% to 90%, with full decoupling being achieved in the 2030s.

Another challenge, which arose in relation to the size of the nuclear units, is meeting the operational reserve margin requirement. The required operational reserve for the network in Abu Dhabi is directly affected by the largest operating unit on the grid as it forms the largest single credible contingency event. After the integration of the first nuclear unit in April 2021, the size of the largest operating unit increased by 120%, which resulted in a significant increase in operational reserve requirements. Holding an increased amount of generation in reserve increases system costs in absolute terms, which has the potential to increase costs for end use customers. Moreover, securing the required operational reserve during winter operation, where thermal units are displaced by nuclear and solar PV generation, as shown in Figure 8, became more challenging.

The integration of more renewable and clean energy sources into the Abu Dhabi grid is projected to reduce annual emissions from 43 Mt CO_2 in 2021 to 23 Mt CO_2 by 2025. This significant reduction is largely attributed to the integration of four nuclear units into the system. In addition, the integration of solar PV units provides energy at less than 50% of the cost from new gas generation and around 20% of the cost of new nuclear units. Although technical challenges for PV use (i.e. intermittency and energy storage) currently cap the total amount of PV that can optimally be connected to the grid, the existing cost competitiveness of solar power, rapid reductions in energy storage cost and ongoing improvements in the efficiency of solar technologies make a compelling case for a pathway to a net zero grid in the UAE based on a combination of existing nuclear capacity combined with solar, energy storage and strong grid interconnections between the different emirates as well as regional neighbours in the Gulf Cooperation Council.

Overall, the integration of nuclear and PV power units into the grid in Abu Dhabi continues to reduce the carbon intensity of power and water production and is supporting current progress towards the UAE achieving its ultimate net zero objective. However, this transition presents a number of challenges to network operation, security of generation, asset management and overall system cost. EWEC, in collaboration with the energy sector in Abu Dhabi, has managed to provide a pioneering roadmap for the early identification and response to these potential challenges. While the details of these challenges and the mitigation techniques that EWEC has implemented may be unique to the system in Abu Dhabi, the overall approach of EWEC and the government of Abu Dhabi can guide other network operators in systems across the world in terms of the successful integration of cleaner, renewable energy sources.



03

Nuclear production of heat, potable water and hydrogen: Enhancing climate benefits by serving non-electric markets

Key messages:

- **In addition to low carbon electricity, nuclear capacity is able to supply heat and hydrogen as an alternative energy product, providing a large scale, decarbonized, reliable means to significantly lower emissions beyond the power sector.**

- **High emitting fossil fuels power most industrial processes, transport and building heating systems today. An expanded use of the non-electric applications of nuclear power, including desalination, district heating and hydrogen production, can be used to reduce emissions and increase the security of supply of the global energy system.**

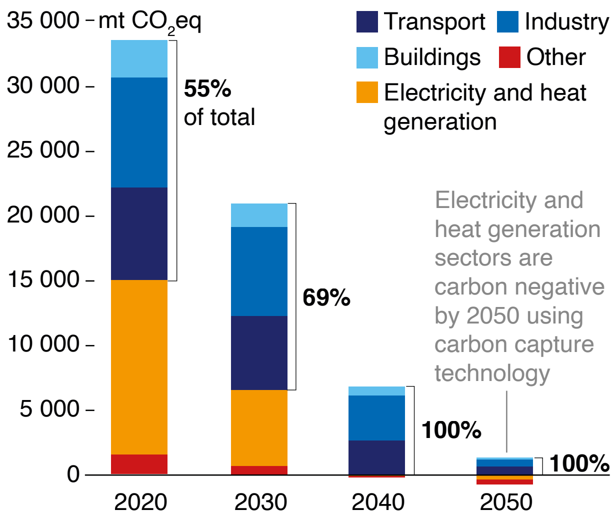
To achieve deep decarbonization of the global economy, decision makers must target emissions outside the power sector. Most global energy related emissions today can be attributed to the industrial, building and transport sectors. While the share of global emissions from these sectors is projected to grow, total emissions are projected to fall (IEA, 2021e). Although nuclear technology is mainly known for supplying low carbon electricity, it can also supply low carbon heat as an alternative energy product, providing a large scale, reliable means to significantly lower emissions beyond the power sector.

High global hydrocarbon prices have put renewed focus on nuclear options to ensure energy security in the power sector and beyond. In 2021, the cost of producing heat from natural gas plants more than doubled from the year before, while the output from nuclear plants proved to be nearly impervious to commodity price volatility (Cameco, 2021; World Bank, 2021a).

Most industrial processes, along with processes in the building and transport sectors, rely on high emitting fossil fuels to provide heat. Fossil fuel use is thus deeply embedded in existing operations, representing a significant barrier for the entry of low carbon technologies. A combination of policymaking, financing, technological developments and safety measures can effectively reduce emissions when low carbon nuclear options replace incumbent heat and power sources, achieving decarbonization across all sectors.

Nuclear energy can deliver various low carbon products to energy systems, including electricity and process heat for industry, desalination, district heating and hydrogen production. These low carbon energy products can provide both supplemental electrical output and the ability to store power to complement wind and solar generation as a means of mitigating climate change (IPCC, 2022a). This chapter will focus on the climate benefits of nuclear power in serving non-electric applications globally, with a focus on desalination, district heating and hydrogen production.

Figure 9: Global energy sector emissions by sector and decade, 2020–2050 under the IEA Net Zero Emissions by 2050 Scenario.



Source: based on data from IEA (2021c).

While the building, transport and industrial sectors made up 55% of global energy related carbon emissions in 2020, that share is expected to reach 100% by 2040 (see Figure 9 for projected carbon emissions by sector over the coming decades). According to the IEA, this increase results from electricity and heat generation sectors becoming carbon negative by 2040 through use of carbon capture technology, leaving only the industry, transport and building sectors with positive energy related carbon emissions (IEA, 2021c). Approximately 14% of the world's nuclear reactors contributed to the global production of desalinated water, district heat and process heat in 2021 (IAEA, 2021b). Non-electric energy products are always cogenerated with electricity since no dedicated heating plants have been commissioned to date. Because of paired decarbonization efforts and anticipated growth in desalination, electrified heating and hydrogen production, the potential to increase the deployment of nuclear in non-electric energy applications is massive. This trend is particularly strong for nuclear newcomer countries such as Egypt, Saudi Arabia and the United Arab Emirates, as well as China, the country with the largest number of planned nuclear reactors in the world. The opportunities for non-electric energy applications in these countries is discussed in detail in the sections below.

Desalination

The desalination process provides clean water for drinking, irrigation and industrial processes. Desalination is particularly important in water stressed areas. Yet desalinated water is one of the most underserved industries in the world, and demand for clean water will only continue to grow as climate change worsens. The desalination sector today is heavily reliant on fossil fuels, making it expensive and a source of high emissions. Only about 1% of total desalinated water emanates from renewable fuel sources (IRENA, 2012).

The combined electricity and heat requirements for desalination processes such as multistage flash distillation (MSF) or multi-effect distillation (MED) make nuclear a natural fit. However, a combination of technology cost declines and a global push for the electrification of energy-intensive systems such as desalination have increased the popularity of the reverse osmosis (RO) process (see Spotlight 2). Market analysis predicts only a modest increase in MSF and MED technologies, while RO is expected to comprise most of desalination deployment over the next five years (DesalData, 2020).

Nuclear energy can play an important role in furthering decarbonization efforts even beyond the power sector.

Spotlight 2:

A summary of desalination techniques

While there are many desalination techniques, the three main desalination technologies used today are: **reverse osmosis, multistage flash distillation and multi-effect distillation.**

Reverse osmosis made up 70% of the 2020 desalination market by capacity (DesalData, 2020).This technology uses pressure to push feed water through a membrane, separating dissolved salts and other contaminants from purified water (IAEA, 2015). The process is primarily used for seawater desalination and requires an average of 3 to 4 kilowatt hours (kW·h) of electricity per m^3 of drinking water produced (Davies et al., 2021).

Thermal desalination processes such as **multistage flash distillation** use heat to warm the feed water, producing vapour that can then be separated from the condensed brine, resulting in purified water for consumption. In 2020, this technology accounted for 18% of global desalination capacity. On average, it requires between 2.5 and 4 kW·h of electricity and 7.5 to 12 kW·h of 'electrical equivalent heat' (a measure of thermal heat converted to electrical energy) per m^3 of water produced.

Multi-effect distillation, similar to the multistage flash distillation process, takes place through a series of small scale processes requiring heat, with the ambient pressure reduced in successive effects. This technology provided 7% of global desalination capacity in 2020. It requires an average of 1.5 to 2 kW·h of electricity and between 4 and 7 kW·h of electrical equivalent heat to produce a m^3 of purified water.

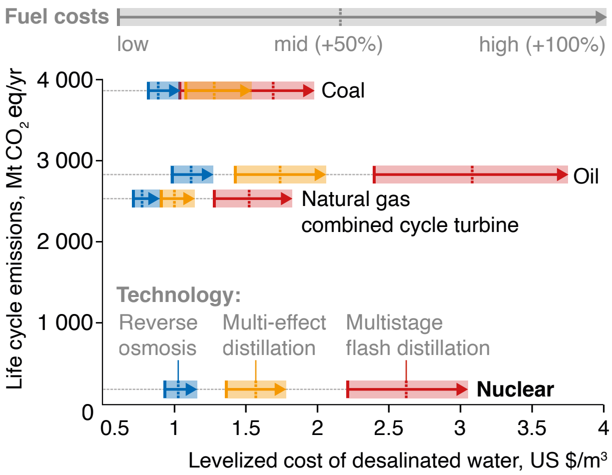
In 2020, the cumulative capacity of operational desalination plants worldwide reached 97.4 million m³/day, a 7% compound annual growth rate since 2010 (Eke et al., 2020). The global desalination industry is predicted to grow with a 9.5% compound annual growth rate from 2020 to 2027 (Business Wire, 2021). With a consumption of approximately 4000 TW·h per year, desalination powered by fossil fuels (which make up 99% of the current desalination market) is responsible for estimated yearly emissions of 250 Mt of CO_2 (IEA, 2021f; IEA, 2022a). Without significant changes to the source of fuel for desalination, emissions from the desalination process will only continue to grow. The Middle East and North Africa (MENA) region, which today accounts for nearly half of global desalination capacity (Jones et al., 2019), along with Asia Pacific, are expected to be the fastest growing desalination markets between now and 2027 (DesalData, 2020).

Current market

Desalination costs are extremely variable as they depend on many factors, making it difficult to directly compare project costs. RO tends to be the cheapest technology, which has led to explosive deployment in recent years compared to thermal technologies (Davies et al., 2021). RO is nevertheless not always the best technology for every site. The benefits of the RO depend on many factors, including the condition of the intake salt water (salinity and impurities) and purity of the product required. Environmental concerns with RO intake systems and the disposal of brine concentrate also must be mitigated in the facility design and during operations (Missimer & Maliva, 2017).

The emissions from desalination depend mostly on the fuel type used. Life cycle emissions from fossil fuelled desalination operations can be between 12 and 19 times larger than the emissions from nuclear desalination (IAEA, 2014). The life cycle emissions of desalination projects with a desalination capacity of 100 000 m³/day, using fossil fuel electricity and heat, are estimated at between 2530 and 3874 Mt CO_2 eq emissions per year, compared to just 193 Mt/year for nuclear energy (IAEA, 2014). Energy cost is the major contributor to the overall cost of water desalination, especially when thermal processes are involved (see Figure 10).

Figure 10: Relationship between the levelized cost of desalinated water and life cycle emissions for different desalination technologies and fuel cost scenarios, assuming a plant capacity of 100 000 m³/day.



Source: based on data from IAEA (2014).

Opportunities for nuclear

Large scale deployment of nuclear desalination on a commercial basis will depend primarily on economic factors. Nuclear desalination may be a good option for regions with water scarcity, considering the siting potential of a nuclear reactor, which can supply the energy requirements for this process. Nuclear provided 40 GW·h of electrical equivalent heat[3] for desalination in 2021, from five reactors across India and Japan (IAEA, 2021b).

In 2021, nearly 61% of all desalinated water came from seawater, 21% from brackish water and 18% from groundwater and rivers (Jones et al., 2019). Nuclear plants fit these locations well, as demonstrated in Figure 11 — 57% of operational and planned nuclear power plants are located on the seacoast and near rivers (IAEA, 2021b). A total of 42% of nuclear power plants are located near the seacoast, with 12% of those considered to be in areas of 'high' to 'extremely high' water stress today (WRI, 2019). That share could rise to as much as 32% by 2040.

[3] A measure of thermal energy converted to electrical energy which depends on the thermodynamic efficiency of the nuclear power plant.

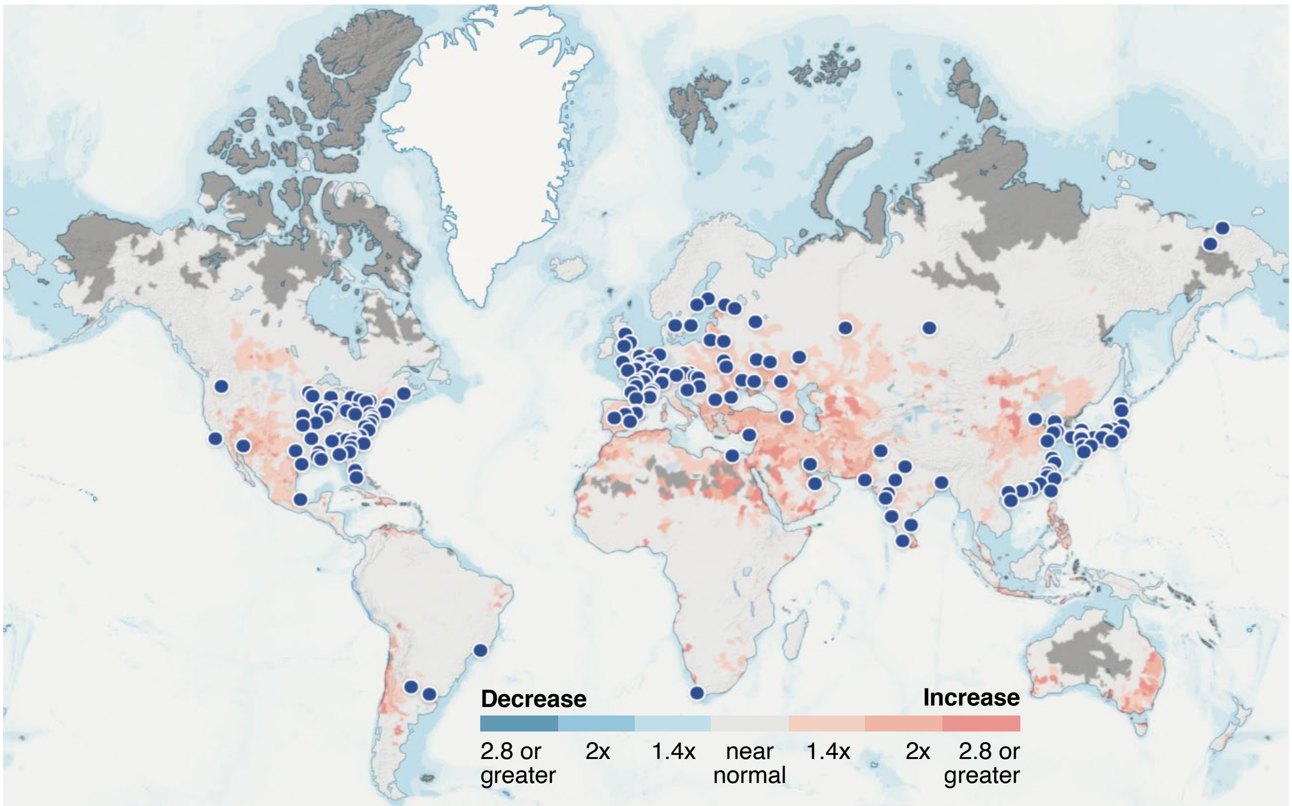
Desalination has emerged as a vital part of the water industry in the MENA region. The UAE is the largest market for desalination in the world today. The country recently commissioned two units totalling 2.8 GW of capacity at its first nuclear power plant, Barakah NPP. Two additional reactors are under construction, which will add another 2.7 GW of capacity. Saudi Arabia has plans to add 17 GW of nuclear capacity by 2040, although the country has no specific plans for power plants to date. Egypt's first nuclear plant, El Dabaa, is likely to be paired with desalination capacity.

Economies of scale are vital to the future of desalination. Despite there being more than 20 000 desalination plants around the world today, 7% of the world's desalination capacity is represented by just ten plants, all located in Israel, Saudi Arabia and the United Arab Emirates (Aqua Tech, 2021). Many countries across the MENA region are expected to rapidly expand their desalination capacity, and several are already considering nuclear desalination, which will provide the opportunity for large energy and heat sources to be connected to a desalination project.

Pakistan began a nuclear desalination demonstration project in 2011 and operates 2 GW of capacity (two reactors) at the Karachi nuclear plant. A study using IAEA simulation models to calculate the costs of desalination technologies under varying parameters found that coupling the Karachi nuclear power plant with desalination technologies could result in water costs ranging from US $\$0.97/m^3$ with the MED technology to US $\$1.57/m^3$ using the MSF technology (Khan & Khan, 2017).

As embarking nuclear countries in the Middle East and North Africa grapple with water stress, there is, in parallel, an enormous potential for nuclear desalination. Global water demand is expected to increase between 20–50% by 2050, with a growing share projected to be met by desalination (UN, 2019).

Figure 11. Change in water stress from 2019 to 2040 in a 'business as usual' case, with operational NPPs and new nuclear construction.



Source: water stress data adapted from WRI (2019) and nuclear data from the IAEA (2021b).

Spotlight 3:

El Dabaa nuclear desalination

Desalination capacity in Egypt has rapidly expanded in recent years and is expected to keep growing. Since 2014, Egypt has constructed 82 desalination facilities with plans to build 14 more by the end of 2025 (Egypt Today, 2022). The country is now facing even more serious water scarcity issues as it begins to compete for the resource with Ethiopia's 5.15 GW capacity hydropower dam that began producing electricity in February 2022 (Patel, 2022).

The possibility of pairing nuclear power and desalination at the El Dabaa site has been studied for years (Megahed, 2009). In 2015, the Egyptian Nuclear Power Plants Authority signed a project development agreement for a two unit AES-2006 nuclear power plant, associating an RO desalination facility equipped with 1.2 GW of capacity per reactor.

The desalination facility, once online, is expected to be able to produce up to 170 000 m^3/day of water from a single desalination unit, using just 2% of the total capacity from the nuclear power plant once the nuclear component of the project is in service (TAM Environmental Services, 2019). The nuclear desalination plant, once connected, could avoid approximately 2000 Mt of life cycle CO_2 eq emissions per year (IAEA, 2014).

Desalination capacity in Egypt has rapidly expanded in recent years and is expected to keep growing as Egypt is facing even more serious water scarcity issues.

Box 4: Contributed by the Permanent Mission of Pakistan to the United Nations

Pakistan Karachi Nuclear Power Plant nuclear desalination

The Nuclear Desalination Demonstration Plant (NDDP) at the Karachi Nuclear Power Plant (KANUPP) was commissioned in 2009. The NDDP was installed to produce desalinated water via a thermal desalination process using the K1 nuclear reactor from KANUPP as a source of energy. The first desalination unit installed at the NDDP, with a capacity of 1600 m^3/day, was procured from a foreign vendor and installed for demonstration purposes. A second desalination unit was designed but not built. The steam productivity was 26.7 tonnes per hour (enough for a total production of 3200 m^3/day as per the original project plan), with actual steam consumption of 11.26 tonnes per hour.

The project cost was split evenly between two major components: the MED plant and other infrastructure related costs, including the sea water system and intermediate coupling loop (ICL). The installed sea water supply system and ICL was enough to produce 3200 m^3/day of potable water despite the 1600 m^3/day capacity of the MED plant.

In 2021, the KANUPP K1 reactor began the process of permanent shutdown, and thus the NDDP is also currently in shutdown condition. The NDDP will be shifted to the site of reactors K2 and K3 for continued operations. The nuclear desalination demonstration project at the K1 reactor is estimated to have avoided approximately 287 Mt of life cycle CO_2 eq emissions per year (IAEA, 2014).

During its 11.6 years of operation with the K1 reactor, the NDDP produced 5 080 800 m^3 of desalinated water. The total revenue produced during its operational life is about 2.42 billion Pakistani rupees (approximately US $13 million).

Factors impacting the cost of desalinated water

Many factors have affected the cost of water produced by the NDDP. The higher cost of investment in infrastructure with double capacity had a negative impact as a result of the higher value of the fixed cost and running cost of bigger electrical loads. The NDDP had no backup heat source, and so it remained unavailable during KANUPP shutdowns. The non-redundancy of the NDDP components also had an effect on availability, which included frequent failure of the sea water pump. The water produced at the NDDP met all of KANUPP water needs, with a daily consumption of about 302 to 378 m^3 and a total reservoir capacity of about 3200 m^3. KANUPP was the only off taker of water, and so after filling all reservoirs in about two to three days, the NDDP would be shut down.

The cost of desalinated water is based on the overall availability of 64% (i.e. 85% availability of NDDP during KANUPP operations, with its annual availability of 75%). Of the total cost, fixed costs account for 48.6%, electricity cost 22.7%, labour cost 12.7%, heat cost 6.3%, maintenance cost 5.5% and chemical cost 4.1%. The higher values of fixed and electricity costs are due to higher investment in the sea water system and the ICL, and in the bigger electrical loads of these systems.

The cost of water produced by the NDDP was calculated as US $2.15/$m^3$, which is much higher than the international benchmark of US $0.75/ m^3 to $0.95/$m^3$ for nuclear desalination plants utilizing the MED technology. The first major factor contributing to the higher cost is higher specific investment cost as compared to the international benchmark. The second major factor is the overall availability factor compared to other nuclear desalination plants that operate at above 90% availability, given the higher availability of the nuclear power plant, backup heat sources and redundancy in components.

Water quality

The water produced using the NDDP is of high quality and may have a very high commercial value as drinking water, with small value additions through remineralization. Product water from RO plants normally produce water with total dissolved solids (TDS) of 300 to 400 parts per million (ppm). The NDDP produced desalinated water with TDS < 50 and conductivity of 25 microsiemens per centimetre.

Conclusion and outlook

Because all of the water needs of KANUPP were met by the NDDP, the desalination project is considered a success. Potentially lower quality water, which could have been supplied by water tankers, would have cost more than the product water from the NDDP. The planned construction of a thermal desalination plant using the MED technology will produce about 40 000 m^3/day from the excess steam of the K2 and K3 reactors. The two reactors, together totalling 2200 MW of capacity, will then be able to use the desalinated water for operations.

The water produced using the NDDP is of high quality and may have a very high commercial value as drinking water, with small value additions through remineralization.

District heating

District heating systems distribute heat through a pipe network for industry, buildings, and agricultural uses. District heating systems exist in many countries across Europe and in North America and are now being built in East Asia. The district heating sector, which still primarily depends on fossil fuel, was responsible for an estimated 1.2 Gt of CO_2 emissions in 2020 (IEA, 2021f; IEA, 2022a). Approximately 40% of global district heating networks serve the industrial sector, but this share is much higher in China, where more than 50% of the country's district heat is consumed by industry. While many countries are working to add low carbon district heating, fossil fuels still made up about 89% of all global district heat sources in 2020 (IEA, 2021f). The heating sector requires a complete shift in order to achieve decarbonization goals – in the IEA NZE, 90% of industry heat in 2050 is met by renewable and low-carbon sources (IEA, 2021c).

Current market

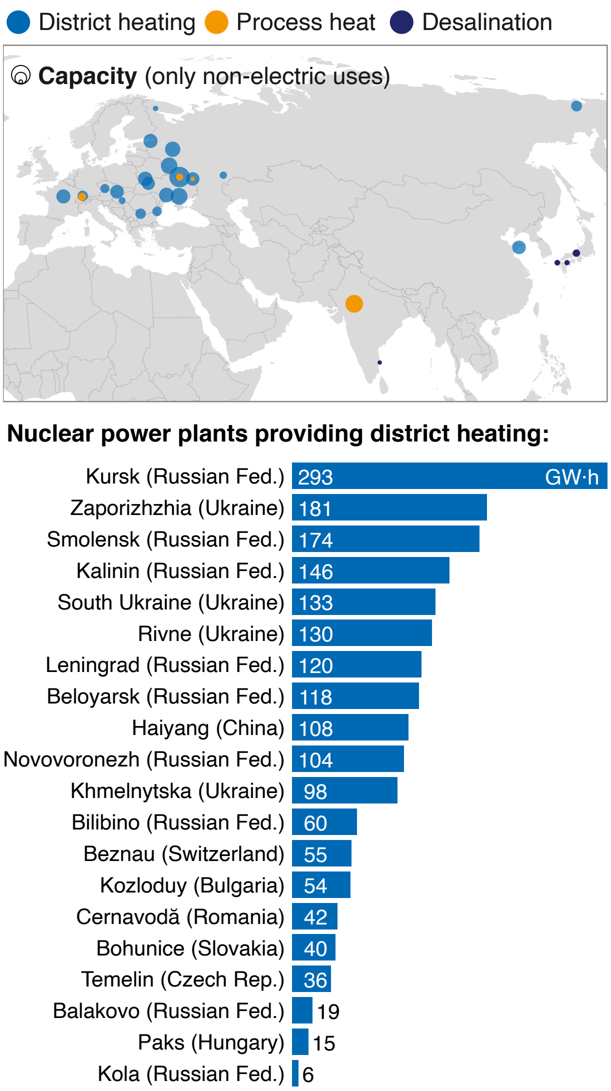
China, Europe and the Russian Federation are responsible for more than 90% of global district heat production, and therefore have a critical influence on the average carbon intensity of the district heating sector (IEA, 2021f). China is the world's largest producer of district heat, responsible for more than 35% of global district heat production. Emissions from China's district heating sector quadrupled between 2000 and 2020, and on average are more carbon intensive than district heating anywhere else in the world. To achieve net zero emissions, the IEA suggests that China will need to nearly halve the carbon intensity of its district heat production by 2030 (IEA, 2021c), which may prove to be increasingly challenging as China continues to expand its district heating capabilities.

In 2020, total district heating production worldwide amounted to 16 EJ, a 2.3% increase from 2019. The growth was driven by China and the Republic of Korea, each of which experienced 7% growth in district heating production (IEA, 2021f). While the Republic of Korea's 7% growth is much smaller than growth in China, its district heat production has nearly doubled since 2000. The district heating sector is also growing in the United States (IEA, 2021f). These countries both operate multiple nuclear power plants and are constructing new nuclear plants, making them candidates to use nuclear heat for district heating purposes in order to help them fuel their growing district heating sectors.

Opportunities for nuclear

Nuclear heat is well suited to meeting decarbonized district heating needs. Nuclear energy supplied more than 2 TW·h of electrical equivalent heat from 55 nuclear reactors in nine countries for district heating in 2021 (IAEA, 2021b), as shown in Figure 12.

Figure 12. Nuclear energy utilized for non-electric applications in 2021.



*Source: based on data from IAEA (2021b) and IAEA estimates for the China Haiyang plant based on data provided by SPI China. Note: the values shown measure thermal energy converted to electrical energy using the following formula: electrical equivalent GW·h=1.16 * total heat measured in giga calories * 0.3, unless otherwise specified by a Member State to the IAEA.*

Box 5: Contributed by VTT Technical Research Centre of Finland

Small nuclear reactors: A cost efficient option replacing fossil fuels in the district heating grid of the Finnish capital region

According to 2020 figures, the Helsinki region still uses a large share of coal (40%) and gas (40%) in units generating district heating and electricity. The fossil fuel share remained large despite 2020 being a relatively warm year and recent investments in large heat pumps and biomass fuelled units. Existing fossil fuelled district heating capacity consists of 1.3 GW of district heat from coal, 1.1 GW of district heat from natural gas combined heat and power (CHP) units and 1.5 GW of district heat from natural gas heat-only boilers. Replacing these fossil fuels for district heating requires significant investments in new energy technologies for district heat production.

A recent study by Pursiheimo et al. (2022) examines two alternative investment pathways involving: (i) district heating heat pumps from low quality heat sources; and (ii) heat only and CHP small modular reactors (SMRs). The study did not examine a third pathway for high quality heat sources because cities have already utilized all available high quality heat sources (e.g. wastewater, local industry excess heat and data centres). However, the study scenarios assume that new data centres with 200 MWe of heat capacity would be built before 2030.

For both investment pathways, three climate ambition levels were studied: 1) phasing out coal; 2) phasing out coal and gas CHP units; and 3) replacing gas in gas boilers with gaseous chemical products such as hydrogen created from low carbon energy sources. In addition, a range of sensitivities were analysed, including varying electricity, fuel and CO_2 prices, allowing or disallowing further investments in biomass, and varying the capital costs of new investments. All alternative scenarios were compared by modelling the existing system and investment with an optimization model that minimizes the costs (maximizes the profits) of investments and annual operations under given assumptions and constraints.

All SMR based scenarios had lower total annual costs than all of the heat pump based scenarios. SMR scenarios have high investment costs, but very low annual operation costs. The heat pump option is very sensitive to electricity prices and some technologies, such as combined district heating and cooling systems, which become competitive in the Finnish climate only with 20 €/ MW·h annual electricity prices. The SMR option is somewhat less sensitive to varying electricity market prices, although the study models an investment in CHP SMR units with a 60 €/MW·h annual average electricity market price.

The model typically invested only in SMRs or a combination of biomass fired boilers and large heat pumps. The heat pump technologies that were included in the model benefitted significantly from lower capital expenditure (CAPEX) values. The mix of biomass and heat pumps selected by the model varied depending on operational expenditures (OPEX) and CAPEX assumptions. However, the investment level of SMR units is somewhat less flexible to an increase in CAPEX. The model observed a decreasing amount of SMR investment as capacity increased, but the level of investment in SMR remained very competitive with up to a 40% increase in CAPEX compared to default assumptions.

Finally, although the study results show that the SMR option has an advantage over the heat pump option under the model assumptions used, it is important to note that the SMR technology is still under development and heat pump technologies are taking large steps in terms of technical development. This issue greatly affects the investment cost of these technologies, and therefore the sensitivity analysis concerning CAPEX should be examined with due care.

District heating is the largest non-electric application of operational nuclear power plants. Nuclear district heating systems can be economically delivered from up to 160 km away at competitive cost and with minimal heat loss, making it an attractive solution for heavily populated cities and remote areas alike (IAEA, 2019). District heating provided about 10% of final energy demand for space heating in 2020, and this rises to more than 20% by 2050 in the IEA NZE (IEA, 2021c). Replacing fossil fuel heating in buildings with nuclear district heating has an enormous potential with a real possibility for making an impact on climate change efforts. In the IEA NZE, 91% of building heat in 2050 is met by renewable and low carbon sources (IEA, 2021c).

Nuclear district heating systems have the added capability of producing low carbon electricity as well as heat, creating a multiplier effect outside of the power sector via the electrification of heat pumps. Additionally, infrastructure to provide district heating can easily be converted from fossil fuels to low carbon sources like nuclear power, using the existing district energy network (IPCC, 2022a).

A study by the French Alternative Energies and Atomic Energy Commission (CEA) found that replacing 60% of fossil fuels and 40% of waste incineration district heating systems with 100% nuclear cogeneration could avoid up to 200 000 tonnes of CO_2 per TW·h (OECD NEA, 2013).

Hydrogen production

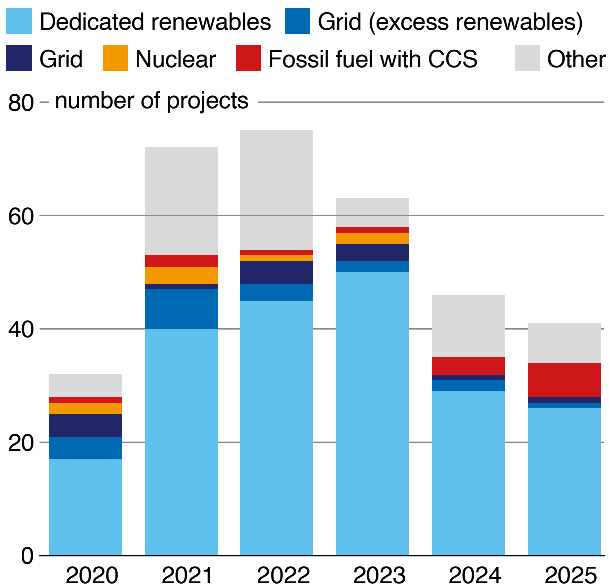
Nuclear heat can also be used in a wide variety of industrial applications. Several countries are currently studying the economic and technical viability of using nuclear electricity and process heat for hydrogen production. Hydrogen use can have many benefits across its varying use cases, including aiding with economy wide decarbonization and security of supply.

Current market

While hydrogen is primarily used as a chemical feedstock today, there are opportunities for hydrogen deployment in the power, transport and industrial sectors. Hydrogen may help to diversify energy and fuel mixes and boost backup capacity to serve as an energy storage mechanism. Different electrolyser technologies use either electricity (low temperature electrolysis) or a combination of heat and electricity (high temperature electrolysis) to produce hydrogen. Any electricity or heat that is produced in excess of real time demand may be used to instead produce hydrogen, which can then be stored for future electricity use, or used as transport fuel or input into industrial processes, such as steel or ammonia production (IEA, 2021g).

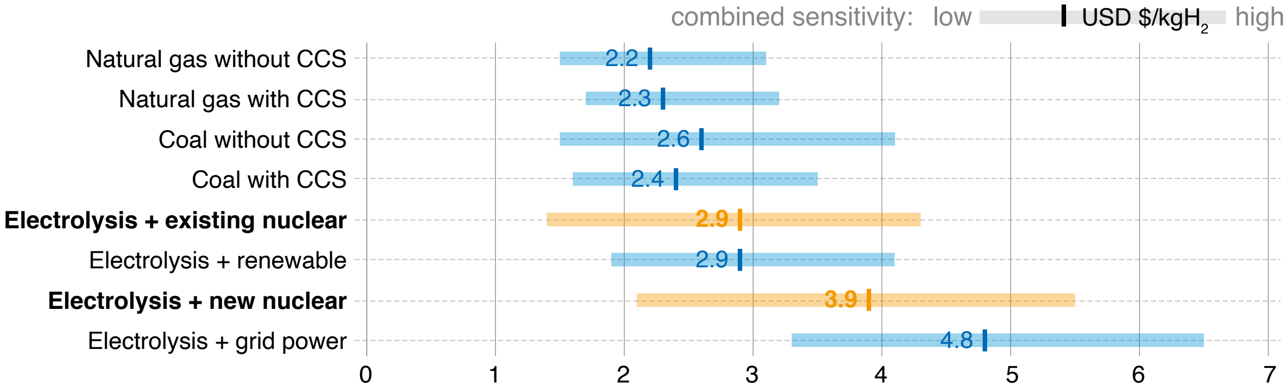
Figure 13 shows hydrogen projects that are under development by the year they are anticipated to come online, demonstrating the expected demand for low carbon hydrogen production in the near term. Hydrogen produced from low carbon energy sources is itself low carbon. Nuclear power provides the additional benefit of heat, which can improve the efficiency of the electrolyser. Nuclear hydrogen production can thus help to decarbonize historically hard-to-abate sectors, for example aviation or shipping, or energy-intensive industrial processes. In 2021, nuclear power plants provided 250 GW·h of dedicated process heat (excluding district heating production) from 9 reactors in India, the Russian Federation and Switzerland (IAEA, 2021b).

Figure 13. Historical and potential hydrogen production projects, by year online.



Source: based on IEA (2021h).

Figure 14. Hydrogen production cost by technology.



Source: based on data from IEA (2019a) and nuclear data from IAEA (2021b). Note: Assumptions refer to Europe in 2030. Natural gas price — US $ 8/MMBtu (Metric Million British Thermal Unit), renewable electricity price — US $40/MW·h at 4000 full load hours at best locations, existing nuclear electricity price — US $30/MW·h at 7900 full load hours, grid electricity price — US $114/MW·h. Sensitivity analysis based on variations in capital expenditures, operational expenditures, fuel costs and carbon prices where applicable. CCS refers to carbon capture and storage.

Major technological barriers for hydrogen production include scaling up current hydrogen electrolyser demonstration projects and shifting use cases from petrochemicals and fertilizers to other industries. As is the case for desalination and district heating, the majority of hydrogen is produced from fossil fuels today. In 2020, 80% of hydrogen was produced using natural gas reforming and coal gasification, and the remainder is a by-product of other industrial processes. Hydrogen production in 2020 accounted for approximately 900 Mt of CO_2 emissions (IEA, 2021g).

Opportunities for nuclear

To reach net zero by 2050, the IEA estimates that hydrogen demand would need to grow to six times higher than today (IEA, 2021c). Low carbon hydrogen is expected to account for about 7% of final energy demand in 2050 (Wood Mackenzie, 2021). The global low carbon hydrogen market will be dominated by Europe in the near term, but it is expected to be outpaced by China and the United States in the late 2030s (Wood Mackenzie, 2021). Europe's growing low carbon hydrogen demand may be met by renewables and existing nuclear power plants, but as Chinese and US low carbon hydrogen demand quickly outpaces available supply, there will be massive opportunities to pair hydrogen with nuclear power plants. China will be an especially promising market, as the country currently has the most planned nuclear capacity of any country worldwide (IAEA, 2021b).

Like district heating and desalination, nuclear hydrogen must be competitive on a cost basis with either the incumbent fossil fuel methods, or with renewables as a low carbon alternative. Depending on various factors, including location and discount rates, nuclear new build in combination with hydrogen generation can be competitive with other fuel options (see Figure 14). Nuclear power can provide 24/7 availability of both electricity and heat to support the efficient production of hydrogen through different processes. Using nuclear power to produce hydrogen can provide strong incentive for operating nuclear power plants as a means of avoiding curtailment, and the hydrogen can also be paired with renewable energy generation to create a decarbonized and flexible energy system (see Spotlight 4). Regional and national nuances will determine the best uses for hydrogen in each country, and a combination of hydrogen applications in each sector will ultimately contribute to global decarbonization goals (see Spotlight 5). The option of using existing nuclear capacity for hydrogen production is currently being explored at the IAEA. The Agency is bringing together utilities with various hydrogen production projects and examining when and how hydrogen production makes sense economically. An IAEA study, Building the Business Case for Hydrogen Production with Operating Nuclear Power Plants, will be published in 2022, and will include case studies of existing nuclear hydrogen demonstration projects to assess project similarities and differences.

Spotlight 4:

Balancing solar generation with nuclear hydrogen at the Palo Verde Generating Station

PNW Hydrogen, LLC, an affiliate of Pinnacle West electric utility holding company, recently secured $20 million of funding from the US Department of Energy (DOE) to demonstrate a nuclear hydrogen project at the Palo Verde Generating Station. The project will study the production of nuclear hydrogen during peak solar output hours when solar power may otherwise have been unusable by the electricity system.

Hydrogen stored at the project site can be used to produce ~200 MW·h of electricity. The electricity will be used when power demand is high and there is insufficient solar irradiation. It could be used, for example, in the production of fuels and chemicals. The DOE states that "The demonstration project will provide insights about integrating nuclear energy with hydrogen production technologies in high-renewable energy systems and inform future clean hydrogen production deployment at scale." (US DOE, 2021)

A techno-economic assessment of nuclear hydrogen from the Palo Verde plant shows that nuclear hydrogen co-fired with natural gas in a peaking turbine is economical when compared to battery storage with a duration of more than four hours (PNW Hydrogen LLC, 2021). The hydrogen electrolyser at the site will have a capacity of approximately 17 MW and will be installed with a compression and storage system. The demonstration project will seek to generate nuclear hydrogen during hours when solar output is high, and the nuclear energy is not needed for electricity generation. The stored nuclear hydrogen will be co-fired as a 30% mix with 70% natural gas in the Saguaro Power Plant unit 3 gas fired peaking power plant, also owned by Pinnacle West (PNW Hydrogen LLC, 2021).

The economic benefits of co-firing hydrogen in a natural gas turbine increases during periods of high gas prices. In this case, the nuclear hydrogen production displaces relatively expensive natural gas as fuel, decreasing the cost of producing electricity.

Solar output grew rapidly in Arizona and neighbouring California over the past decade, from 504 MW of installed solar capacity in 2010 to 16 885 MW in 2020 (EIA, 2022a). Installed solar capacity in California and Arizona is expected to grow at a 10% compound annual growth rate to 2025. At the same time, instances when the region had too much solar generation to be economically delivered to customers ('curtailment') reached 1.5 MW·h of utility scale solar in 2020 (EIA, 2022b).

Spotlight 5:

Bruce Power nuclear hydrogen development

The Canadian nuclear utility, Bruce Power, launched a study in 2021 with the Canadian Nuclear Innovation Institute to examine the technical and business case for nuclear hydrogen from the Bruce nuclear power plants in Ontario, Canada (NII, 2021). The company aims to launch the nuclear hydrogen demonstration project in 2023 (Dalton, 2022). Bruce Power is reported to have invested about 2.3 billion Canadian dollars in the project, with a total cost of 15 billion Canadian dollars (approximately US $10 billion) (Dalton, 2022).

As demand for low carbon hydrogen is expected to pick up pace, Ontario's >90% nuclear, hydropower and renewable power mix could give it a global advantage in producing low carbon hydrogen (NII, 2021). Ontario's existing oil refining and chemical industries, in addition to high demand for home heating, highlight examples of possible use cases for local hydrogen demand.

Nuclear hydrogen co-fired with natural gas can be economically competitive with long duration battery storage.

Prospects for advanced reactor designs

Various types of advanced reactor designs offer smaller capacities and higher temperatures, with many added benefits. These designs have a wide array of applications, and their smaller capacity (as well as their projected lower construction costs), in addition to high temperature output, may lead to their increased use as a low carbon heat source for buildings, industrial processes and transport fuels. Advanced reactor designs have more siting flexibility because of lower cooling water needs and smaller projected emergency planning zones compared to higher capacity nuclear power plants. Several development projects may hasten the deployment of lower capacity advanced reactors, potentially paving the way for targeted applications such as desalination, district heating and hydrogen production.

Japanese and US companies collaborate to develop sodium fast reactor

In January 2022, the Japan Atomic Energy Agency (JAEA), Mitsubishi Heavy Industries (MHI), Mitsubishi Fast Breeder Reactor Systems and the US company, TerraPower, signed a memorandum of understanding to share data and resources related to the development of an advanced sodium fast reactor (TerraPower, 2022). The project, funded in part by the DOE Advanced Reactor Demonstration Program, will culminate in a commercial advanced reactor planned to be operational by 2028 (US DOE, 2021). The JAEA and MHI will provide technical assistance and data for construction of the demonstration project. The JAEA has been researching and operating prototype sodium cooled fast reactors for decades (JAEA, n.d.).

High temperature gas cooled reactor in China makes history — A long time in the making

In December 2021, the 200 MWe/500 MWt Shidao Bay high temperature gas cooled reactor pebble bed module (HTR-PM) demonstration project was connected to the grid at Shidaowan, in Shandong province, China. The event made history as the first operating modular high temperature gas cooled reactor with characteristics of an advanced generation IV nuclear power system (China Huaneng, 2022). The use of HTR-PM technology for non-electric applications has been pursued for decades, since the first designs appeared in Germany in the 1980s (Barnert et al., 1984). The two units have an output temperature of 750°C, which could be used for industrial heat applications and hydrogen production via a high temperature steam electrolyser. This reactor technology could be used for other non-electric applications as well. In 2017, for example, China signed an agreement with Saudi Arabia to deploy this reactor technology for desalination applications (CAEA, 2017).

High temperature gas cooled reactors serving low carbon hydrogen needs in Japan

In April 2022, the JAEA and MHI announced the establishment of a nuclear hydrogen demonstration project, which could be enabled for large scale hydrogen production in future, in combination with a high temperature gas reactor. Both Japan's Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (METI, 2021b), and the country's Strategic Energy Plan (METI, 2021a), mention the use of high temperature gas reactors for low carbon hydrogen production.

Several development projects may hasten the deployment of lower capacity advanced reactors, potentially paving the way for targeted applications such as desalination, district heating and hydrogen production.

04

Climate resilient nuclear infrastructure: Mapping future climate, weather and water risks

Key messages:

- **Global energy infrastructures will be increasingly exposed to frequent and severe climate hazards.**

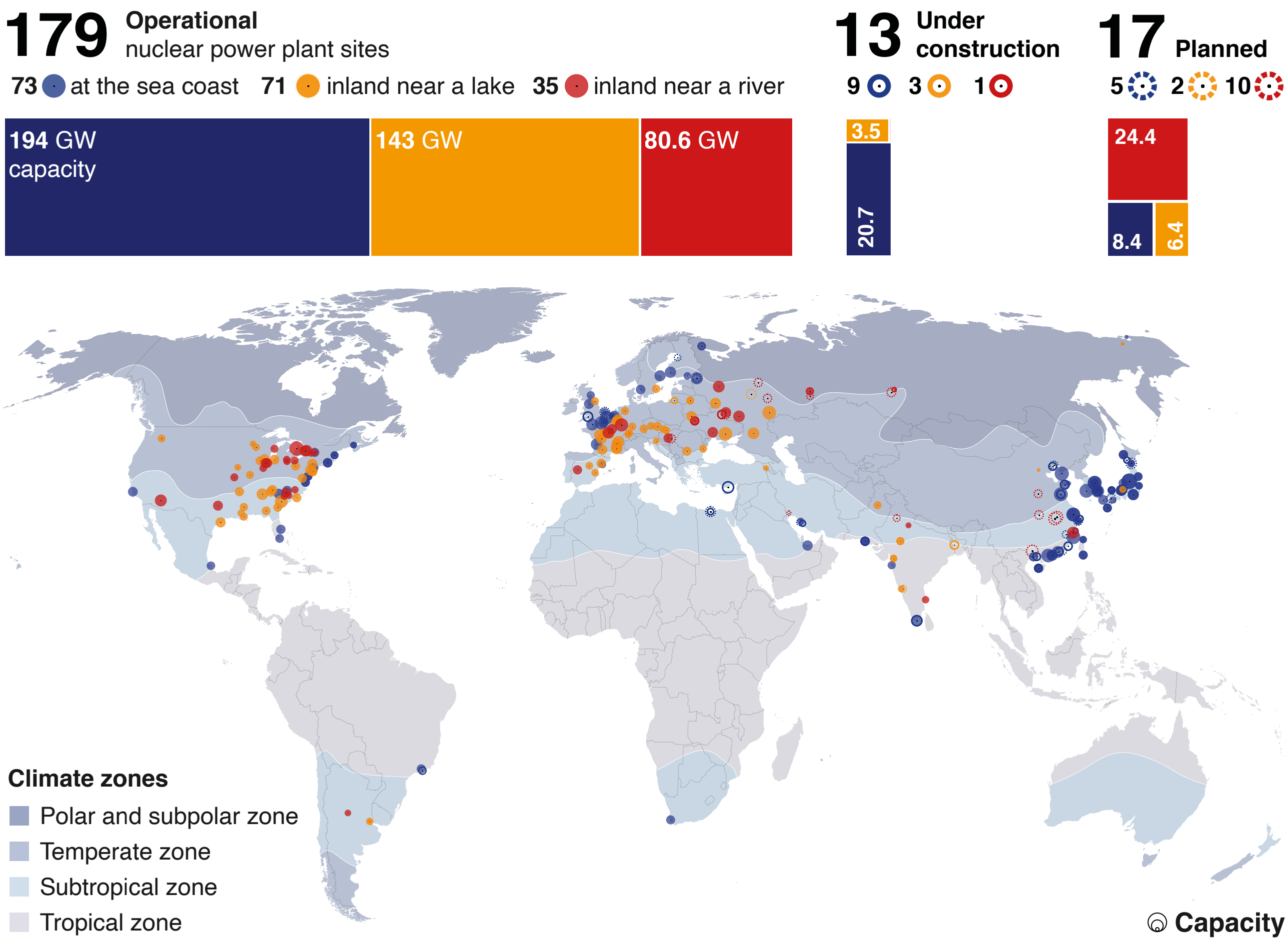
- **The nuclear sector is well prepared to face changing environmental conditions in the foreseeable future.**

- **New climate hazards, including compounded risks resulting from cascading, low probability, extreme weather events, must be included in the siting and design of new nuclear installations, particularly in countries embarking on nuclear power.**

- **Integrating the latest advances in climate science, including the better representation of future climate risks at the local scale, can greatly contribute to strengthening the climate resilience of nuclear infrastructures and foster the security of electricity supply.**

After providing an overview of historical disruptions in nuclear production caused by severe weather events, this chapter takes stock of the latest findings in climate science and highlights key trends in climate, weather and water risks that may affect nuclear sites in the future. It also introduces novel approaches to risk assessment, including in relation to safety.

Figure 15: Location of nuclear power plant sites: operational, under construction and planned.



Source: IAEA (2021b). Note: each bubble represents a nuclear site. Bubble size indicates installed capacity. The contours of climatic zones are indicative; their borders are likely to evolve with the changing global climate. Nuclear sites with additional reactors under construction or planned are counted as a single plant site.

The first mapping of nuclear operations and climatic conditions

The latest IPCC message is unequivocal: all infrastructures can be affected by extreme and slow onset events, resulting in economic losses, disruptions of vital services and impacts to well-being. Without adaptation measures and new design standards, energy infrastructures will be exposed to changing environmental and water conditions that will impact their reliability and competitiveness. A natural disaster related to either a weather, climate or water hazard has occurred every day on average over the last 50 years – killing 115 people and causing US $202 million in losses daily (WMO, 2021).

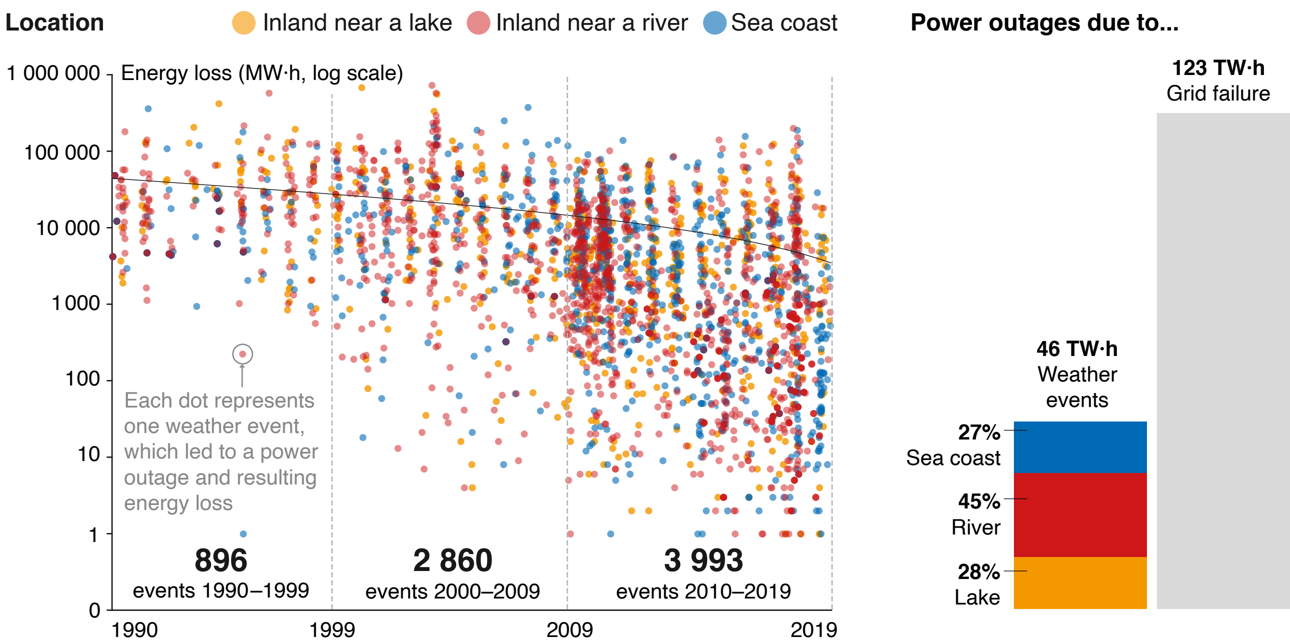
Without immediate and decisive climate action, the severity of climate impacts will result in decoupled and long lasting damages (IPCC, 2022a). The location of nuclear plants the climatic conditions under which they operate and the availability of the water that is indispensable to plant cooling will determine their individual exposure to future climate risks (see Figure 15). The remainder of this chapter presents detailed estimates of future climate impacts, collected by the IPCC, in an effort to provide an original framework to design the climate resilience of nuclear power plants.

Insights from historical, weather related disruptions in nuclear production

Adverse weather conditions that routinely disrupt nuclear power operations have increased almost fivefold in three decades, with a notable acceleration since 2009. Despite more frequent occurrences, the incurred production losses remain modest. The power outages reported by operators provide useful insights into the overall performance of the nuclear sector in the face of extreme weather conditions (see Figure 16). Less than 50 TW·h of production losses were directly attributed to weather events globally since 1990 (i.e. less than 0.1% of nuclear electricity generated over the same period), leaving annual capacity factors at very high levels (IAEA, 2021). For almost three quarters of reported events, production outages generally concern plants that are located by rivers or lakes. The continuity in production directly depends on their strictly regulated access to water bodies, ensuring minimal impact on ecosystems. By contrast, interrupted access to the grid caused almost three times more production losses than weather events.

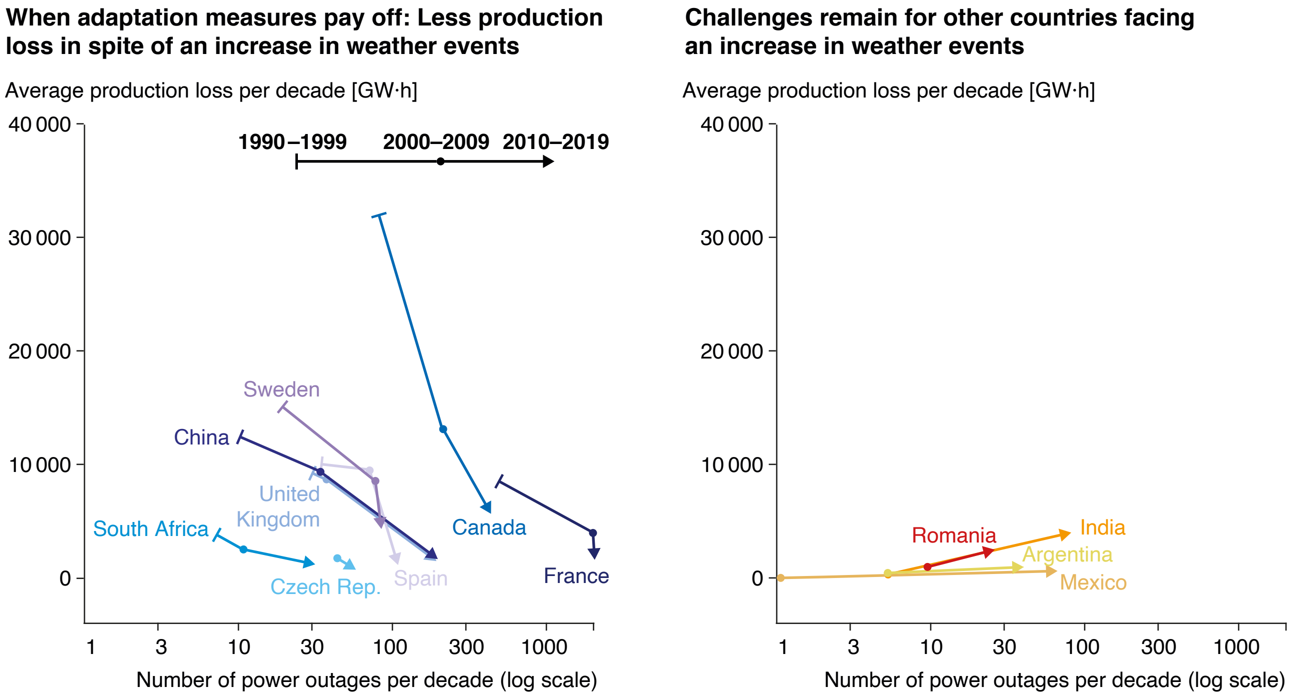
On average, the impacts of weather incidents diminished appreciably in many countries thanks to revisions to regulatory regimes and improved

Figure 16: Reported nuclear power outages due to weather events, by plant location.



Source: based on data from the IAEA (2021b).

Figure 17: Country level nuclear production losses between 1990–2019.



Source: based on data from the IAEA (2021b).

operational experience. Nuclear plants in Canada, China and France, which experienced numerous forced outages following acute weather episodes, saw a steady decrease in decadal economic losses since the 1990s (see Figure 17). Other nuclear sites, particularly those located in subtropical areas, such as Argentina, India and Mexico, did not report production disruptions due to weather and water conditions prior to 2000, but have suffered both more frequent outages and higher average production losses since this time.

Overall, the evolving nature of weather events has led many countries and regulators to revise their safety guidelines so as to maintain or strengthen the overall resilience of nuclear operations. Episodes of extreme heat, lack of cooling water, frazil ice phenomena or floods were at the origin of specific adaptation measures (OECD NEA, 2021). Plant designs were adapted with a variety of engineering solutions: (i) a reduction of the usage and consumption of cooling water; (ii) modification of water intake; (iii) investigation of on-site water production; (iv) increase and more efficient use of heat exchanger capacity; and (v) the redesign of condensers to offset river intake of warmer water.

Extreme weather events exhibit strong seasonal patterns, generally peaking during the summer months when electricity needs are the greatest in some regions such as North America, notably because of space cooling requirements. Recent years have seen a widening of the peak outage season towards spring and autumn. The IPCC reports more frequent and lasting episodes of drought and heatwaves worldwide. Operations at many plants located in high water stress areas are thus exposed to increasing risks throughout the year. Anticipating weather and water related events by resorting to new predictive tools, such as seasonal and sub-seasonal forecast models, and planning for the availability of individual power infrastructure assets is essential to mitigate the economic and societal impacts of such events (see Figure 18).

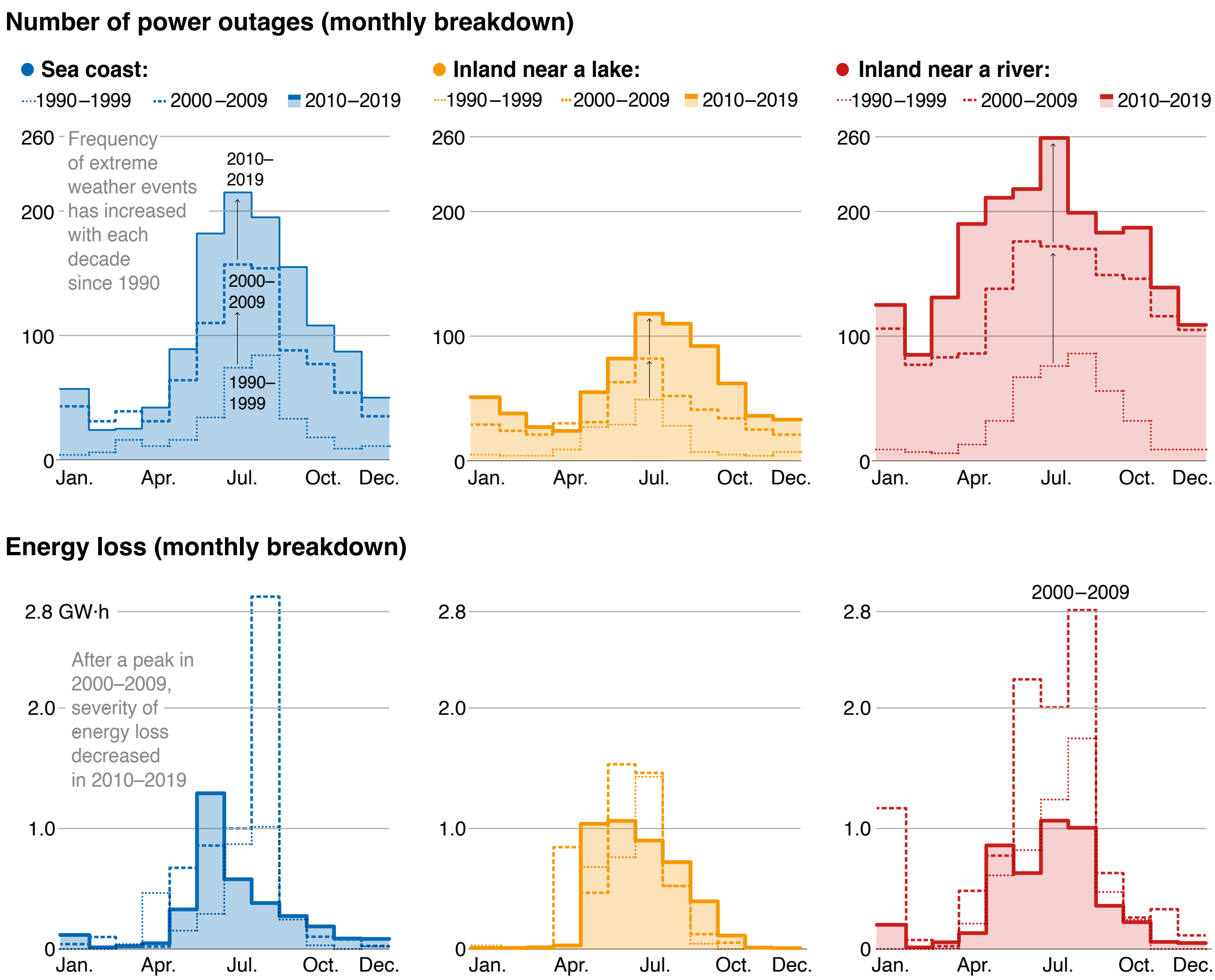
Characterization of future climate impacts on nuclear sites

Integrating the latest advances in climate science, including the better representation of future climate risks at the local scale, can greatly contribute to strengthening the climate resilience of nuclear infrastructures. The latest IPCC assessment lays out contrasted outcomes on the future state of the climate and extreme weather occurrences through distinct emission pathways and narratives.

A comprehensive climate framework for risk assessment

The Shared Socioeconomic Pathways (SSPs) describe alternative socio-economic futures in the absence of climate policy intervention. SSP1 outcomes, for example, are compatible with sustainable development objectives and the Paris Agreement, keeping global temperatures well under two degrees, as shown in Figure 19 (O'Neill et al., 2017; Riahi et al., 2017; IPCC, 2021). Conversely, the SSP3 storyline exhibits regional rivalry, leading to high temperature increases. SSP2 is a middle of the road situation. Other scenarios leading to unresolved global inequalities (SSP4) and an unlikely fossil fuel intensive future (SSP5) are not reported here. The combination of SSP narratives and climate projections (i.e. IPCC Representative Concentration Pathways or RCPs) provides an integrative framework for climate impact and policy analysis. The likelihood and severity of extreme weather occurrences will ultimately depend on the realization of these climate futures. Extreme heat and rainfall episodes could impede the reliability of nuclear plants and the timely achievement of carbon neutrality. It is therefore important to establish a framework that delineates the boundaries of contextual risk assessments for nuclear sites. The IPCC has translated the complexity of observed and modelled climates through comprehensive overviews that group the

Figure 18: Monthly patterns of nuclear production losses, 1990–2019.

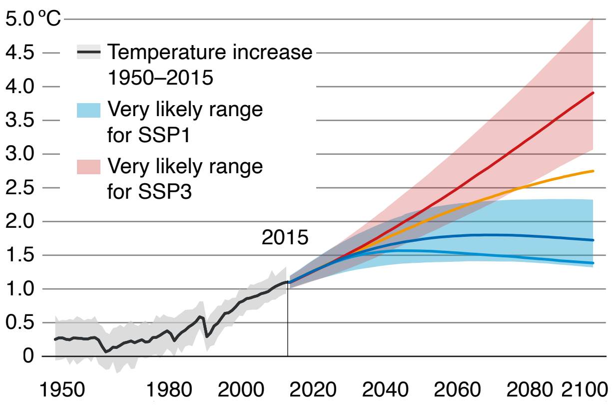


Source: based on data from the IAEA (2021b).

Figure 19: Distinct climate outcomes under various IPCC Shared Socioeconomic Pathways.

Global surface temperature increase

Scenario	Global surface temperature change	Socio-economic challenges for mitigation and adaptation
SSP1 Sustainability	+1.9°C / 2.6°C	**Low**
SSP2 Middle of the road	+4.5°C	**Medium**
SSP3 Regional rivalry	+7.0°C	**High**



Source: IPCC (2021, 2022).

Increase in frequency of extreme heat and rainfall

Projected increase in the frequency of high temperatures and heavy rainfall in one day, which only occurred once every ten years on average in a climate with minimal human influence.

Extreme heat

Past	Present	Future global warming levels		
1850–1900	**1°C** warming	**1.5°C** warming	**2°C** warming	**4°C** warming
Once every 10 years	Now likely to occur **2.8 times**	Likely to occur **4.1 times**	Likely to occur **5.6 times**	Likely to occur **9.4 times**

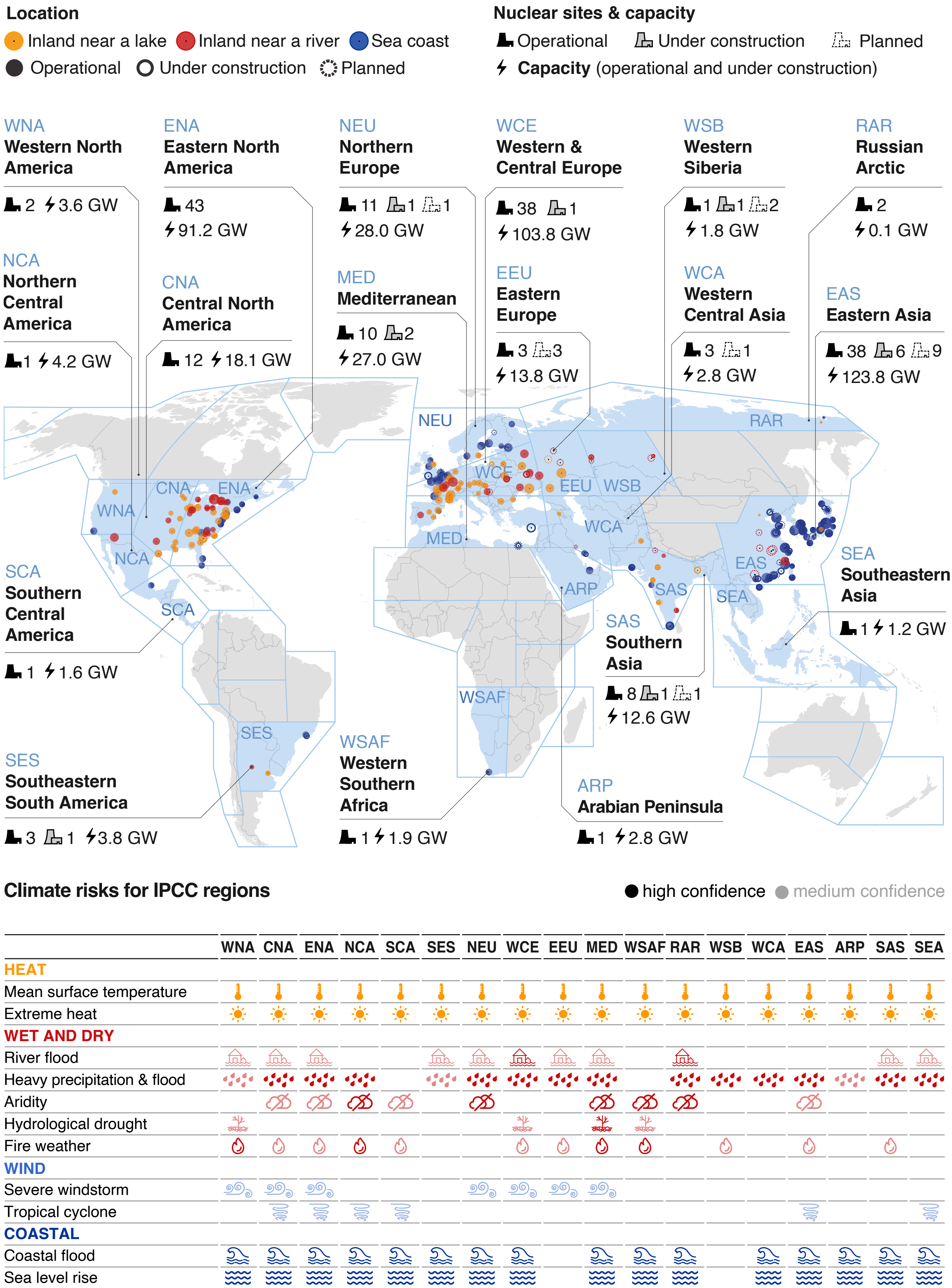
Extreme rainfall

Past	Present	Future global warming levels		
1850–1900	**1°C** warming	**1.5°C** warming	**2°C** warming	**4°C** warming
Once every 10 years	Now likely to occur **1.3 times**	Likely to occur **1.5 times**	Likely to occur **1.7 times**	Likely to occur **2.7 times**

results in so-called reference regions, representing consistent regional climate features (Iturbide et al., 2020). This geographical coverage allows for a first qualitative overview of regional climate risks that could affect the 211 nuclear sites surveyed in this chapter. The results compiled in the IPCC Working Group I Interactive Atlas cast some light on climate impacts for a large combination of parameters (IPCC, 2021). This analysis is based on the Coupled Model Intercomparison Project, 6th phase (CMIP6) model ensemble, a selection of SSP scenarios and various time horizons (short term 2021–2040; medium term 2041–2060; and long term 2081–2100). It is important to note that other climate projections are reported in the Atlas (IPCC, 2021), with a focus on specific variables, different higher grid resolutions and more detailed representations of specific regional climates that may lead to different outcomes. The 35 climatic impact drivers available in the Atlas were grouped into 7 types. Those that are directly relevant to environmental conditions affecting nuclear sites are: heat (and cold), wet and dry, and wind and coastal groups of impact. A selection of climate indicators relevant to nuclear site locations (e.g., inland near a lake, inland near a river or near the seacoast) are summarized in Figure 20.

Thermal power plants need to accommodate regular restrictions on water availability. Without the rapid reversal of global emissions, all 18 regions hosting nuclear sites will undergo further and profound environmental transformations, exacerbated by the compound risks of extreme weather events. One third of thermal power plants relying on freshwater availability for cooling are already located in high water stress areas. This is also the case for 15% of existing nuclear power plants, a share expected to increase to 25% in the next 20 years (IEA, 2021a). Over 70% of installed capacity in operation or under construction is in three regions – Eastern North America, Western and Central Europe and East Asia – all of which will face a wide variety of climate hazards in the future, including extreme heat conditions, heavy precipitation, coastal and river floods and tropical cyclones. Such climate hazards

Figure 20: Regional climate risks and climatic impact drivers.



Source: based on climate data from IPCC (2021; 2022a) and nuclear data from the IAEA (2021b). Note: Nuclear sites with additional reactors under construction or planned are counted as a single plant site.

will make the design and the implementation of resilience plans even more complex, but also central to comprehensive climate strategies. Many of these individual risks, described in detail by the IPCC, could be mitigated provided that nuclear owners and operators alike undertake the necessary adaptation steps to help face these changing conditions. The grid resolutions of climate models, sometimes under 0.5 degrees or 55 km, allows for a detailed representation of the amplitude of environmental changes expected at the level of individual nuclear sites. These scenario dependent changes are introduced in the sections below.

Heatwaves and aridity: A major source of potential vulnerability

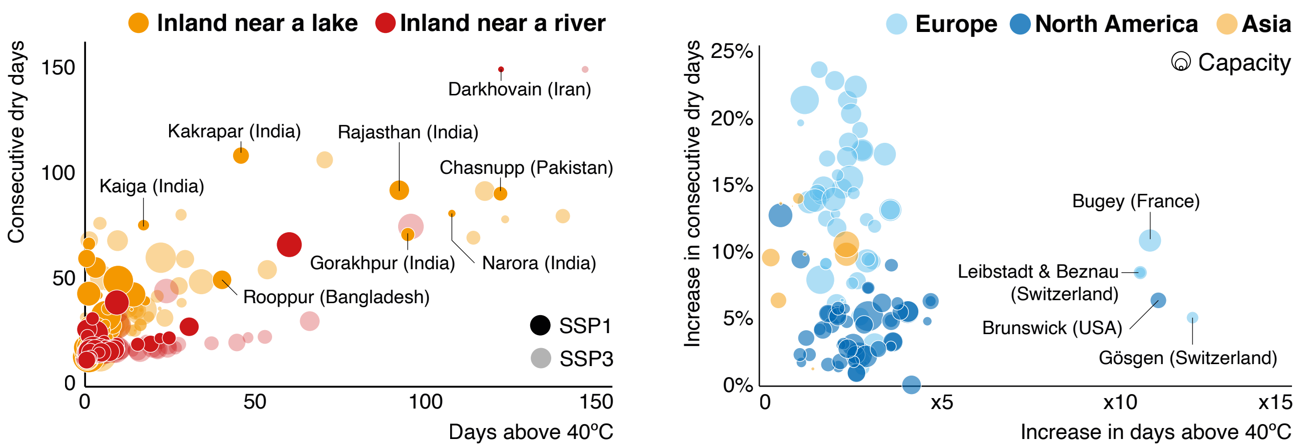
More pronounced and severe heatwaves and droughts are potentially among the most impactful extreme climate manifestations in terms of threats to the good functioning of power systems, ultimately slowing down the transition to clean energy. In 2020, 87% of electricity generated globally, including nuclear energy, other thermal power plants and hydropower, depended directly on connections to water bodies. Heatwaves alter power generation and transmission efficiencies and intensify cooling demands (IEA, 2021i). The extensive climate data surveyed by the IPCC includes notably heat and aridity indices, such as the projected maximum temperatures, the number of consecutive dry days or days above 40°C. These indices can serve as useful proxies to characterize the exposure of individual nuclear plants to future risks under various long term climate outcomes.

Extreme heat manifestations are likely to alter water availability for nuclear plants and, without adaptation measures, these manifestations may increase the risk of production disruptions at specific sites. The IPCC projections indicate that the production of lake and river based plants could be particularly sensitive to global warming in the future and may face more regular water restrictions as water outlets exceed regulatory limits (IPCC, 2021). South Asian plants will be particularly exposed to high temperatures and long lasting drought episodes (see Figure 21), as shown in the Indian context discussed below. But European plants, particularly in the South of France, could see the largest percentage increases in consecutive dry days, underlining the importance of establishing adaptation provisions associated with strict safety revisions (see Figure 21). The Palo Verde plant in the Arizona desert could see extreme temperatures above 40°C increased by almost 60% (see Figure 22). However, this plant provides a unique example of a successful design adapted to withstand and operate under severe environmental conditions. The effluents from surrounding sewage stations are treated to

Figure 21: Global exposure of inland nuclear sites to projected heat and aridity risks.

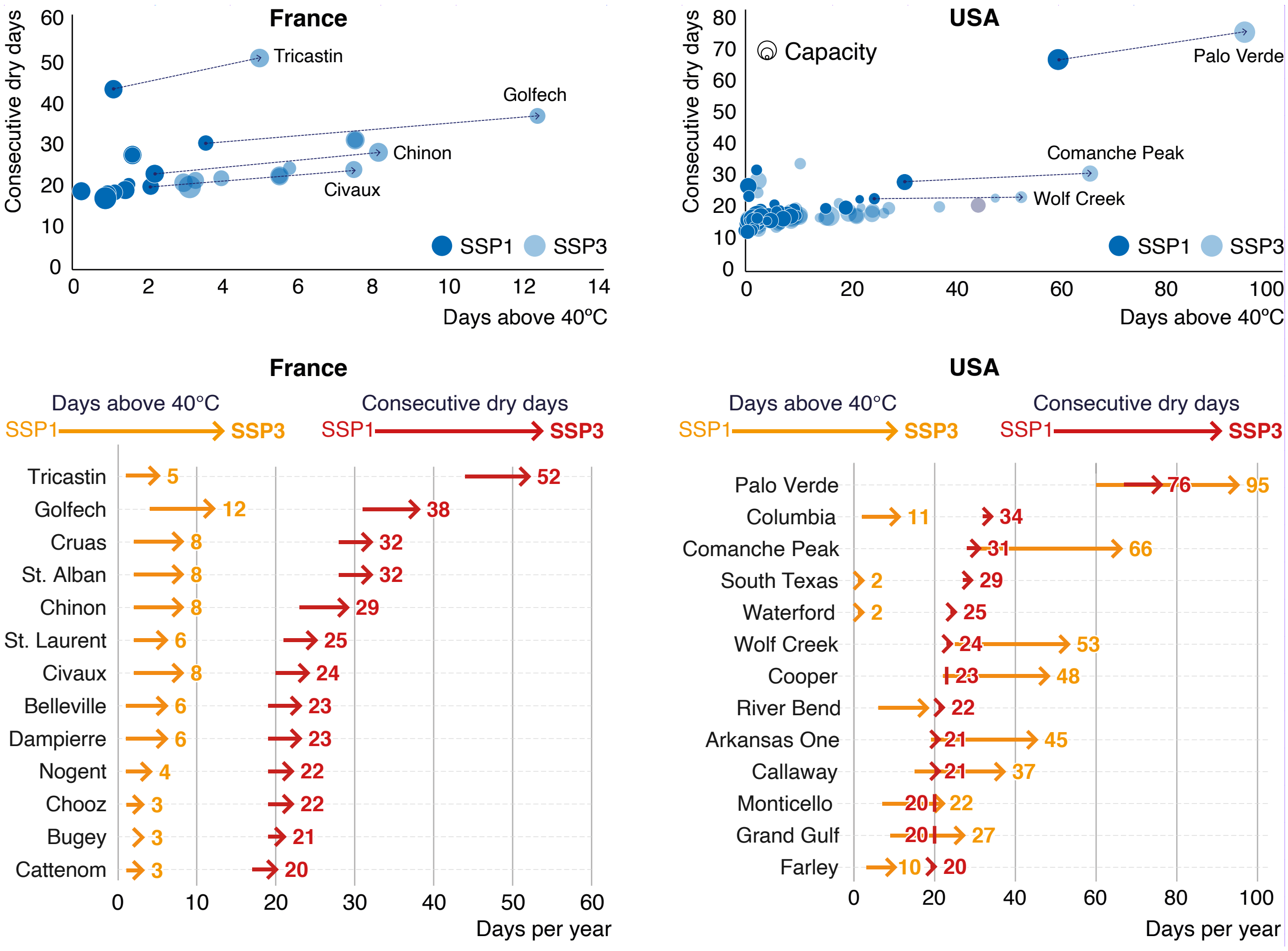
Each dot represents a nuclear site, plotted according to **heat** (days above 40 degrees) and **aridity** (consecutive dry days) in the long term (2081–2100) according to SSP1 and SSP3 scenarios.

Each dot represents a nuclear site, plotted according to the expected **increase in heat** (percentage change in days above 40 degrees from SSP1 to SSP3) and **increase in aridity** (percentage change in consecutive dry days) 2081–2100.



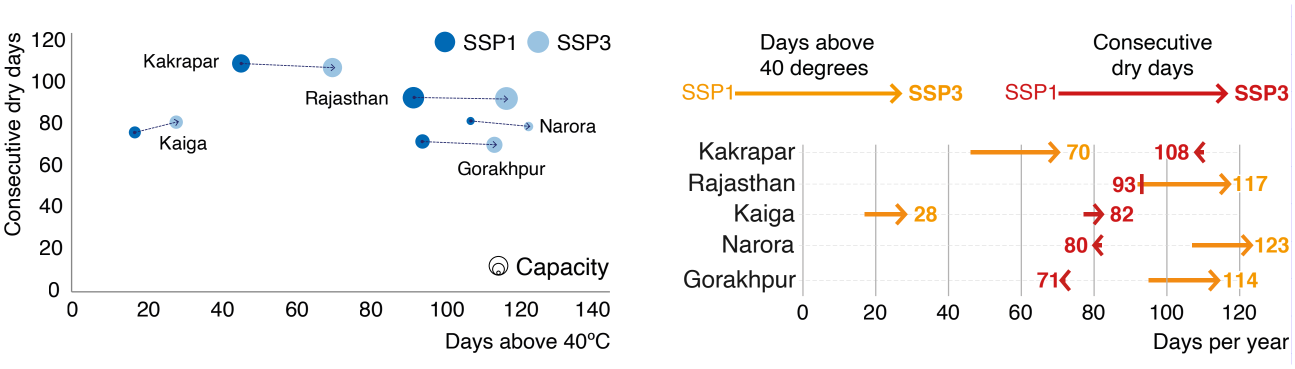
Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b).

Figure 22: Projected climate impacts on selected inland nuclear sites in France and the United States.



Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b). Charts represent long term scenarios (2081–2100).

Figure 23: Projected consecutive dry days and days above 40°C in 2081–2100 at inland NPP sites in India.



Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b).

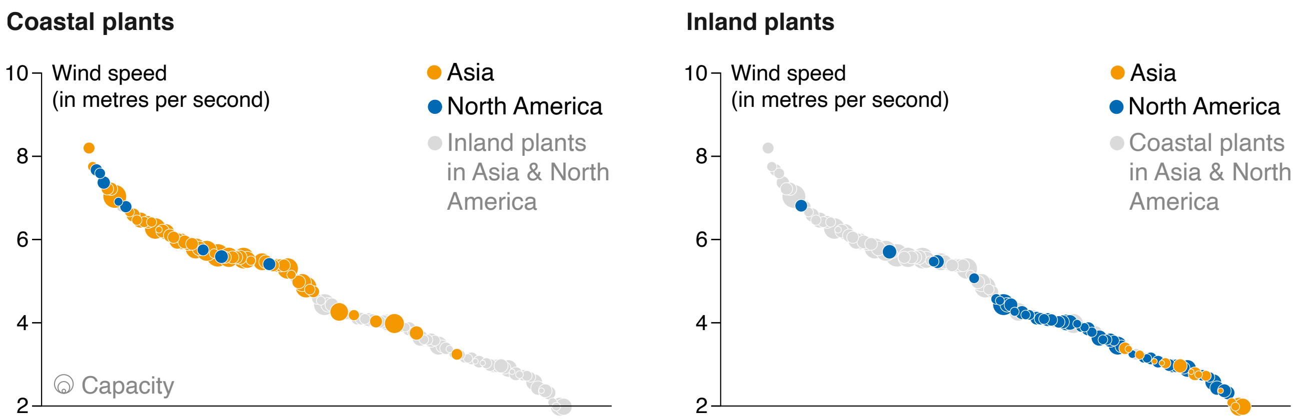
compensate for the lack of freshwater, thus cutting water consumption needs drastically. Temperature levels could reach record highs in India, pointing to further vulnerabilities for some of the inland nuclear power plants. The record heatwave that hit India in March 2022 triggered an increase in power demand and led to power outages across many states (Hrishikesh, 2022). The duration of drought episodes is not foreseen to vary substantially with global warming in the long run (see Figure 23). However, the number of days at peak temperatures above 40°C may reach 110 days or more a year, potentially impacting northern nuclear plants. Plans to reduce India's reliance on thermal coal plants and planned nuclear new build will foster the climate resilience of the electricity supply.

Other key climate risks

Intense windstorms and tropical cyclones hitting North America, and to a lesser extent Europe, are expected to increase in severity and frequency, potentially causing direct or indirect disruptions of nuclear operations. The sturdiness of a nuclear plant often prevents direct damages on-site but severe storms may impact the plants' direct surroundings and interrupt access to power transmission networks, a key source of indirect vulnerability forcing plant shutdown. One quarter of global electricity networks are already highly exposed to destructive cyclone winds (IEA, 2021a). Globally, the proportion of the most devastating category 4–5 tropical cyclones, maximum wind speeds and heavy precipitation are projected to increase with global warming (IPCC, 2021). Plants located on the eastern coast of the USA are likely to be among the most exposed to such severe storms (see Figure 24). Conversely, plants from eastern China, on the Korean Peninsula and the Japanese Archipelago, which have been confronted with intensifying typhoons since the mid 1980s, may face relatively less extreme storms in the future. The major floods accompanying hurricanes and typhoons during landfalls, or the hot, dry and windy events at the origin of fire events, can be particularly damaging to grids. In cold climates, wind speeds of 5 to 10 metres per second are strong enough to generate frazil ice, blocking the cooling sea water intake, and also forcing production outages (OECD NEA, 2021).

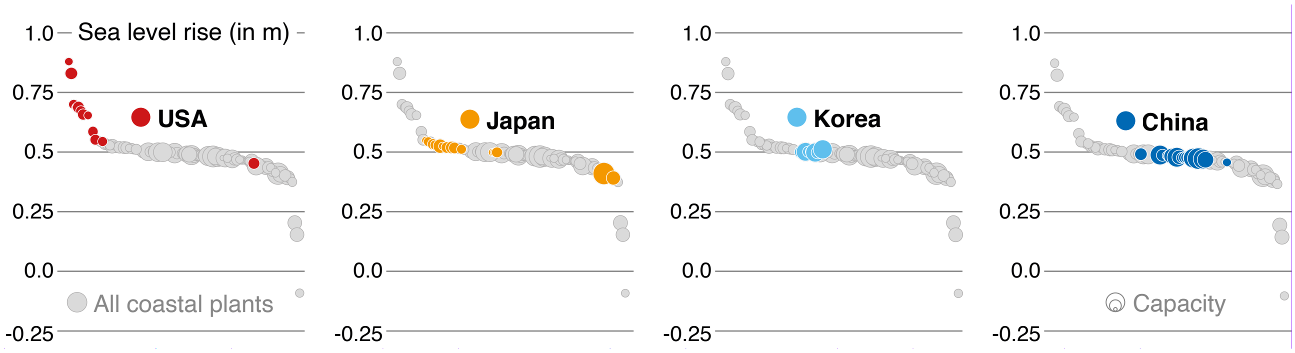
Because of past and future GHG emissions, a gradual and irreversible rise of the sea level will occur throughout the century and well beyond, irrespective of the future state of the climate, with consequences for the design and siting of current and future facilities located on coastlines. A further increase in global sea level rise is now certain, and will be caused by continuing ice loss on land and thermal expansion from deep ocean warming, with sizeable variations at the local scale (IPCC, 2021; Woodworth et al., 2019). Under a 4°C increase in global mean temperature (SSP3 narrative), nuclear power located on the north east coast of the USA and in Florida, as well as many Japanese and Korean plants, would see increases in sea level above 50 centimetres compared to current levels (see Figure 25), in addition to the 20 centimetre increase that has occurred since 1900. The physical protection of nuclear sites can be progressively upgraded in response to this steady increase in sea levels. However, increased sea levels could exacerbate the impacts of other unpredictable but more frequent extreme weather manifestations underpinning high emission scenarios, such as large storms causing coastal flooding, storm surges and high water events, as well as coastal erosion and landslides. A total of 10% of dispatchable generation fleets are already exposed to severe coastal flooding (IEA, 2021a).

Figure 24: Ranking of projected average wind speeds at NPP sites in Asia and North America, 2041–2060.



Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b). Note: Average wind speeds do not vary vastly across SSP storylines and time frames, hence the choice of the intermediate SSP2 case in the medium term (2041–2060) for illustration purposes.

Figure 25: Projected change in sea level at coastal nuclear plant sites from near (2021–2040) to long term (2081–2100) by country.



Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b).

There is growing concern among climate scientists about the emergence of the more frequent compound risks associated with large economic and societal impacts. Compound events take place when several weather or climate events — not necessarily extreme — occur either at the same time, in close succession or concurrently in different regions. If we fail to limit global warming within the limits set by the Paris Agreement, the combined occurrences of more frequent and more damaging individual events could create compound events of exceptional scale (IPCC, 2021). These events include concurrent heat waves and droughts, fire weather conditions resulting from compound hot, dry and windy events, compound flooding following storm surges, extreme rainfalls and/or river flow. Other climate driven hazards, such as lightning strikes or tornadoes, could also occur concurrently, putting additional pressure on vulnerable energy infrastructures. Nevertheless, more evidence needs to be collected to attribute compound events to climate change with enough certainty.

The mounting environmental pressure highlighted above suggests that various nuclear sites could be increasingly exposed to compound events in the future. The concurrent hazards projected by the IPCC for each area where nuclear sites are located could affect nuclear operations and/or cut access to transmission networks for extended periods (see Figure 26). East Asia hosts 43% of global nuclear new build, with three quarters in China alone. Tropical cyclones, floods and droughts in the region have increased significantly over the last decades, with severe and destructive impacts on coastal communities (World Bank, 2022b). Infrastructures in some regions, such as the Guangdong region, seem particularly vulnerable given the large concentrations of key assets, including nuclear sites. Indeed, historical records have shown an acceleration of disruptions in nuclear operations. In the last decade, for example, the number of reported outages due to environmental conditions were more than three times higher than in the previous two decades. China's long-standing experience with natural hazards has provoked design and regulatory modifications to better withstand adverse weather conditions (see Box 6). Mindful of such risks, the Chinese Ministry of Ecology and Environment has already included the objective of "making all-out efforts to prevent floods and droughts" in its latest Climate Action Plan (Ministry of Ecology and Environment of the People's Republic of China, 2021).

The North American continent is also among the top regions at risk of large and impactful events. The World Meteorological Organization (WMO) estimates that North America, Central America and the Caribbean accounted for 18% of weather, climate and water related disasters, and 45% of economic losses incurred worldwide over the last half century (US $1.7 trillion) (WMO, 2021). A recent study connects the rise of sea surface temperatures in the North Atlantic to continental extreme rainfalls (Reed et al., 2022). A re-examination of safety hazard assessment methods is therefore necessary to take into account these compound risks. The chapter's last section introduces a new analytical approach developed by the IAEA, notably to anticipate multi-risk hazards and to prepare for complex emergency situations.

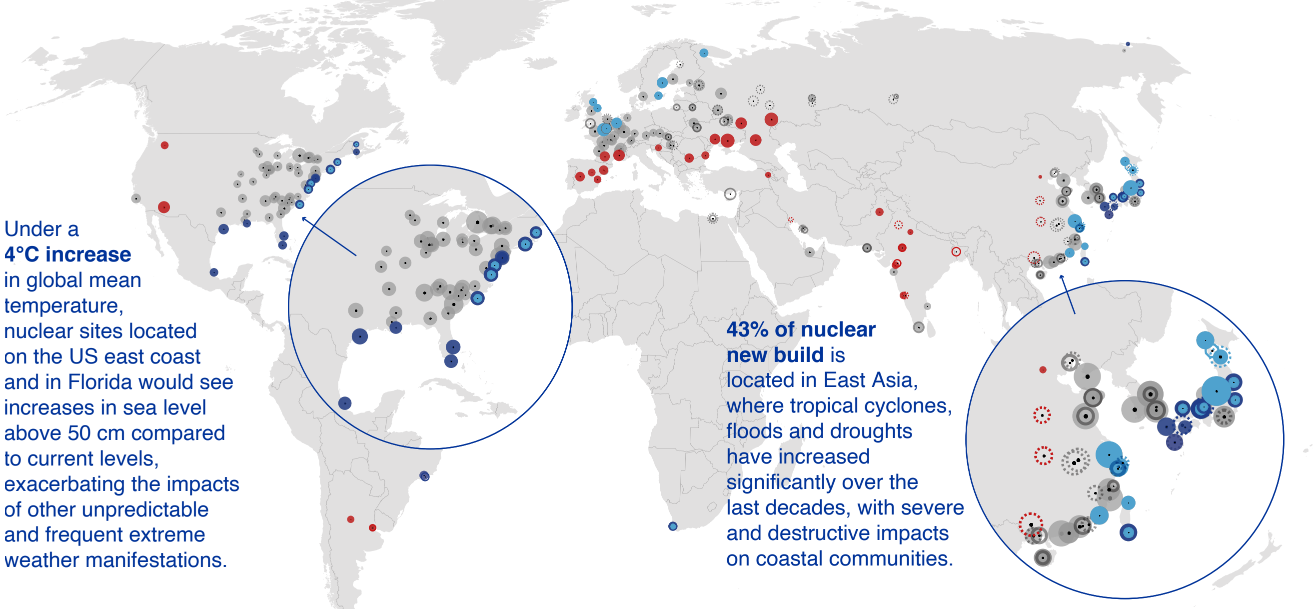
Figure 26: Global overview of the most significant environmental changes around selected nuclear site locations.

Climate risks

High winds Sea level rise Aridity
Compound risk of high winds & sea level rise

Nuclear sites

Operational Under construction Planned
All nuclear power plants (less affected than top 30)



Nuclear sites by climate risks

Ranking	Aridity (in consecutive dry days/year, SSP3)		High winds (in m/s, SSP2 medium term)		Sea level rise (in m, from near term to long term SSP3)	
1.	Darkhovain, Iran, Islam. Rep.	157	Onagawa, Japan	8.20	Waterford, USA	0.88
2.	Kakrapar, India	108	Tokai, Japan	7.75	South Texas, USA	0.83
3.	Rajasthan, India	93	Calvert Cliffs, USA	7.67	Calvert Cliffs, USA	0.70
4.	Kaiga, India	82	Hartlepool, United Kingdom	7.65	Hope Creek, USA	0.69
5.	Chasnupp, Pakistan	81	Seabrook, USA	7.59	Salem, USA	0.69
6.	Narora, India	80	Doel, Belgium	7.37	Surry, USA	0.67
7.	Cofrentes, Spain	78	Millstone, USA	7.37	Millstone, USA	0.66
8.	Palo Verde, USA	76	Maanshan, Taiwan, China	7.22	Point Lepreau, Canada	0.65
9.	Gorakhpur, India	71	Shimane, Japan	7.22	Seabrook, USA	0.65
10.	Asco, Spain	70	Torness, United Kingdom	7.20	Pevek, Russian Fed.	0.59
11.	Cernavoda, Romania	69	Kashiwazaki Kariwa, Japan	7.04	Brunswick, USA	0.58
12.	Zaporizhzhia, Ukraine	61	Point Lepreau, Canada	6.91	St. Lucie, USA	0.55
13.	Almaraz, Spain	61	Kola, Russian Fed.	6.89	Tokai, Japan	0.55
14.	Rooppur, Bangladesh	56	Brunswick, USA	6.81	Onagawa, Japan	0.54
15.	Armenia, Armenia	52	Surry, USA	6.79	Turkey Point, USA	0.54
16.	Tricastin, France	52	Oskarshamn, Sweden	6.71	Shimane, Japan	0.53
17.	Volgodonsk, Russian Fed.	50	Kuosheng, Taiwan, China	6.66	Sendai, Japan	0.53
18.	Kozloduy, Bulgaria	48	Sanmen, China	6.59	Laguna Verde, Mexico	0.53
19.	South Ukraine, Ukraine	45	Forsmark, Sweden	6.48	Takahama, Japan	0.52
20.	Cefr, China	45	Takahama, Japan	6.47	Tsuruga, Japan	0.52
21.	Trillo, Spain	43	Tsuruga, Japan	6.47	Mihama, Japan	0.52
22.	Embalse, Argentina	40	Higashidori, Japan	6.42	Ohi, Japan	0.52
23.	Golfech, France	38	Tomari, Japan	6.42	Ikata, Japan	0.52
24.	Hongshiding, China	37	Ohma, Japan	6.42	Kaminoseki, Japan	0.52
25.	Xianning, China	36	Qinshan, China	6.27	Genkai, Japan	0.51
26.	Novovoronezh, Rus. Fed.	36	Koeberg, South Africa	6.25	Kuosheng, Taiwan, China	0.51
27.	Balakovo, Russian Fed.	36	Shidaowan, China	6.24	Koeberg, South Africa	0.51
28.	Columbia, USA	34	Zhangzhou, China	6.20	Shika, Japan	0.51
29.	Krsko, Slovenia	33	Paluel, France	6.20	Maanshan, Taiwan, China	0.51
30.	Taohuajiang, China	33	Penly, France	6.20	Angra, Brazil	0.50

Operational Under construction Planned compound risk of high winds & sea level rise

Source: based on climate data from IPCC (2021) and nuclear data from the IAEA (2021b). Note: m/s — metres per second, m — metres.

System level risk mitigation measures and priorities for action

The nuclear sector will be confronted with climate change induced natural hazards at an increasing pace and intensity. The failure to consider the full magnitude of these risks in future regulations, plant designs and updated operational practices could hinder the contribution of nuclear technologies to achieving net zero and other energy security objectives in future. The early inclusion of climate constraints in the strategic environmental assessment — a systematic process for assessing the environmental consequences of a specific project — is now an indispensable step in the preliminary phase of the development of any nuclear programme (IAEA, 2018b).

Climate impact data and scenarios, now available at fine scale, will help power and grid operators to adjust their system monitoring to meet new demand patterns that are altered by climate change. The French grid operator RTE recently conducted a holistic study identifying possible avenues leading to the transformation of the French power system, offering a guide for government strategy in particular in relation to future nuclear developments. The resilience component of the analysis, which is based on multiple climate stress tests (including the impacts of heat waves, droughts, extreme cold and the absence of wind in continental Europe), has an influence on future market fundamentals (see Figure 27). In parallel, RTE is developing seasonal and sub-seasonal forecast models that can help identify severe weather events in advance and ensure the continuity of grid service. Other impact studies have been conducted in the context of Nordic countries and the United States, combining the experience of utilities and academic research, and drawing on the track record of industrial responses to external environmental shocks. These impact studies have confirmed the climate robustness of the nuclear sector. In other words, the industry has appropriately identified risks and is well prepared to respond to emergency situations in the foreseeable future (Energiforsk, 2021; EPRI, 2021b).

Figure 27: General methodology for power system simulation and representation of climate impacts.

Long term climate reference (e.g. 2050)	Modelling of hourly supply and consumption	Power system simulations for a wide range of random outcomes
Weather time series (temperature, wind, rainfall, etc.) from climate simulations for multiple configurations at local and regional scales	Variable renewable production and consumption patterns turned into load curves	Balance of supply, demand and grid operations

Source: RTE (2021).

The nuclear sector will be confronted with climate change induced natural hazards at an increasing pace and intensity.

However, various impact studies have confirmed the climate robustness of the nuclear sector.

Box 6: Contributed by the Institute of Nuclear and New Energy Technology, Tsinghua University

Resilience of nuclear power plants in China: Building on a long history of natural hazards

Drawing on its long track record of exposure to natural hazards, along with its experience responding to such events, China has reinforced its nuclear power plants to withstand severe natural disasters, guiding new principles for site selection and construction specifications. After the Fukushima Daichi accident in 2011, China's National Nuclear Safety Administration started a nationwide review of the design and safety standards of existing plants to ensure safe operations during extreme weather conditions, notably with anti-flood protection and response mechanisms in relation to external natural disasters. The most recent design features of nuclear power plants integrate safety characteristics to enhance their climate resilience.

Most nuclear power plants in China are located on the coastline and are regularly hit by typhoons, with even more typhoon occurrences expected in the future due to climate change. During the design phase, all Chinese nuclear power plants take into account the full history of tropical cyclones observed within a 300–400 km distance from each nuclear site (Code of meteorology for nuclear power plant GB/T50674). Each site ensures that the plant can withstand the strongest tropical cyclone likely to occur once per millennium.

After the Fukushima Daichi accident, even more attention was devoted to risks such as potential storm surges, tsunamis and other astronomical tides that may affect coastal nuclear sites. Chief among them is the risk of storm surge. However, the base heights of all Chinese nuclear plants have a considerable safety margin and can withstand waves of over 8 metres in height, which can be generated during exceptional storm surges.

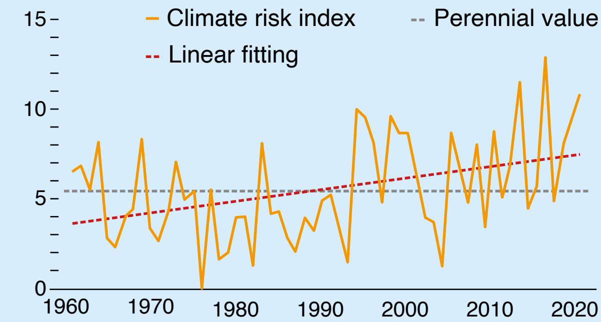
Future rises in the sea level are therefore not seen as a major threat to Chinese nuclear operations. According to China's 2020 Blue Book on Climate Change, the sea level rise observed in China in the past 40 years is around 0.15 metre (see Figure 28). This rise is far less than the base height of Chinese nuclear power plants, which thus have enough of a safety margin to accommodate increases in the sea level expected over their lifetimes.

Other events, such as changes in seawater temperature, are not expected to affect nuclear operations significantly and can be mitigated through adjustments to operation protocols.

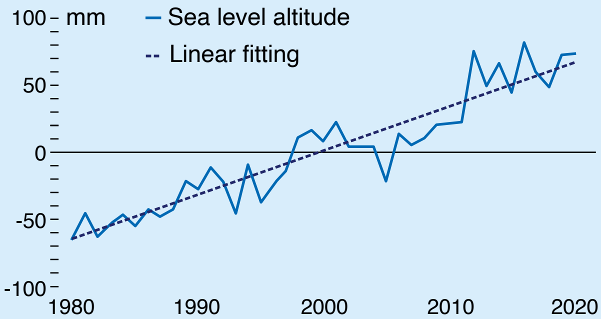
Overall, the impacts of extreme weather in China have been duly factored into the siting and design of nuclear power plants, including both new and inland plants, confirming the safe and reliable production of electricity in the face of climate change.

Figure 28: The climate risk index in China and the sea level from 1960–2020.

Climate risk index



Sea level altitude



Source: CMA (2020).

In recognition of the increasing sensitivity of nuclear plants to the changing climate, many public and private decision makers are nonetheless investing in dedicated research and are strengthening their adaptation plans. In France, climate adaptation is now an integral part of the Électricité de France (EDF) strategy. EDF identifies physical risks and transition risks (inherent to the energy transition) as strategic risks for its business in the long term, recognizing the sensitivity of the EDF operating power fleet to future climatic conditions (EDF, 2022). In the United States, the Argonne National Laboratory is developing advanced analytics for resilience modelling capabilities at various geographical and time scales in the United States (see Box 7). US power utilities are also joining forces under EPRI's umbrella and are launching a new, three-year Climate READi initiative to ensure resilient energy systems. By conducting a joint analysis and sharing common applications for climate data, the framework will enable better planning, design and operation of more resilient energy systems.

A system level approach, including the establishment of effective emergency preparedness plans involving a wide range of stakeholders to ensure a smooth coordination, is paramount and increasingly seen as good practice. Because climate impacts are being felt across many continents, sometimes causing enormous damage to property and infrastructure, and costing many lives — as demonstrated by South Africa's deadliest storm in the country's history in 2022 (Nyoka, 2022) — climate resilience considerations and plans for disaster risk reductions are now being included in selection criteria for nuclear projects. In addition to the traditional seismic studies, the design and site selection of nuclear plants will need to integrate local constraints related to extreme weather conditions. Because of the growing complexity and interdependency of systems, nuclear power plants are now putting in place strategies and underlying analytical efforts at the system level, sometimes encompassing a very broad view on the definition of system boundaries. The French nuclear fleet, for example, is confronted with a major sustainability challenge as top safety and security standards need to be maintained in a context of a changing climate. Only an assessment that goes beyond the sole technical design will be relevant when studying the full impacts of climate change on nuclear installations. EDF has initiated such a thorough analysis in the context of the French nuclear fleet, as illustrated by the original and systematic approach of EDF in France (see Box 8).

Large physical risks, such as the rise in sea levels or large scale flooding, cannot always be averted. Despite efforts to integrate scientific information in adaptation strategies, many uncertainties remain surrounding the future state of the climate, as well as the associated costs of risk mitigation measures. Some precautionary principles should apply and new financing channels should be established so as to help increase the resilience of energy infrastructures, including low carbon nuclear plants. Estimation methods to measure the benefits of adaptation measures against investments need to be revisited, in particular to improve and value the ramifications of cascading, compounding and aggregating impacts on cities, settlements, infrastructure, supply chains and services due to extreme events. New science-informed policies are critical to stimulate innovation in the domain of climate resilience. Providing enough financial support is also essential to develop systemic risk management strategies and implement solutions at the local level (IEA, 2021i; OECD NEA, 2021).

In addition to the traditional seismic studies, the design and site selection of nuclear plants will need to integrate local constraints related to extreme weather conditions.

Box 7: Contributed by Argonne National Laboratory

Advanced analytics and resilience modelling capabilities in the United States

The US electric power grid has evolved rapidly in the past 10–15 years, and this transformation is expected to accelerate over the coming 20– 30 years, touching every aspect of how electricity is generated, transmitted, distributed and consumed. The shift to carbon free resources, and often to variable renewable generation, will continue, and the lines between distribution and transmission systems will progressively blur. The roles and consumption patterns of historically passive consumers will also dramatically change, and the interdependencies with other vital physical and digital infrastructures will continue to grow. As the grid is undergoing this transformation, the landscape of natural hazards and emerging threats is also changing. These hazards and threats pose significant risks to the reliability and resilience of the grid and its interconnected critical infrastructures. Annual costs of severe weather related power outages already range from $18 billion to $33 billion per year in the United States.

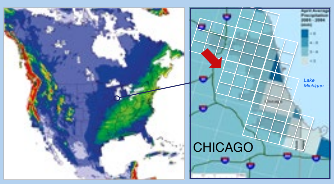
Protecting, restoring and recovering interdependent critical infrastructures from severe events require advanced data analytics, and modelling and simulation approaches. The information from these advanced tools can: (i) support enhanced operator training, drilling and exercising in preparation for future events; (ii) enable improved real-time situational awareness and informed operational decision making to optimize response and recovery during events; and (iii) help incorporate climate change considerations in long term capital expenditure and asset investment planning so as to harden the grid and other infrastructure in the face of these emerging threats. Such an analysis typically starts with understanding the threat environment. The DOE recently published an updated set of 50 state and 10 regional energy risk profiles to

Figure 29: Climate risk informed operational and investment planning.

HIGH RESOLUTION CLIMATE MODELLING

Downscaling with regional climate model over a smaller spatial domain using input from global climate models

- Covers North America
- Spatial scale of climate modelling with a 12 km resolution is relevant to local and regional asset planning. An even more granular resolution of 4 km is coming soon.

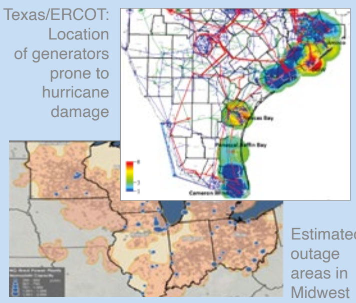


INFRASTRUCTURE OPERATIONS IMPACTS

Infrastructure models identify critical components and operational impacts

- Linearized direct current power flow tools to rapidly study n-k scenarios and impacts of large extreme events
- steady-state and transient dynamic alternating current power flow tools for detailed assessments

Texas/ERCOT: Location of generators prone to hurricane damage

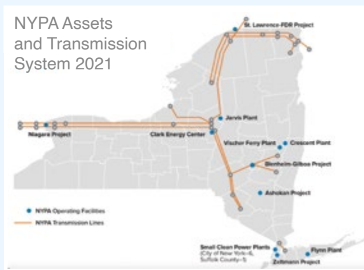


Estimated outage areas in Midwest

INFRASTRUCTURE ADAPTATION & INVESTMENT PLANNING IMPACTS

Infastructure models identify investment opportunities

- Vulnerable assets for hardening or identifying locations for new resilience investments



Source: Argonne National Laboratory. Note: ERCOT — Electric Reliability Council of Texas, NYPA — New York Power Authority.

illustrate the relative magnitude of risks to electric, petroleum and natural gas infrastructures from natural and human made hazards. The profiles are based on historical hazard data and are designed to increase awareness among local and regional stakeholders and decision makers on the current risks to critical infrastructures, and to enable better preparation for any potential energy infrastructure disruptions.

For long term investment decisions about infrastructures with operational lifetimes of 30+ years, current hazard information may be insufficient. Decision makers need to complement historical hazard data with projections from climate models that can help determine the future risks to infrastructure investments by mid-century and beyond under various climate change scenarios. For this information to be actionable, results from climate models need to be translated to inform decision making at the local level. Recent research advances now enable the assessment of climate change impacts both at a hyper-local scale and in direct alignment with stakeholder needs, resulting in actionable projections to inform resilience planning and investment. Physics based regional climate models, for example, can now project mid- and end-of-century impacts for all of North America at a 12 km resolution. A 4 km model is currently being run with results that will be made available soon. These models project over 60 climate variables — including traditional impacts such as precipitation and temperature, but also drought risk, wind intensities, flooding, heat waves and wildfires. These projections were recently used by Pacific Gas and Electric and AT&T for resilient infrastructure investment planning. Combining climate modelling outcomes with infrastructure and decision science analytics as shown in Figure 29 — including transmission grid modelling, facility and system risk assessments, and financial analysis — can inform broader holistic infrastructure resilience planning. These combined climate and infrastructure/decision science capabilities are currently being used to assess the climate resilience of the New York Power Authority (NYPA).

For effective and resilient long term energy infrastructure planning, such as nuclear power planning, decision makers need science based information about the potential impacts that climate change will have decades into the future, and for specific regions. Therefore, analysts must use climate models that can project climate impacts down to regional and local scales. Incorporating climate projections into risk and vulnerability assessments enables science driven adaptations to extreme weather in the face of climate change. This integration can also aid in planning and preparing for the energy systems of the future by helping design systems that can adapt to evolving environmental conditions, and thereby meet the requirements of coming generations.

For effective and resilient long term nuclear power planning, decision makers need region specific and science based information regarding potential climate change impacts.

Box 8: Contributed by Électricité de France

A new framework for the system wide assessment of climate impacts: The EDF approach in France

Lessons from the 2003 heatwave

The resilience of nuclear installations to climate hazards is rightly perceived as an objective that should be addressed primarily through the lens of nuclear safety. In this context, EDF nuclear facilities have been designed from the start to withstand significant meteorological hazards, such as temperature anomalies, flooding, high winds and tornados. These risks are reassessed every ten years to reflect advances in knowledge. New thresholds are set beyond risk levels experienced thus far and in anticipation of projected risk in future. This safety approach therefore integrates the impact of climate induced external events by design.

Some of the lessons learned from the exceptionally hot summer in France during 2003 led to a vast programme of modifications to facilities in order to better cope with high heat episodes, as part of the periodic review process. On this occasion, air conditioners were resized if not scaled up and operating practices were reviewed, among other measures.

In a pioneering move following the 2003 summer experience, French public authorities issued environmental authorizations taking explicit account of exceptional climatic conditions and of the challenges inherent to the security of the domestic electricity supply. With the design upgrades mentioned above, the safety of nuclear power plants was guaranteed throughout the summer of 2003. In addition, the regulatory framework for the protection of the environment was also adapted. A transitional regime by derogation was put in place to avoid the accumulation of simultaneous production reductions in relation to several reactors because of environmental provisions, including those concerning the water temperature of the rivers used for cooling. Such reductions would have threatened domestic power supply at a time when, for example, meeting refrigeration needs was indispensable. The production of electricity could thus be maintained at a sufficient level. These exemptions were accompanied by compensatory measures, including increased monitoring of aquatic environments and ecosystems, which confirmed the absence of significant impacts from thermal discharges. The episode revealed the system wide effects of heatwaves and the need to adapt the regulatory framework.

EDF has further developed its analysis of climatic events, going well beyond the demonstration of nuclear safety and environmental preservation objectives. The analysis has confirmed that other global phenomena could affect the production capacity of its facilities without jeopardizing safety. A specific project, called the ADAPT project, was then initiated to evaluate the impacts of climate change on EDF's nuclear production capacities.

Consequences of climate conditions beyond industrial facilities

A close examination of the consequences of climate change shows that they cannot be restrained to the physical boundaries of the operating facility. The production capacity of a nuclear power plant, similarly to other industrial installations, also depends on its ability to maintain connections with a very broad ecosystem whose perimeter is difficult to define with precision. To operate efficiently, each site must be able to exchange data with the outside world, for instance by purchasing packaging products and receiving spare part deliveries. Workplace access must also be preserved for employees and suppliers. In spring 2020, public authorities decided to close schools so as to curb the progress of the COVID-19 pandemic, which gave rise to challenges in terms of the presence of on-site staff. Overall, the resulting disruptions had no direct operational consequences in 2020, but they required organizations to adapt and take compensatory measures (e.g. shifts in non-compulsory training).

Consequently, EDF has decided that a climate adaptation plan for its operating fleet should not revolve solely around the guarantee of nuclear safety. A broad, system wide approach, beyond technical elements linked to production, supply chains, the plant's surrounding area and its communities, is essential. Even if optimal levels of safety are maintained during a heatwave, for example, a site's normal operations can be disrupted with consequences for its production performance. The experience in central France during the heatwave in June 2019, as schools were closed and students sent home, showed that a deficient integration of the nuclear site and the surrounding communities in the adaptation plan may lead to operational disruptions, with impacts such as performance drops during reactor shutdown. A variety of situations, ranging from a supplier's unusable premises due to flooding to unbearable heat in a prefabrication workshop, could potentially affect the regular functioning of a nuclear site.

Climate scientists anticipate profound changes in local living conditions, including a significant modification of coastlines, a major alteration of the great water cycle with more severe and frequent low water periods, as well as longer heat waves. Some adaptation measures should be taken long before the occurrence of any hazard and could include: (i) changing a forest's tree species composition; (ii) redesigning engineering structures in anticipation of new climate hazards;

and (iii) adding more summer comfort to a building's performance. Following the traditional engineering approach, a building and organization upgrade would be driven by key parameters such as the expected frequency and intensity of a hazard. However, while climate scientists are confident about the direction of such key trends, the nature and extent of climate impacts at the local level within mid-century remain largely uncertain.

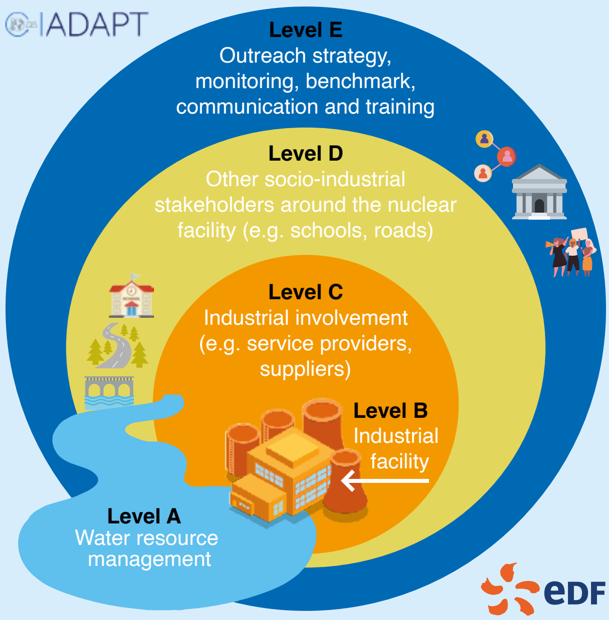
Results from climate models used for long term projections are based on a few key parameters, such as air temperature and precipitation levels. Uncertainties around the evolution of these key parameters and GHG emission levels affect the accuracy of climate projections as the time horizon extends, typically to beyond 2040. In this context, adapting the ecosystem surrounding a nuclear production site to climate change consists of first identifying no-regret actions and planning their implementation so that, as climate science advances and uncertainties are clarified, industrial and territorial players will be better prepared to withstand and respond to climate shocks.

Addressing resilience through a cross disciplinary approach

Only a very broad approach, based on many disciplines and going beyond the sole question of industrial facility performance, can effectively prepare a power generating fleet against the full range of climate changes. EDF has mobilized a small cross functional unit to this end. This compact structure focuses on monitoring and developing analytical tools, and it works across teams of climatologists and nuclear engineers in charge of fleet oversight, as well as with operators, local stakeholders around the plant and suppliers of nuclear facilities. The work was assigned to EDF, given its capacity to contribute directly to climate action. Particular attention is being given to water access, which is a central issue. Water is a matter of identity for communities, an economic conundrum among competing users, and is essential to biodiversity conservation. A team has thus been devoted to climate impacts in relation to industrial buildings and site specific production capacities. A dialogue has been established with the full supply chain and, more generally, with any stakeholder that has potential contractual obligations (e.g. operators of electricity transmission or data transmission networks, or who supplies spare parts). Finally, the EDF approach also addresses local communities, without entering into contractual agreements, for example with local school management and supermarket management, supplying local customers and ensuring continuity of service.

By addressing the ecosystems connected to nuclear sites in their entirety, efforts on the part of EDF could nonetheless be compromised. The project will thus start with an experimental phase, followed by generalization–industrialization. The first few years will see efforts concentrated on one of the 20 French nuclear sites. The selected area in north eastern France concerns a site currently operating some of the most recent EDF assets, although operations on this site started in the 1960s. In this first case study, some emphasis will be placed on the development of analytical methods, notably targeting the local socio-economic context but also accounting for the site's natural characteristics. These methods will then be replicated in the context of other relevant sites.

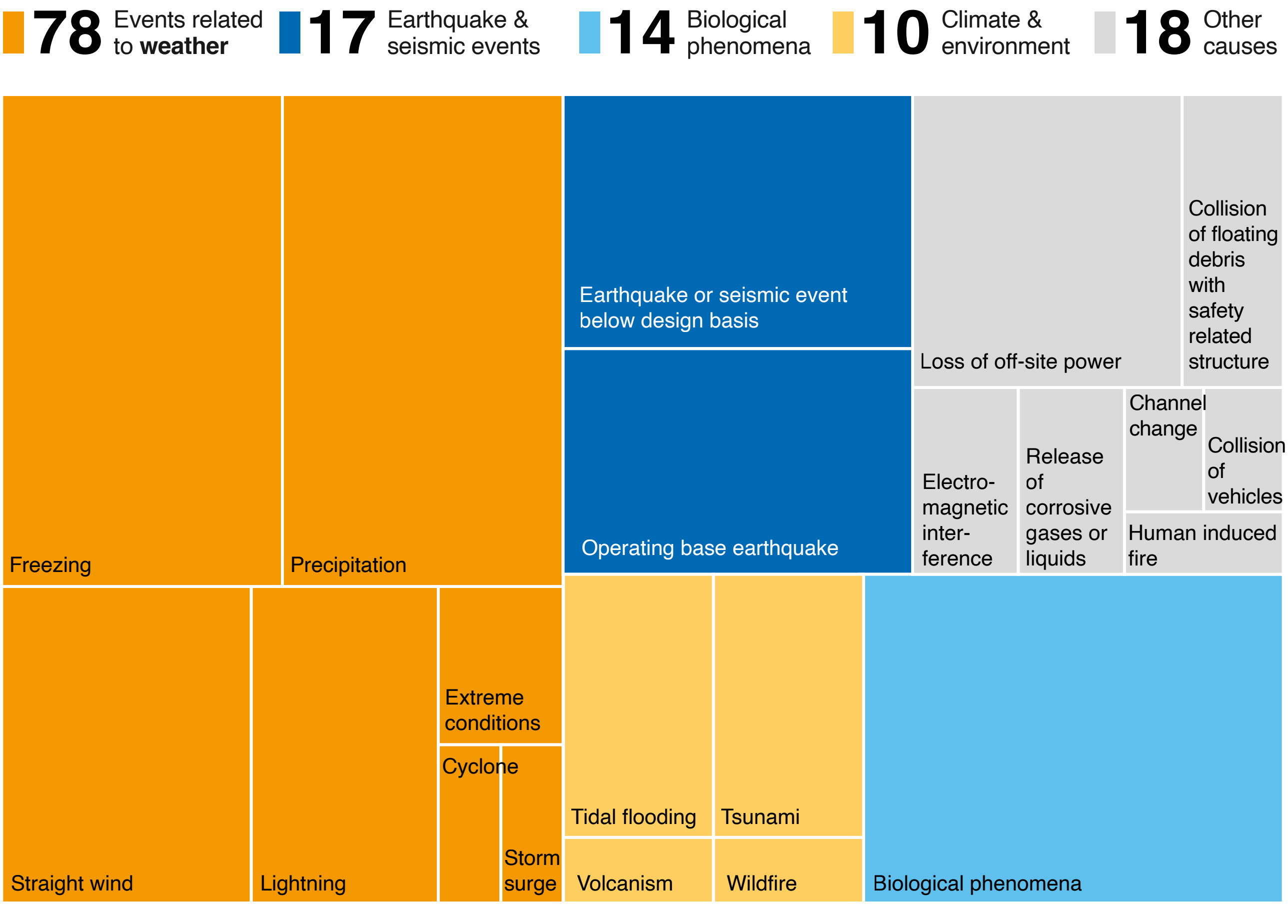
Figure 30: ADAPT climate change adaptation project structure.



Source: EDF

Through this iterative work, including both scientific and industrial characteristics, EDF wishes to play its part in France's efforts to achieve its climate objectives while maintaining access to reliable and inexpensive energy.

Figure 31: Climate related incidents affecting nuclear facilities since 2000.



Source: IAEA (2022).

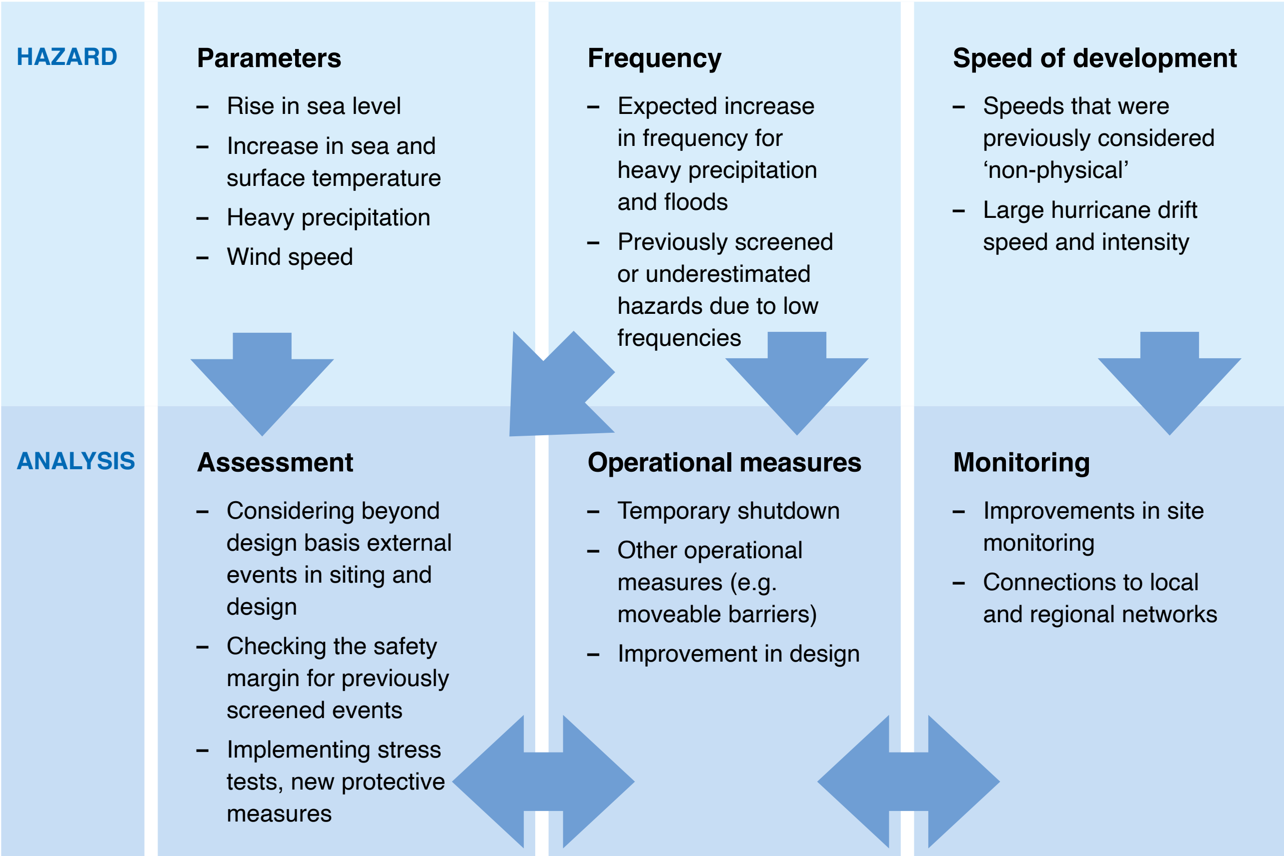
Implications for the safety assessment of nuclear facilities: The IAEA approach

Climate related hazards (e.g. meteorological, hydrological, fire related) are proving to be an increasing threat to the nuclear safety of all types of nuclear installations worldwide. Since 1980, a total of 3000 safety related incidents — affecting nuclear power plants, research reactors and fuel fabrication facilities — were reported in a database administered by the IAEA, known collectively as the Incident Reporting Systems for Nuclear Installations (IRS). A recent analysis of IRS events in relation to external events has highlighted that the most reported incidents in the last 20 years worldwide are related to scenarios affected by climate change, with increasing frequency in recent years (see Figure 31).

Historical incidents

The most reported incidents are related to combinations of events or consequential hazards, which were screened out at the design phase because they were considered unlikely, although many of them can likely be attributed to climate change. The most affected structures, systems and components by all types of events included: electrical components, the service water system, the primary system and structural protection. Some damages recorded at nuclear sites in recent years may be direct manifestations of climate change. These include site flooding, high temperature damage to components (especially digital), wildfires affecting site access and operation, sandstorm impacts on the site and at the plant, salt spray impacts on filters, impairment of vehicle access on-site, damage to electric stations, damage/availability of ultimate heat sink, water availability (from ice and debris), off-site grid availability, impairment of emergency evacuation/access and required shutdowns because of the lack of grid for dispatching power.

Figure 32: IAEA framework for hazard assessment of climate change impacts in new and existing NPPs.



Mitigating future incidents

Currently available hazard identification and assessment methods are under scrutiny because of a significant increase in risks to nuclear plants, with incidents triggering unplanned shutdowns and plant modifications that can prevent further losses and safety breaches. Climate change affects the amplitude of various meteorological and hydrological hazard parameters, their frequency and the speed of development for certain events; therefore, all these aspects need to be evaluated within a multidimensional framework as shown in Figure 32.

Climate models exhibit large variations across projections in terms of the rise in sea level and the increase in atmospheric and oceanic temperatures. The expected increases in temperature and sea level are spatially non-uniform. Therefore, the effects on nuclear installations in colder climates will be different from plants located in warmer and tropical areas. Moreover, these main variables significantly affect other parameters and their frequencies. For example, extreme precipitation will become more intense and frequent in many regions, the areas under the influence of monsoon systems will increase, and rotational winds may occur at higher latitudes. The non-stationary characteristics of these hazards should be carefully analysed when determining the design basis parameters for extreme events and other rare meteorological conditions. Also, the beyond design basis for extreme events must be considered during the siting and design of new nuclear installations. Stress tests must also be conducted in existing nuclear installations to evaluate the safety margins for hazard parameters affected by climate change, and protection measures should be updated accordingly.

When modelling potential risks to NPPs, it is important to examine scenarios that were not anticipated in the design of the plant and cannot be passively mitigated. These risks are increasingly common with the proliferation of climate change and go beyond the traditional hazard assessment methods. The speed at which an event develops has a major impact on risk based decision making. It usually takes several days or even a week for a tropical storm to grow into a powerful hurricane; however, Hurricane Ida of 2021 evolved from category 1 in the Gulf of Mexico to category 4, as it made landfall in less than 1 day. This recent example underlines the need for improved monitoring systems at the site, and in coordination with the local and regional monitoring networks for meteorological and hydrological hazards.

The multidimensional hazard assessment framework should also include operational measures to reduce the modelled risks to NPPs. The probability of potential hazards and their probable duration should be identified so as to improve plant safety. The time frame and frequency are particularly important for decision making and operational measures, such as temporary shutdown of the plant. Safety systems must be maintained, and the ability to monitor risks should be well established.

Adapting long term climate change scenarios to the multidimensional hazard assessment framework is vital. The IAEA Safety Standards Programme contains strong recommendations regarding the evaluation of climate change impacts on site hazards. The Programme suggests including these effects in the development of the design basis for nuclear installations. However, technical guidelines are lacking, mainly as a result of the heterogeneity of Member State experiences.

A novel IAEA initiative

Against this backdrop, the IAEA has initiated a technical project that draws on the most recent experience of Member States in the application of climate predictive methods for the assessment of site hazards and safety issues related to existing and new nuclear sites. The project will identify new generation site monitoring systems oriented to the continuous assessment of site hazards for the timely management of plant response. The project is currently supported by the Canadian Nuclear Safety Commission, France's EDF, Germany's GRS, Japan's Nuclear Regulation Authority, Switzerland's Swissnuclear, the United Arab Emirates Federal Authority for Nuclear Regulation, and the US State Department.

Special methods to assess the evolution of climate hazards over long time frames need to be developed and validated for an adequate safety assessment of nuclear installations. State of the art methods drawing on climate change projections will allow for reduced uncertainties on potential climate risks. The project will combine statistical and numerical methods with meteorological and hydrological approaches to assess time dependant hazards through the lens of sustainability. The main investigation areas are summarized in the next section. Safety relevant actions for on-site hazards and the design of new protection measures will be identified for both existing installations and new designs. Measures will aim at increasing the robustness and resilience of nuclear power plants in the face of climate change, combining engineering provisions (i.e. improved barriers) and operational, performance related procedures (i.e. preventive shutdown).

Adapting long term climate change scenarios to the multidimensional hazard assessment framework is vital.

The IAEA has initiated a technical project which will identify new generation site monitoring systems oriented to the continuous assessment of site hazards for the timely management of plant responses.

IAEA climate predictive methods: Project overview

Main project investigation areas

1. Investigation of evaluation practices in relation to time dependent hazards in Member States, specialized national agencies (e.g. the United States National Oceanic and Atmospheric Administration) and international organizations (e.g. World Meteorological Organization).

2. Examination of modelling issues in the evaluation of hazards.

3. Analysis of IAEA Member State experiences in terms of the protection of nuclear installations against the effects of climate change, and analysis of recent challenging events.

4. Development of recommendations and guidelines: modelling; data analysis; design of protection measures in relation to the effects of climate change; and design of site monitoring systems for to the continuous assessment of time dependent hazards.

Expected project outcomes

5. Improvement of documentation, made available to Member States as a guide when addressing climate change in the case of both existing and new nuclear installations. The documentation will be supported by climate change analysis, studies and research on projections of climate change; assessments and comparisons of time dependent hazards at nuclear sites; modelling issues and uncertainty management.

6. Analysis of recent challenging events recorded at nuclear sites, plant performance and challenges to nuclear safety. Analysis of Member State experiences regarding the protection of nuclear installations against climate change effects.

7. Provision of enhanced assessment techniques and methodologies that incorporate climate change considerations. Development of recommendations and guidelines on modelling, data analysis, design of protection measures and site monitoring systems in relation to the effects of climate change. Distribution of guidelines through periodical updates of climate change information and hazards.

8. Deployment of an IAEA External Event Notification System, able to make alerts available in real time; provision of the services of the IAEA Incident and Emergency Centre to issue alerts on the slow development of extreme phenomena (rotational winds, river flooding, etc.); assembling of lessons learned and updates to safety assessments in the context of a posteriori damage assessments.

New protection measures will aim at increasing the robustness and resilience of nuclear power plants in the face of climate change, combining engineering provisions with operation and performance related procedures.

05

Regional focus on the Middle East and North Africa, and on sub-Saharan Africa: Energy transformations in a changing climate

Key messages:

- **The emergence of large clean energy projects in the Middle East and North Africa (MENA) region, including some landmark nuclear projects, is driving energy transformations in the region.**

- **Unreliable electricity supply in sub-Saharan Africa is an impediment to economic development and employment.**

- **Financial aid is critical to support the development of large infrastructure programmes, including nuclear projects.**

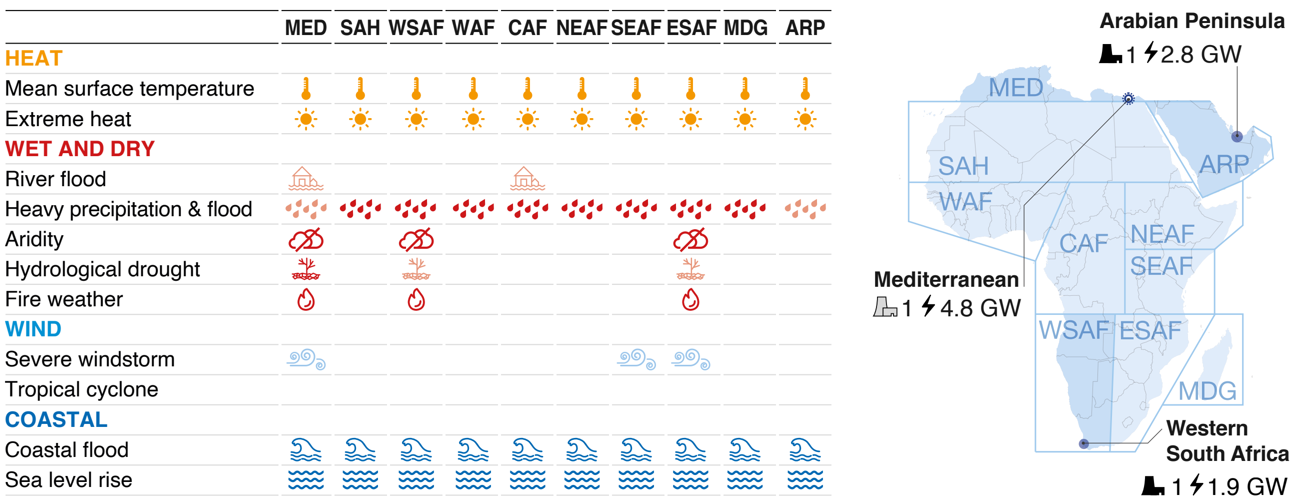
This chapter takes stock of some of the key economic and environmental characteristics of Middle Eastern and African countries, provides some rationale to nuclear developments in the region and outlines some of the barriers to deployment in the near term.

Intensification of climate change damage without climate action on the African continent

Some of the most severe and damaging manifestations of climate change can already be observed in Africa and are expected to accelerate across the African continent and the Middle East putting the environment and the life of populations at risk. The World Meteorological Organization (WMO) estimates that Africa alone accounts for over a third of the extreme weather events observed globally since 1970. By contrast, the economic losses resulting from these events make up just one percentage point of global counts, notably because of the lower living standards and lower grade infrastructure compared to higher income regions (WMO, 2021). In its latest assessment, the IPCC concludes that the MENA region is already the hottest and driest region in the world (IPCC, 2022b). Temperatures could reach 60°C or more in these regions and in other regions in Africa, rendering some places inhabitable. In just the six weeks between January and February 2022, three tropical cyclones and two tropical storms hit South Eastern Africa. Extreme rainfall and floods in Madagascar, Malawi and Mozambique caused 230 deaths and left more than 1 million people in distress (Otto et al., 2022). According to the IPCC, deteriorating environmental conditions are expected across the African continent due to the changing climate and weather, as well as to water shortages (see Figure 33). Coastal areas will be confronted with more damaging floods and tropical cyclones, while inland subtropical areas may be particularly exposed to aridity and ecological droughts (see Chapter 4 for a more in-depth discussion on climate risks).

It is critical to jointly address mitigation and adaptation to climate change, designing more climate resilient habitats and infrastructures, including clean energy systems, and improving

Figure 33: Exposure of the Arabian Peninsula and Africa to severe manifestations of climate change.



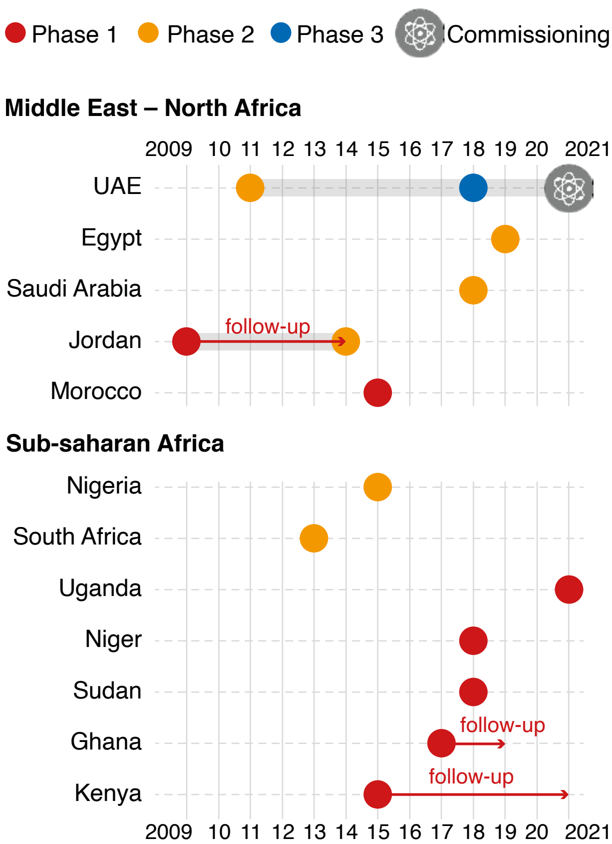
Source: IAEA analysis based on (IAEA, 2021c) and (IPCC, 2021). See Chapter 4 for more details on methodology.

emergency preparedness plans. African electricity infrastructures are often seen as critical contributors to sustainable development, but these infrastructures were designed to function under historical climatic patterns. A thorough assessment of current and future environmental conditions, including in terms of water availability and predictable weather patterns, is necessary for the planning of energy developments in Africa and the Middle East, as well as for the development of nuclear programmes. The IEA also points specifically to escalating variability in hydropower capacity factors and output, along with the potentially harmful consequences on the future reliability of electricity supply in Africa (IEA, 2020). Failure to consider future climate scenarios will only aggravate the climate risks facing infrastructure and supplies (IPCC, 2022b). The African continent still lacks effective early warning systems to anticipate weather and climate hazards. New lines of services, including predictive tools and integrated water management systems to alert governments, communities and individuals, are central to the security and reliability of the power supply (WMO, 2022).

Regional IAEA engagement in support of nuclear programme developments

Nuclear energy is gaining traction among the leaders of many African and Middle Eastern countries. In response to the climate emergency and other great challenges faced by this continent, such as those associated with economic stimulation and poverty alleviation, multiple Middle Eastern and African countries are increasingly integrating nuclear solutions in their economic, social and environmental strategies, as shown by the number of requests from IAEA Member States for Integrated Nuclear Infrastructure Reviews (INIR). This assistance programme, based on the IAEA Milestones Approach, is a holistic peer review of the national infrastructure needed for nuclear power, including the national policies, the legal and regulatory regimes, human resources, electrical grid infrastructure, suitable sites and supporting infrastructure (IAEA, 2015). Out of the 34 INIR missions conducted in 24 Member States between 2009 and 2022, 9 of the INIR main missions and 2 follow-up missions were requested by African countries (see Figure 34).

Figure 34: IAEA Integrated Nuclear Infrastructure Review missions conducted in the Middle East and Africa, 2009–2021



Source: IAEA (2021d). Note: The three phases indicate the stage of programme developement in accordance with the IAEA Milestones Approach. The regional classification of countries follows the World Bank analytical grouping.

IAEA support, including an INIR mission in 2011 requested by the United Arab Emirates (UAE), led to the successful and timely roll-out of the nuclear programme in the UAE, the first country in the Gulf Cooperation Council to produce nuclear energy. Nine years after the construction began, the first of Barakah's four reactors started its commercial operations in September 2021, followed by the second unit in March 2022. Once the programme is fully operational, the Barakah nuclear plant will supply a quarter of the country's electricity needs. INIR missions have also been requested by other Middle East Member States, for example Jordan and Saudi Arabia, and more recently Egypt, where the preparatory work for the contracting and construction of a nuclear power plant is underway.

While nuclear technologies — both existing and under development — have the potential to meet some of the needs of sub-Saharan countries, many hurdles remain before a nuclear power plant can be connected to the grid. The remainder of this chapter is devoted to the review of a selection of countries that are at various stages in their development of a nuclear programme. The main features of this discussion, be they demographic, economic or financial, as well as the policy levers highlighted in this chapter, remain relevant to other African countries that may be considering the nuclear option, without having yet initiated a careful assessment.

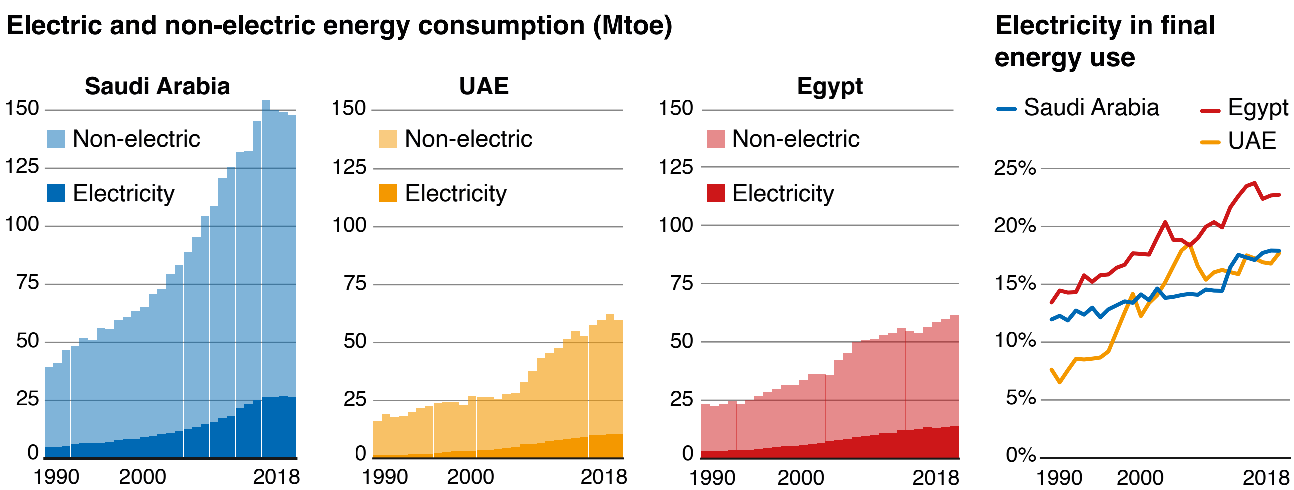
Embracing the clean energy transition in the MENA region

The emergence of large clean energy projects in the MENA region marks a new era in the energy landscape. The Middle East now hosts some of the largest solar farms in the world, with flagship projects such as the Benban Solar Park (1.6 GW) completed in 2019 in Egypt; the Noor Abu Dhabi solar plant (1.2 GW) and the Mohammed Bin Rashid Al Maktoum Solar Park (currently with a capacity of 1.3 GW and up to 5 GW expected by 2030) in the UAE; and the Sudair solar project (1.5 GW) in Saudi Arabia. These projects demonstrate the willingness of MENA governments to substitute conventional natural gas power capacities in a resolute effort to decarbonize electricity production. The scheduled ramp up of production at the Barakah nuclear power plant in the UAE will contribute considerably to this regional shift (see Box 3 in Chapter 2). To date, however, clean sources supply a mere 3% of total electricity needs in the Middle East, similar to levels seen a decade ago, and despite a 43% increase in total power production (see Figure 35).

The energy transition is developing slowly in terms of energy transformations and other end use sectors. Regardless of the increasing availability of clean electricity, the electrification of energy usage in the MENA region — an indispensable step towards carbon neutrality — has stalled in many countries. The increase in direct fuel use that accompanied a surge in activity in extractive and chemical industries has outpaced a swift rise in electricity consumption since 1990, mainly driven by residential and commercial demand. At just 18%, the share of electricity in final energy consumption in Saudi Arabia and the UAE is well below average electrification rates observed in high income economies that are less reliant on fossil fuel industries. Large scale and clean electricity projects under construction in the MENA region will enable a fostered electrification of transport and will also meet the rapidly increasing cooling needs triggered by heat island effects in large cities. Extreme heatwaves will intensify and could last up to four months during the summer in most capital cities (World Bank, 2017).

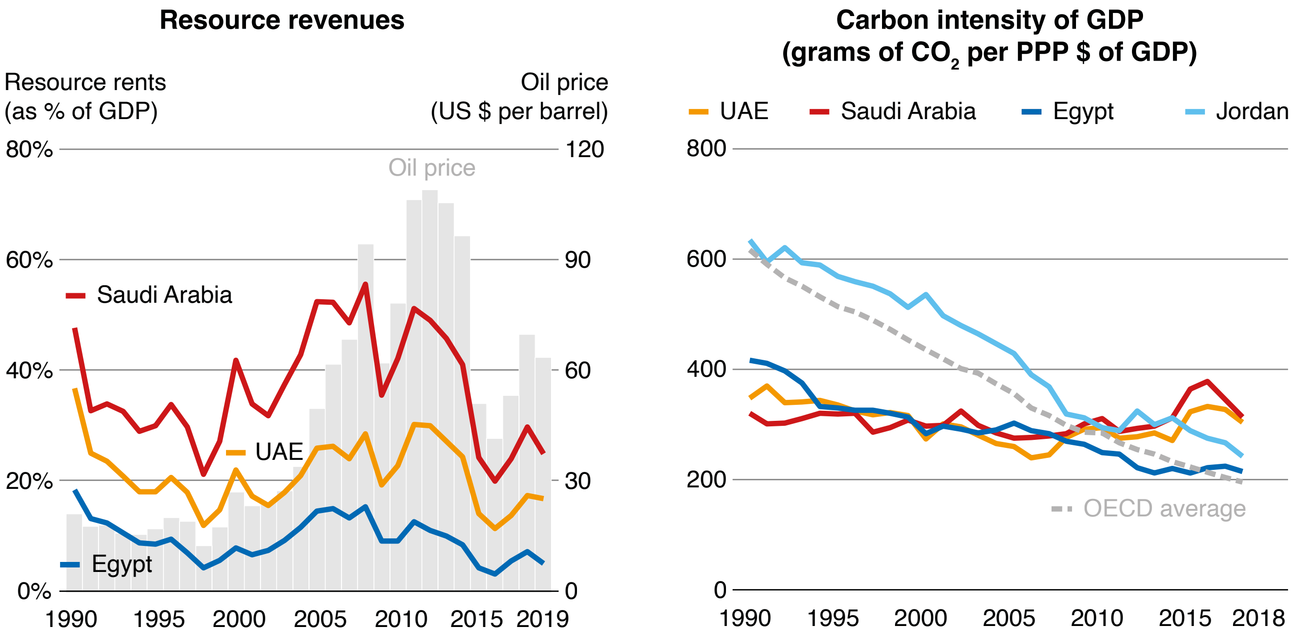
Mindful of the global momentum towards cleaner energy systems, Middle Eastern governments

Figure 35: Electricity and non-electric energy consumption in selected MENA countries, 1990–2019.



Source: IEA (2022d). Note: Mtoe — million tonnes of oil equivalent.

Figure 36: The long standing carbon dependency of MENA countries.



Source: World Bank (2022c). Note: GDP — Gross Domestic Product, PPP — purchasing power parity.

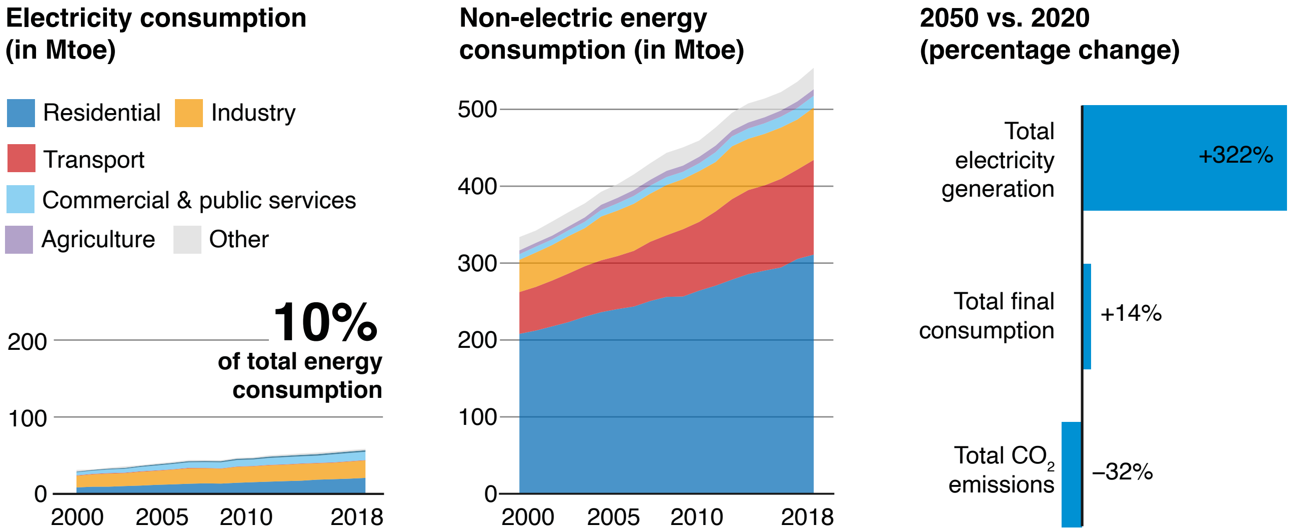
are adapting their industrial strategies to reduce the carbon footprint of their exports and maintain their competitive edge in global markets. Although governments in the region acknowledge the need to transform their economies and respond to the climate emergency, public finances in many Middle Eastern countries remain largely influenced by resource revenues and price levels on international markets. The slow uptake of green energy solutions in the region has kept the carbon footprint of gross domestic product (GDP) at very high levels (see Figure 35). Some structural reforms have been proposed to accelerate the uptake of green industries, boost job creation and support the global energy transition (World Bank, 2022d), including the development of clean public transport systems, revision of urban planning practices and improvements of wastewater management systems, as well as an expansion of desalination plants.

Cleaner power systems and large scale investments are indispensable for such transformations. According to the UAE National Energy Plan 2050, half of energy use will be supplied by low carbon sources in 2050. The carbon footprint of power generation will thus be cut by 70%, generating an estimated US $190 billion in cost savings. The United Arab Emirates, together with Oman, sees an opportunity to change their strategic orientation and position itself as a major green hydrogen hub. Once fully operational, the UAE nuclear plant, a key component of the country's net zero strategy, will supply a quarter of the country's electricity needs and will contribute to the green labelling of its industrial and chemical output. In Saudi Arabia, the production of green, hydrogen based ammonia, a US $5 billion project, is set to begin in 2025. Overall grid related investments to build the sole renewable capacity additions proposed until 2026 in the Gulf region are estimated at US $50 billion (Frost, 2021).

Boosting economic growth in sub-Saharan African with reliable power: Challenges and opportunities

The vast electrification deficits in sub-Saharan Africa are encouraging governments to firm up their sustainable energy strategies. Over 150 developers, ranging from local startups to large utilities from more advanced markets, such as Enel, Engie and EDF, are currently addressing the lack of energy infrastructures across Africa (AEP, 2018). Solar and wind projects have often become default options to fill the electrification gap in rural areas, thanks to favourable economics and ease of installation in poor communities. However, conventional fuels, including traditional biomass

Figure 37: Electricity and non-electric energy consumption in Africa.

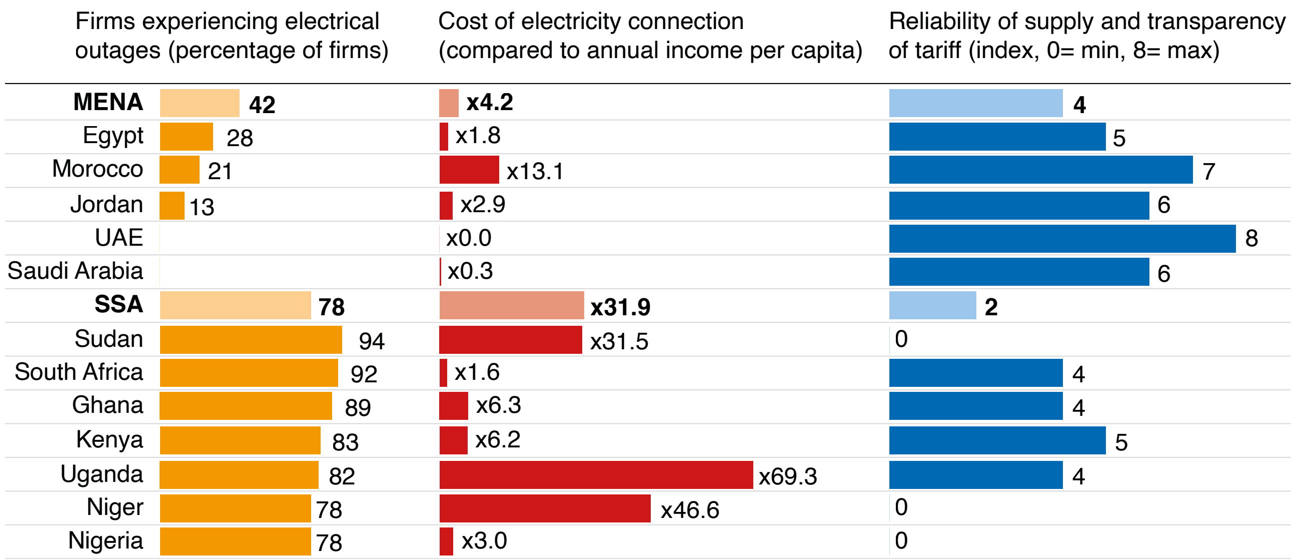


Source: historical data based on IEA (2022e) and projections from IEA (2021a).

mainly for residential usage and oil products, account for about 80% of total energy use on the continent (see Figure 37). In 2018, electricity met only 10% of total energy consumption. Without a strong policy push and directed investments, the uptake of electric solutions will remain far too slow to support sustainable development in Africa in the decades to come. In its latest update of the Sustainable Development Scenario, the IEA estimates that the natural resource endowments of this continent and technology improvements could suffice to move the continent towards a much less carbon intensive development model (IEA, 2019b), with CO_2 emission reduced by a third and with a tripling of electricity use by mid-century.

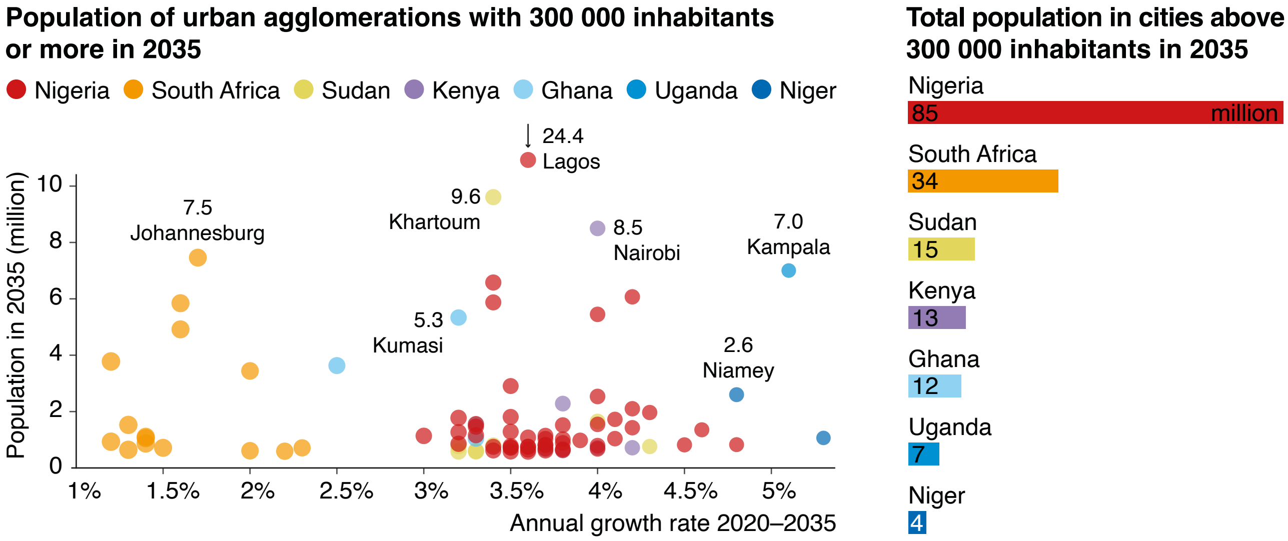
Unreliable electricity supply, commonly seen as an impediment to growth, employment and value creation, should be made a policy priority. The International Finance Corporation estimates that 10 million small enterprises remain without a reliable source of electricity, in addition to about 600 million

Figure 38: Reliability and cost of obtaining an electricity connection in MENA and sub-Saharan Africa.



Source: World Bank (2020). Note: SSA — sub-Saharan Africa.

Figure 39: Anticipated population in sub-Saharan Africa, 2020–2035.



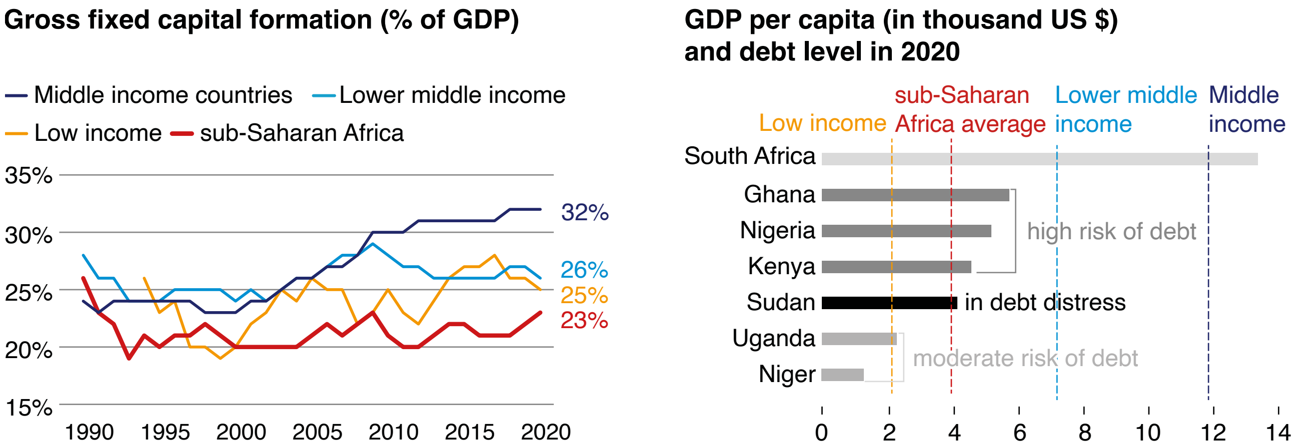
Source: UN (2018) Note: the regional classification of countries follows the World Bank analytical grouping.

individuals. Connection to the grid is by no means a guarantee of quality service. Before their discontinuation, the World Bank Doing Business reports would highlight the disparities in the quality of electricity supply in relation to the level of economic development. Sub-Saharan African business activity suffers greatly from regular power outages. Almost 80% of firms are impacted (see Figure 38). Many companies turn to alternative off-grid solutions to avoid lengthy and costly procedures so as to obtain a connection to the national grid and benefit from more transparent tariffs schemes. However, this vibrant informal sector, which generates revenues for substantial portions of the population, is equally impacted by unreliable power. Recognizing the missed opportunity to boost their economies, some governments have engaged in reforms and are reorientating their long term energy strategies to reduce their reliance on unreliable sources of power, as well as their exposure to unpredictable swings in international commodity markets. The Ghanaian government, for instance, has concluded that the development of nuclear power will resolve the electricity crisis customers are facing and will provide the reliable source of power that the country needs to boost its economy (see Box 9).

Large cities have emerged rapidly across Africa and will host tomorrow's value creation and improved well-being only if well-functioning energy infrastructures are placed at the centre of urban planning. Almost 90 sub-Saharan cities will have 300 000 inhabitants or more by 2035 (in the seven countries shown in Figure 39). Half of them will have reached at least 1 million inhabitants by this date. The number of urban citizens is expected to grow by 3.4% on average every year. The challenge for policymakers and local governments is to integrate and co ordinate different scales of urbanization effectively, from a neighbourhood to the entire agglomeration (OECD, 2020a). African energy demand is growing twice as fast as the global average, largely driven by urban population growth. The associated developments of industrial production, cooling appliances and mobility services are vigorously driving the energy needs from urban and peri-urban areas, with a risk of increasing citizens' exposure to ambient air pollution, accelerating climate change and hampering prosperity (IEA, 2019b). The expected economic and social benefits from clean and reliable sources of power can only be tapped with more integrated and sustainable urbanization plans, including a better offer of public transport in lieu of excessive individual mobility and the progressive electrification of energy use, in conjunction with the deployment of energy efficient appliances.

Some special economic zones, subject to tailored economic regulations that are more likely to attract foreign direct investments, are being built around local and reliable infrastructures, with dedicated substations, mini grids and adapted tariffs. They

Figure 40: Public investment and wealth compared with other global regions (left) and among countries in sub-Saharan Africa (right).



Source: World Bank (2022c). Note: Debt levels as of 31 March 2022, based on IMF Debt Sustainability Assessments.

can also serve as clean energy hubs that will benefit the surrounding communities and act as a catalyst for the energy transition in sub-Saharan Africa. Examples include Kenya's US $18 billion Tatu City and Konza Technopolis in Nairobi, as well as the Enyimba Economic City in Lagos, Nigeria.

Many sub-Saharan African countries burdened by high levels of debt are facing the challenges associated with acute poverty, which greatly limits their borrowing capacity and therefore their ability to finance large infrastructure programmes using their own funds. The provision of clean, reliable and affordable energy infrastructures for households and businesses is generally recognized among decision makers as an essential instrument to steer economies towards more sustainable outcomes, meet the Paris Agreement objectives and alleviate poverty. The US $76 billion joint debt relief initiative of the International Monetary Fund and the World Bank for heavily indebted countries has effectively benefited 31 African nations. However, the levels of public debt in sub-Saharan Africa remain a major impediment to transformative action. Public investment averages 5% to 10% lower than in higher income countries, shown in Figure 40 (IMF, 2021).

A profound debt crisis is looming in sub-Saharan Africa, exacerbated by the spending efforts that were mobilized to bail out economies after the COVID-19 pandemic, and by other uncertainties surrounding the impacts of the conflict in Ukraine, notably in relation to global food and fuel supply. The pandemic has greatly widened budget deficits and caused much faster debt accumulation than in the early years of other recessions (World Bank, 2022e). As a result, many countries (i.e. approximately 60% of low income countries, with most of them in sub-Saharan Africa) are now in debt distress or at high risk of debt distress. In other words, they are unable to fulfil their financial obligations and may therefore require a restructuring of their debt (Chabert et al., 2022). This is notably the case for Ghana, Kenya and Nigeria. The foreseen rise of food and energy prices that will follow global supply disruptions may be particularly harmful to some Middle Eastern and African populations, who are highly dependent on grain and fuel imports from the Russian Federation and Ukraine. This fiscal situation, combined with weak macroeconomic fundamentals, may lead to the postponement or cancellation of otherwise vital long term investments in infrastructures on the African continent (The Brookings Institution, 2021).

Against this backdrop, government decisions to pursue nuclear ambitions in sub-Saharan Africa must be properly informed, and plans carefully crafted. Some considerations may include the following:

– Strengthen climate pledges and place social justice at the heart of net zero strategies. Net zero pledges are under discussion in many African countries (see Chapter 5), but these pledges often lack details on actual implementation schemes (Carbon Trust, 2021). With soils that hold many of the crucial metals and minerals for sustainable energy technologies, Africa has the means to develop local supply chains and conduct a successful clean energy transition, particularly if social challenges are addressed. The Just Energy Transition Partnership announced in the margins of COP26 will provide financial support to South Africa in its move away from coal, with a focus on mining communities and workers (see Spotlight 6). This type of programme, together with revisited education systems, is likely to accelerate the uptake of job creating alternatives to employment in fossil fuel industries and could mean the promotion of nuclear projects.

– Integrate climate resilience and plans for disaster risk reduction in project selection criteria. Climate impacts are being felt across the continent, sometimes causing enormous damage to property and infrastructure, and costing many lives, as shown by South Africa's deadliest storm in the country's history in 2022 (Nyoka, 2022). No energy infrastructure will be immune to future climate and weather disasters. In addition to traditional seismic studies, the design and site selection of nuclear plants will need to integrate local constraints concerning extreme heat, water stress, river floods or devastating storms, which will put transmission and distribution networks to the test.

– Ensure a clear anticipation of future electricity needs, drawing notably on current and future demographic dynamics. Failure to accurately project future needs can deter investment. Kenya's nuclear programme was postponed to the late 2030s essentially because of the misalignment between electricity demand and planned nuclear production (Herbling, 2021) (see Box 10). A clear vision in relation to the future location of urban centres that will host the bulk of energy consumers is essential in order to identify and select a site for a nuclear project. These considerations have led Nuclear Power Ghana, the organization set up to manage Ghana's first nuclear power project, to consider four candidate sites at a distance from populated areas, factoring in future population growth, see Box 9 (Note: at the time of writing, the selected site had not been officially announced.)

– Calibrate nuclear projects with lower financing costs and ensure adequacy with sub-Saharan markets. Drained public resources in many African countries prevent rapid and sizeable improvement in stakeholder engagement, for instance efforts to improve public support for large infrastructures, including nuclear projects. The involvement of international financiers in Africa's nuclear development is therefore crucial. SMR technologies, such as those envisaged for the replacement of the ageing South African nuclear plant, have emerged as prime candidates in this regard, considering the expectations placed on the projects' risk profiles and the easier integration into clean power systems thanks to lower capacities (see Spotlight 6).

– Develop a comprehensive strategy for nuclear waste management. The EU taxonomy regulation requires long term disposal solutions that do not cause significant or long term harm to the environment. A nuclear proposal featuring a safe solution to long term waste storage, in compliance with best industrial practice, is more likely to attract international investors who will evaluate the project against strict sustainability criteria.

– Design functional and reliable power grids, which are key to the integration of clean energy sources and can directly influence the profitability of energy projects and the business climate. The Continental Power System Masterplan (CMP) for Africa, which results from a decade of analysis at the regional and national levels on the integration of sub-regional power systems and markets, is intended to fill the gap in terms of the roll out of clean energy solutions in Africa. The IAEA and International Renewable Energy Agency (IRENA) are among the modelling partners that have been selected by the African Union Development Agency-New Partnership for Africa's Development (AUDA-NEPAD) for the design of the CMP architecture and the assessment of its benefits (see Spotlight 7).

Box 9: Contributed by the Ghana Nuclear Power Programme Organisation

Ghana’s model for economic development

Long before climate change generated the global outcry that it does today, the first President of Ghana placed nuclear power on Ghana’s energy mix agenda in the mid-1960s, after having constructed the largest hydropower plant in the country with an installed capacity of 1020 MW. Ghana’s nuclear programme commenced with the establishment of the Ghana Atomic Energy Commission in 1966, an institution that would drive the nuclear power programme agenda through to human resource development and a research centre for the various applications of nuclear energy.

At the launch of the nuclear project in November 1964, the first President of Ghana made this statement “We have been compelled to enter the field of atomic energy, because this already promises to yield the greatest economic source of power since the beginning of man. Our success in this field would enable us to solve the many-sided problems which face us in all the spheres of our development in Ghana and in Africa.” The nuclear project was, however, truncated after a military coup d’état in 1966. In the early 1980s, Ghana experienced its first nationwide power outages due to insufficient installed generation capacity. These outages led to the inclusion of thermal plants into the energy mix with the use of heavy fuel oil. Energy shortages occurred once again in the mid-1990s and in early 2000.

These shortages, among other factors, led to the government taking a Cabinet decision in 2008 to include nuclear energy into the country’s energy generation mix, following recommendations from the Presidential Committee set up in 2007 to advise the government of the potential of adding nuclear energy to the country’s energy mix. Nuclear energy was subsequently rejuvenated, with the Government of Ghana declaring to the IAEA in August 2013 its intention to pursue a nuclear power programme for peaceful purposes.

Figure 41: Roadmap of the Ghana Nuclear Power Programme.

National Commitment: 2015 – 2018

National Decision: **2020**

2025 — 2030 — 2035 — 2045

Preparation of program: Comprehensive studies & report

- Legal gap analysis
- HR gap analysis & strategy
- Public awareness
- Regulatory body startup
- Competence development program
- Site survey (candidate sites)
- Grid study
- INIR 1 / PCR

Project feasibility & Development phase

- Site selection & assessment (e.g. EIA, PSHA, Dam/Flood)
- HR training & development
- Grid enhancements
- Establishment of licensing procedures
- Regulatory processes for authorisations, inspections & enforcements
- Designation of owner-operator
- Development of IMS
- Technology selection & requirements
- Contract
- INIR 2 / Implementation

Construction of the first nuclear power plant

- Agreement with vendor & construction phase
- HR training & development
- CRR mission

Commissioning & operation of the first nuclear power plant

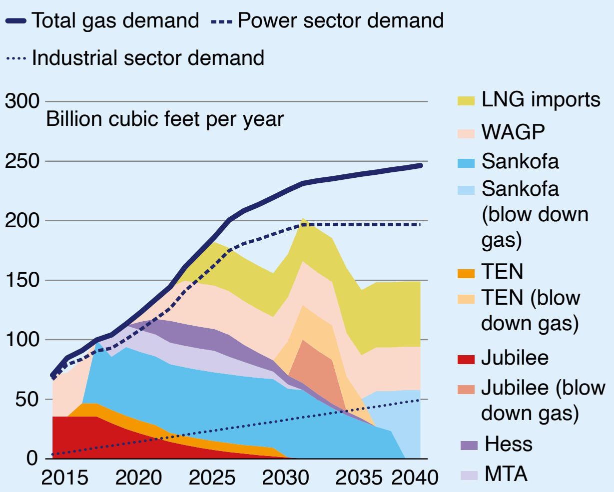
Fuel management

Waste management

Source: Ghana Ministry of Petroleum (2016).
Note: CRR — Country Review Reports, EIA — Environmental Impact Assessment, IMS — integrated management system, PCR — programme comprehensive report, PSHA — probabilistic seismic hazard analysis.

The Ghana Nuclear Power Programme Organisation was established to oversee the implementation and coordination of the nuclear programme and the development of the nuclear infrastructure required for the successful introduction of nuclear energy into the generation mix. However, the discovery of oil and gas in commercial quantities in Ghana slowed activities related to the nuclear programme, which had established a target of commissioning the first nuclear plant by 2024. This date was subsequently postponed to 2030.

Figure 42: Base case scenario of Ghana's gas to power supply.



Source: Ghana Ministry of Petroleum (2016). Note: Various sources of gas supply, including gas fields and pipelines, are listed in the legend.

Studies of hydrocarbon reserves in Ghana have demonstrated that Ghana's reserves will dwindle from 2027, with the country having to depend heavily on imports to meet its energy needs, to the detriment of energy security.

The government has thus established the two key institutions recommended by the IAEA, namely, the Nuclear Regulatory Authority, to regulate the nuclear energy sector and all nuclear installations, and Nuclear Power Ghana, the proposed owner/operator company.

In 2017 and 2019, upon the invitation of Ghana, the IAEA International Peer Review mission undertook a review of Ghana's Phase 1 nuclear infrastructure development studies and concluded that Ghana has undertaken all the prescribed studies for government to make a knowledgeable commitment to a nuclear power programme. These studies and activities have been consolidated into the nuclear programme's Comprehensive Report.

Today, Ghana has identified nuclear power as key to the country's energy transition agenda and has included it in its 2020 NDC to the UNFCCC. Secondly, nuclear energy is expected to serve as a clean baseload energy to support the nation's industrialization agenda. Having nuclear in the energy mix will lower end user tariffs, which will further open the West African Power Pool to Ghana in order to trade energy with the West African region. By the end of 2022, Ghana is expected to identify a vendor country and nuclear technology for the country. Ghana is considering both large reactors and SMRs.

In July 2022, the President of the Republic of Ghana issued a declaration on the inclusion of nuclear technology in the national electricity generation mix after thorough review of the Ghana Nuclear power Programme Organisation Phase 1 report.

Today, Ghana has identified nuclear power as key to the country's energy transition agenda. Secondly, nuclear energy is expected to serve as a clean baseload energy to support the nation's industrialization agenda.

Box 10: Contributed by Kenya Nuclear Power and Energy Agency

Keeping the nuclear option in Kenya

Kenya’s climate agenda

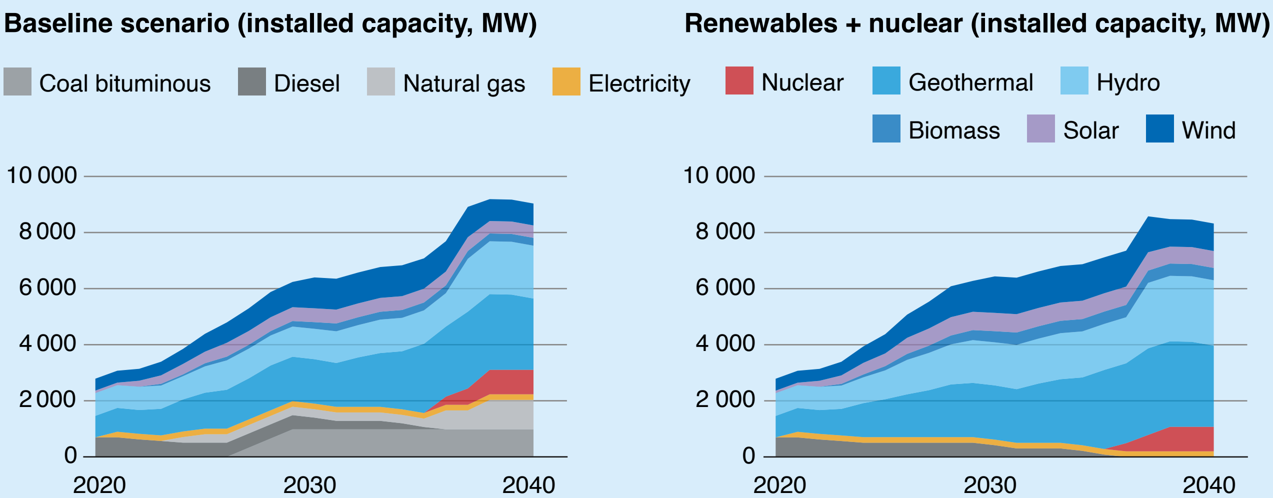
The primary aim of Agenda 2063: The Africa We Want is a “prosperous Africa, based on inclusive growth and sustainable development”. To meet this aspiration, the continent has set a goal for environmentally sustainable and climate resilient economies and communities, which includes prioritizing climate resilience, natural disaster preparedness and prevention and renewable energy. Extreme weather manifestations in Kenya are already causing disruptions in livelihoods. Greenhouse gas (GHG) emissions from electricity generation are already high and are expected to increase significantly by 2030 and beyond.

Kenya has joined global efforts to reduce GHG emissions by signing the Paris Agreement. Kenya’s NDCs set a 30% emission reduction target by 2030 relative to business as usual projections. The 2020 NDC update increased Kenya’s efforts to a 32% abatement by 2030. Kenya’s National Climate Change Action Plan provides a framework strategy for implementation. Emissions from seven sectors are targeted: transport, agriculture, energy demand, electricity generation, waste, industrial processes and forestry. The power sector emissions are to be cut, with a substantial increase in the share of renewables, chiefly from geothermal sources. Kenya is also developing its mid-century (2050) long term strategy for a low carbon development pathway under the Paris Agreement, which includes nuclear energy among the main low carbon energy sources designed to further reduce emissions.

Meeting climate mitigation objectives with a combination of renewable and nuclear energy

Currently, renewable energy sources account for more than 70% of the country’s electricity production. Existing renewable capacity is nonetheless insufficient to meet the projected increase in energy demand, and additional low carbon sources therefore need to be developed in Kenya. Nuclear power, a potential source of low carbon electricity, can be integrated with renewable capacities to form a clean electricity system. An assessment conducted by the Nuclear Power and Energy Agency shows that nuclear power can contribute to Kenya’s climate targets when combined with renewable sources (see Figure 43). In a business as usual scenario, CO_2 emissions grow drastically from 2020 to 2040 as electricity

Figure 43: Installed power capacity and emissions in Kenya, 2020–2040.



Source: Nuclear Power and Energy Agency (2022).

needs are partially met with the deployment of new fossil fuel capacities. By contrast, a scenario drawing solely on renewable and nuclear energy sources leads to a drastic fall in CO_2 emissions. Residual emissions in the renewables & nuclear scenario stem from existing diesel power units, which operate until the end of their planned lifetimes.

Nuclear energy is gaining recognition as a mitigation option to avoid future emissions from growing energy demand. As confirmed by its inclusion in national policies and strategies for climate change mitigation, the country will join global efforts to recognize nuclear power as an important contributor in the reduction of global GHG emissions. Such recognition calls for fast tracking the implementation of the Kenyan nuclear power programme and the timely development of a dedicated infrastructure. Promoting the coordinated deployment of renewables and nuclear energy across relevant state agencies and among non-state actors is also key.

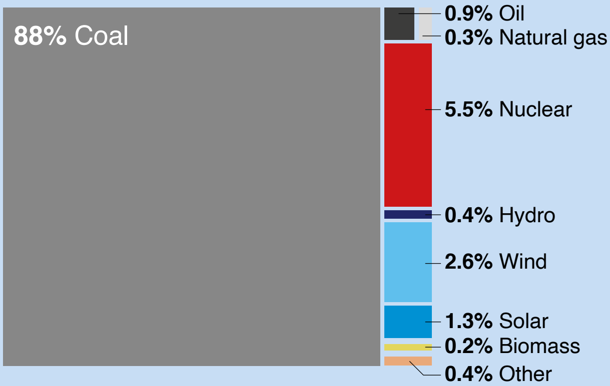
Nuclear energy is gaining recognition as a mitigation option to avoid future emissions from growing energy demand.

Spotlight 6:

The coal challenge in South Africa

South Africa's electricity system is dominated by coal power, making up 86% of generation in 2021, although the country is expected to see significant shifts away from coal. This shift will mainly be driven by plans to decommission around 10.5 GW of the ageing coal fleet by 2030, rising to 35 GW by 2050 (compared to the current 44 GW of installed coal capacity). The move provides South Africa with an opportunity to develop a completely different electricity mix relative to today. The system requirements are largely for incremental capacity addition (modular) and flexible technologies, to complement the existing installed inflexible capacity. The African Development Bank estimates that South Africa would need more than $30 billion for the transition (AfDB, 2022).

Figure 44: Electricity generation mix in South Africa.



Source: IEA (2022e).

Decarbonizing the electricity sector is one of the core elements of South Africa's Integrated Resource Plan (DMRE, 2019), which sets out plans for a long term diversification of the power system by 2030. The government is committed to achieving a 15% reduction in coal power production and an 18% increase in renewable energy by 2030, meeting a growing energy demand and ensuring a socio-economically just transition.

The initial decline in coal power is expected to be met by an increase in the deployment of gas and renewables.

However, in the longer term, nuclear power is considered an attractive option. SMR units are expected to be a much more manageable investment than traditional large reactors.

The Just Energy Transition Partnership announced in November 2021 is an ambitious initiative to support South Africa's decarbonization efforts. The partnership with the EU, France, Germany, UK and the USA aims to accelerate the decarbonization of South Africa's economy, with a focus on the electricity system, and to help achieve the NDC emission goals. It will mobilize an initial commitment of $8.5 billion for the first phase of financing through various mechanisms, including grants, concessional loans and investments, and risk sharing instruments, as well as a through private sector funding (European Commission, 2021a).

The National Development Plan 2030 envisages that adequate investment in energy infrastructure will promote economic growth and development. Through the African Energy Transition Facility, South Africa can leverage on the $8.5 billion in grants from G7 countries in order to generate all of the financing it needs for its just energy transition, without entering into debt. The bank is also preparing a $400 million package to support the country's electricity utility company, Eskom, as it transitions to renewable energy (AfDB, 2022).

The initial decline in coal power in the overall system is expected to be replaced by an increase in the deployment of gas and renewables. However, in the longer term, nuclear power is considered an attractive option. In this regard, SMR units are expected to be a much more manageable investment than traditional large reactors.

South Africa has benefited from nuclear power for almost four decades, with the Koeberg Nuclear Power Station reaching its 40 year design life in 2024. Plans are already in place to extend its design life and nuclear safety licence for another 20 years.

Of the advanced generation IV nuclear technologies, South Africa is particularly interested in the pebble bed nuclear reactor technology, an SMR technology that would be particularly well suited to South Africa for a range of reasons, for example, it:

- builds on domestic experience and knowledge;
- contributes to job creation and skills development;
- reinforces economic and industrial stimulation;
- represents lower costs, shorter construction times (important for replacing a rapidly ageing coal fleet);
- eliminates dependence on large amounts of water for cooling;
- reduces dependence on location/siting of the power plant, eliminating the need for long transmission lines.

However, increasing nuclear capacity in South Africa is not without its challenges given the ageing workforce and shortage of skills. There will be a need to attract new workers into the nuclear workforce and build the skills required. Long term planning on the part of government will also be essential if nuclear energy projects are to be implemented in the context of overall decarbonization objectives.

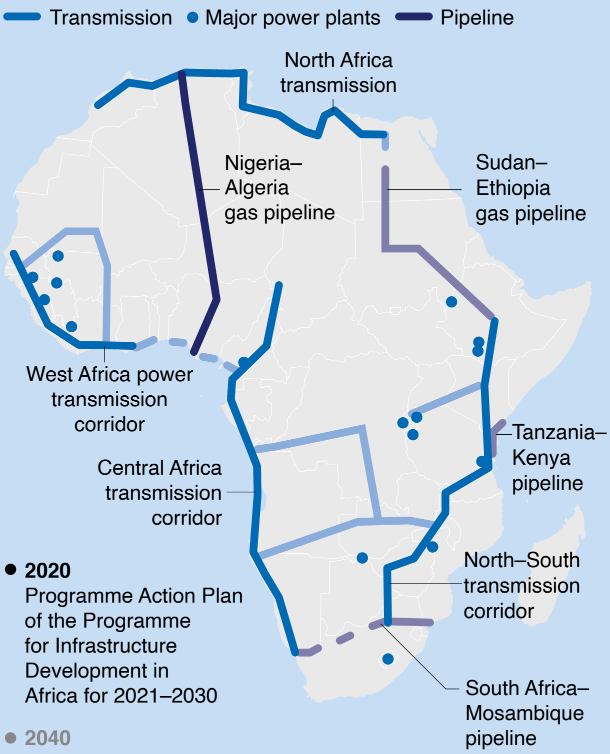
Spotlight 7:

The Continental Power System Masterplan for Africa

The CMP Africa initiative, supported by the EU Technical Assistance Facility, is a response to Africa's acute energy challenges. It will serve as a 'blueprint' for the African Single Electricity Market. By prioritizing national initiatives and projects, the CMP will make it possible for countries to take advantage of complementarities between national systems, leveraging national and regional diversity in resources and demands.

The CMP will create a common and harmonized platform for project decision making regarding the location, size and timing of investments in generation and transmission infrastructures, unlocking cross border power exchanges and trade among sub-regional power pools. The development of regional energy infrastructure is thus expected to catalyse the creation of large and competitive markets by exploiting economies of scale, both on the supply and demand sides.

Figure 45: Electric transmission and natural gas interconnections in Africa.



Source: adapted from African Development Fund (2021).

Many identified generation or related interconnection projects are large scale. These projects can be competitive and realized only through strong sub-regional cooperation, cost/ownership sharing and power systems integration so that supply and demand areas are connected and well matched. Many of the supply options are dispersed among sub-regions, and joint operations would enable the deployment of complementarities among the technological options.

Through the provision of energy system assessment tools and technical assistance in conducting energy and electricity system analysis, modelling partners under the CMP initiative are oriented towards:

- Detailed modelling and development of case studies of sub-regional power systems and interconnections;
- Provision of training in the use of the IAEA (and IRENA) energy system assessment tools;
- Comparative assessments of supply and trade options to meet electricity demands in a regional context, and identification of priority power generation and transmission projects, as well as analysis of alternative scenarios reflecting sustainable development on the African continent;
- Meeting the goals of regional integration, increased energy accessibility and affordability, security of supply and environmental protection, including mitigation of adverse impacts on the climate.

06

Policies enabling investment for a secure, low carbon energy transition: Shaping markets, sharing risk and empowering partnerships

Key messages:

- **A coherent set of policy, regulatory, infrastructure and other measures is vital to guide markets and investors, foster cooperation and manage risks.**

- **Significant mobilization of energy investment for climate action, balanced with support for broader development and energy security needs, can drive nuclear investment.**

To achieve climate neutrality and limit global warming to 1.5°C, energy sector investment must be scaled up and directed towards more sustainable activities that support climate change mitigation and adaptation. At the same time, the world is confronted with the need to reinvigorate and rebalance energy sector investment to address energy security vulnerabilities and broader development challenges. These goals can be supported and facilitated in a number of ways by decision makers in government, and to an increasing degree, by the private sector, for example through direct public investment, project and financial risk sharing arrangements, market instruments, regulations, standards (including sustainable investment classification taxonomies) and other measures.

Investment needs for net zero

To achieve net zero emissions by 2050, the IEA estimates that global electricity sector investment will need to more than double from recent levels to over US $2 trillion annually between 2023 and 2030 (IEA, 2021j). This includes an almost 2.5 fold increase in annual nuclear energy investment to over US $100 billion, along with a similar increase in investment in renewable power and electricity networks. Such a surge in investment will enable the development of substantial low carbon electricity infrastructure for the coming decades, helping to reduce future investment requirements over the longer term (IEA, 2021c). The IEA nevertheless estimates that more than US $50 trillion of cumulative investment will be needed in the electricity sector by 2050, including more than US $2 trillion in nuclear power — primarily in the Asia Pacific (especially in China), Europe and North America — to transition the global energy system onto a pathway to net zero (IEA, 2021a).

Mobilizing sustainable investment

Despite some positive developments (IAEA, 2021e), including an increasing recognition of the role of nuclear energy in meeting national climate commitments (see Spotlight 8), recent trends indicate that the current market and policy environment may be unable to mobilize the scale of investment needed to achieve net zero. Given the amounts of investment required and the current misallocation of financial resources, providing investors with additional guidance on which activities are compatible with long term climate and sustainability goals is a key element in the framework of policies and measures needed to drive the low carbon energy transition.

In this context, both governments and the private sector — the latter as part of environmental, social and corporate governance (ESG) frameworks — are developing classification systems with clear definitions of what constitutes ‘sustainable’. These classification systems seek to facilitate the flow of finance by providing security for investors, mitigating market fragmentation and supporting companies to become more climate friendly. It is increasingly recognized that such guidance can also mobilize finance towards investments that address short and long term energy security as an additional pillar of a sustainable energy system.

Examples of sustainable investment classification systems around the world range from approaches led by the private sector, such as self-labelled ‘green bonds’, with or without independent certification, through to comprehensive frameworks established by governments that specify particular activities and eligibility criteria in detail. These classification systems differ in their treatment of nuclear energy.

Private sector green bonds

In the broadest sense, green bonds are financial instruments used to fund projects that have measurable environmental or climate benefits. The issuance of self-labelled green bonds (i.e. bonds designated as ‘green’ by the issuer) has grown rapidly across the world (see Figure 47), with the total value of new green bonds projected to hit US $1 trillion in 2023 (CBI, 2021a). Within the private sector, classification and certification regimes have emerged to support investors in prioritizing investments that genuinely address climate change; examples include the Green Bond Principles (GBP) — a set of guidelines established by Bank of America Merrill Lynch, Citi, Credit Agricole and JP Morgan Chase, which is now administered by the International Capital Market Association (ICMA, 2021) — and the Climate Bonds Standard (along with the associated Climate Bonds Taxonomy) (CBI, 2021b), under which 17% of green bonds were certified globally in 2019 (CBI, 2020).

Nuclear energy is excluded from some of these private sector green financing initiatives, such as the Climate Bonds Standard, despite its strong performance across many ESG criteria (see Box 11), while it is permitted (often implicitly) by others, including the GBP.

Spotlight 8:

Nuclear energy in 2030 commitments and long term strategies

As of mid-2022, 14 countries have assigned an important role to nuclear energy in their latest nationally determined contributions (NDCs) submitted under the Paris Agreement (UNFCCC, 2022b). Notably, this does not include any of the 13 EU countries that use nuclear power, which are covered by the NDC submitted by the European Commission (which does not mention nuclear power).

Beyond NDCs, close to 20 countries include nuclear energy in their so-called “long term low GHG emission development strategies” (LTS), communicated under the Paris Agreement (including 14 countries that do not include nuclear energy in their NDCs) (UNFCCC, 2022a). Together, these countries accounted for over 70% of global energy related emissions in 2019 (IEA, 2021k).

Figure 46: Nuclear energy in national commitments and strategies, mid-2022.

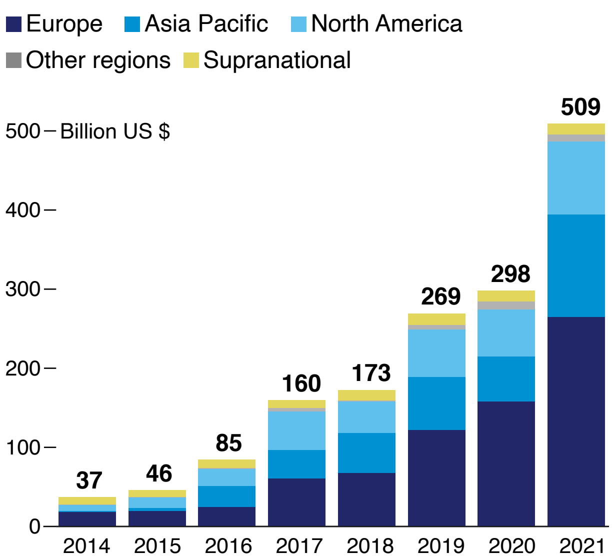
	Using nuclear power today	Constructing first nuclear power plant	Other countries
Nuclear energy in NDC and LTS	Canada, China, Ukraine, UK, USA		
Nuclear energy in NDC only	Argentina, Armenia, India, Iran (Islamic Rep.), Russian Fed., United Arab Emirates	Türkiye	Korea (DPR) Ghana
Nuclear energy in LTS only	Czech Rep., Finland, France, Hungary, Japan, Mexico, Netherlands, Slovakia, Slovenia, Sweden		Australia, Colombia, Morocco, Singapore
Nuclear energy not included in NDC or LTS (or mentioned in the context of moratoria or phase-outs)	Belarus, Belgium, Brazil, Bulgaria, Germany, Korea, Rep., Pakistan, Romania, Switzerland, South Africa, Spain	Bangladesh, Egypt	Rest of the world

Source: UNFCCC (2022a; 2022b); IAEA (2021a). Note: the Republic of Korea recently announced plans to revise its NDC and LTS to increase the role of nuclear power (Republic of Korea, 2022). Korea (DPR)— Democratic People’s Republic of Korea, INDC — intended nationally determined contribution, NDC — nationally determined contribution, LTS — long term low GHG emission development strategy.

The issuance of green bonds has grown rapidly across the world.

The success of the Canadian nuclear utility Bruce Power in raising 500 million Canadian dollars in late 2021, in accordance with the GBP “to finance or re-finance eligible investments associated with life extension and increasing output of [the utility’s] existing units…” illustrates the potential to finance nuclear energy via green bonds under private sector classification systems (Bruce Power, 2021a; Bruce Power, 2021b). Nevertheless, the existence of a diverse range of definitions and criteria for sustainable investment, alongside the risks for investors from self-labelled green bonds (particularly greenwashing),[4] has driven the development of sustainable classification systems (or taxonomies) by governments, central banks and regulators.

Figure 47: Global green bond issuance.



Source: based on data from CBI (2021a; 2022).

[4] The deceptive use of marketing to overstate the environmental performance of a product or activity.

Box 11: Contributed by George Borovas, Hunton Andrews Kurth LLP

Should nuclear energy be a top priority for green financing?

Over 110 countries have established sustainability goals and pledged to be carbon neutral by 2050, resulting in a greater focus on the environmental awareness and sustainability practices of companies. ESG criteria are an increasingly popular way for investors to evaluate companies in which they might want to invest.

Nuclear energy is arguably one of the cleanest and most efficient sources of energy and has the potential to contribute significantly towards providing a sustainable, scalable and relatively economical option to meet the growing global energy demand. So, should nuclear energy then be a top priority for ESG financing?

Nuclear energy satisfies a number of important ESG criteria:

- Nuclear energy outperforms many other low carbon forms of energy because nuclear power plants generate practically carbon free electricity 24/7 while producing very low quantities of hazardous waste.

- Nuclear power plants require significantly less land and materials than other low carbon forms of energy, thereby lowering their life cycle environmental impact.

- Nuclear power is a demonstrably safe form of energy with one of the lowest fatality rates per unit of electricity output compared with other energy sources.

- Nuclear waste is fully accounted for and its costs are considered as part of the development of a nuclear energy project.

- The nuclear power industry is one of the most highly regulated industries globally, with worker safety and local community impact continuously considered throughout the life cycle of a nuclear power plant.

- The construction and operation of nuclear power plants require highly educated and trained employees, increasing the pool of highly skilled workers in the labour force, from which other economic sectors can also benefit.

- Staff engaged in the nuclear power sector have long term job prospects and comparative job stability.

While the potential for nuclear accidents — a very low probability, but potentially high impact, event — and the disposal of nuclear waste are the most commonly cited issues when assessing nuclear energy against ESG criteria, the very low carbon footprint of nuclear energy compared to other energy sources makes it a critical contributor to meeting global environmental policy goals. The technology's contribution to a skilled and educated workforce with high paying local jobs should make an even stronger case for investors to reassess nuclear energy against ESG criteria.

The very low carbon footprint of nuclear energy compared to other energy sources makes it a critical contributor to meeting global environmental policy goals.

Sustainable investment taxonomies

One of the most prominent green investment classification systems established by governments is the **EU** taxonomy for sustainable activities (European Commission, 2022b), which currently covers areas such as energy, manufacturing, forestry, water supply, waste management, transport and construction, with more activities likely to be included over time (McGuinness, 2022). Implemented under the EU taxonomy regulation (EU, 2020), it addresses six environmental objectives: (i) climate change mitigation; (ii) climate change adaptation; (iii) sustainable use and protection of water; (iv) the transition to a circular economy; (v) pollution prevention and control; and (vi) protection of biodiversity and ecosystems. The taxonomy also incorporates the principle of 'do no significant harm' (DNSH) — i.e. in addition to contributing significantly to one or more of the six environmental objectives, activities must also avoid significant harm to other objectives. An initial list of eligible activities and technical screening criteria for climate change mitigation and adaptation was adopted in 2021 (European Commission, 2021b).

Recognizing the potential contribution of nuclear energy, the EU recently proposed criteria for nuclear energy activities to qualify as contributing substantially to climate change mitigation and adaptation, covering advanced pre-commercial nuclear technologies, lifetime extension of existing nuclear plants (for electricity generation) and new nuclear plants (for electricity, heat or hydrogen production) (European Commission, 2022c). The criteria address the DNSH principle in relation to water, recycling, pollution and biodiversity, and establish requirements for radioactive waste disposal and accident tolerant fuels which provide "additional protection against accidents resulting from structural damages to fuel or reactor components" (European Commission, 2022c). Under the EU proposal, which will enter into force in 2023, new or existing nuclear power plants must be authorized before 2045 or 2040, respectively, to qualify (see Table 1 in Appendix).

While the taxonomy only provides guidance, and neither mandates nor prohibits investments (McGuinness, 2022), companies that fall under its scope are required to report information about the sustainability of their activities and products. It is also expected that the companies will use the taxonomy to guide their activities and product design (European Commission, 2021c). The development of the EU taxonomy has also informed other emerging taxonomies. One example is the **Republic of Korea's** green K-Taxonomy announced in 2021, which adopts the same six environmental objectives as the EU taxonomy (Republic of Korea, 2021a; 2021b). The Ministry of Environment recently announced plans to include nuclear energy in the K-Taxonomy (Republic of Korea, 2022).

Figure 48: Examples of nuclear energy in sustainable investment taxonomies.

	Nuclear energy included	Nuclear energy currently excluded	Nuclear energy classification to be determined
National and regional sustainable finance taxonomies and roadmaps	China, European Union, Japan *(implicit)*, Korea, Rep., Malaysia *(implicit)*, Philippines, Russian Federation	ASEAN, Bangladesh, Canada, Colombia, Kazakhstan, Mongolia, South Africa, Thailand	Chile, Indonesia, Singapore, UK *Under development/ discussion:* Dominican Republic, India, Mexico, New Zealand, Sri Lanka, Viet Nam
Private sector initiatives	Green Bond Principles (ICMA) *(implicit)*	Climate Bonds Standard (CBI)	

Source: ASEAN Taxonomy Board (2021), Bangladesh Bank (2020), Canada (2022), Chile (2021), People's Bank of China (2021), Colombia (2022), European Commission (2022b), Indonesia (2022), Japan (2017), Kazakhstan (2021), Republic of Korea (2022), Central Bank of Malaysia (2021), Financial Stability Commission of Mongolia (2019), Philippines (2021), Russian Federation (2021), Republic of South Africa (2022), Thailand (2020), UK Government (2021), CBI (2021b), FoSDA (2021), GFIT (2021), ICMA (2021), OECD (2020b). Note: ASEAN — Association of Southeast Asian Nations.

The **Russian Federation** has also adopted a Green Taxonomy (Russian Federation, 2021), which draws on the recommendations from the Technical Expert Group for the EU taxonomy when specifying the criteria for electricity generation (adopting the same emissions threshold for gas fired power plants of 100 grams of CO_2 equivalent per kW·h) (European Commission, 2022c). The Russian taxonomy is among the most permissive regarding nuclear energy, listing a range of activities (e.g. nuclear power plants, equipment, fuel and waste) without additional criteria.

Sustainable finance definitions and classifications have also been adopted, or are under development, in many other countries as shown in Figure 48. As in the case of the examples listed above, these countries (and others) are also following taxonomy developments in other parts of the world to inform the design of their own systems. In total, at least 33 countries, representing almost half (48%) of global energy emissions, are covered by taxonomies (implemented and proposed) that include nuclear energy, either explicitly or implicitly. Countries that have excluded nuclear energy from their taxonomies account for less than 10% of global emissions.

Among the examples of countries that include nuclear energy, **China** (and more specifically the central bank, the National Development and Reform Commission and the China Securities Regulatory Commission) has issued a catalogue of projects, industries and activities eligible for green financing (People's Bank of China, 2021) that includes the manufacture of nuclear power equipment and the construction and operation of nuclear power plants.[5] Green bond issuance in China almost doubled between 2019 and 2021, amounting to US $62.5 billion (CBI, 2022).

Unlike China, the EU and the Russian Federation, **Japan** has adopted an approach similar to private sector green bond initiatives via the Green Bond Guidelines issued by the Ministry of Environment (Japan, 2017). These guidelines establish a non-prescriptive framework under which issuers are responsible for defining objectives, criteria and processes for determining the environmental sustainability of projects. The guidelines provide only a non-exhaustive list of examples of green projects

[5] In a recent update (2021), "the clean use of coal and other fossil energy" was excluded from the catalogue (Yingzhe, 2021).

and criteria, which does not explicitly exclude nuclear energy. Almost US $4 billion worth of major green bonds had been issued for energy projects by the end of 2021 (from a total of almost US $33 billion), with over 80% dedicated to renewable energy sources, and in particular solar, and with no bonds issued for nuclear projects (Japan, 2022).

Similar to Japan's Green Bond Guidelines, the Climate Change and Principle-based Taxonomy (CCPT) issued by the Central Bank of **Malaysia** in 2021 defines broad guiding principles and provides a non-exhaustive list of activities compatible with climate change mitigation, adaptation and no significant harm (along with remedial measures), as well as prohibited activities. The CCPT does not explicitly exclude nuclear energy, and in fact, refers to the IAEA Safety Standards and Nuclear Security Series among examples of third party certifications and verifications that financial institutions should implement as part of their due diligence (Central Bank of Malaysia, 2021).

In contrast, the Sustainable Finance Policy for Banks and Financial Institutions, issued by the central bank of **Bangladesh**, includes a more specific and detailed list of eligible activities and criteria for sustainable financing, stipulating several excluded activities such as "[n]uclear power generation and related assets" (Bangladesh Bank, 2020). **Canada's** Green Bond Framework and **Thailand's** Sustainable Financing Framework also explicitly exclude nuclear energy (Canada, 2022; Thailand, 2020). While not listing excluded activities, **Mongolia's** Green Taxonomy provides a more exhaustive list of activities eligible for green investment, which does not include nuclear energy.[6] The recently launched Taxonomía Verde de **Colombia**, **Kazakhstan** green taxonomy and **South African** Green Finance Taxonomy similarly do not include nuclear energy in their lists of eligible sectors and activities (Colombia, 2022; Kazakhstan, 2021; Republic of South Africa, 2022).

While many (if not all) of the sustainable finance taxonomies and roadmaps discussed above acknowledge that the classification of activities (including nuclear energy activities) is subject to further development and revision, this is especially the case for taxonomies in earlier stages of development (for example in **Chile, Indonesia, Singapore** and the **UK**).[7] One illustration is the first version of the Association of Southeast Asian Nations (ASEAN) Taxonomy for Sustainable Finance (**ASEAN** taxonomy), published in 2021, which initially focuses on climate change and proposes a classification of activities as 'red', 'amber' or 'green'. Nuclear energy is listed as an example of a red activity that could transition towards amber or green "when DNSH issues are addressed for nuclear waste management" (ASEAN Taxonomy Board, 2021).

Beyond taxonomies: Investment and financial coordination and cooperation

Taxonomies and similar frameworks represent one important way in which governments and the financial sector are seeking to direct and mobilize private financial flows towards sustainable investment. However, given the scale of the challenges around climate change — both mitigation and adaptation — additional forms of public–private collaboration will also be critical. The same is true to a large extent for efforts to rapidly enhance energy security and to diversify energy sources. For both climate and security goals, public sector coordination and financing of infrastructure development is likely to be necessary to leverage private investments and fully unlock the large potential of financial markets (IPCC, 2022a). This includes both 'hard' (e.g. energy grids, critical supply chains, physical adaptation measures) and 'soft' infrastructure (e.g. regulatory and legal frameworks, and human capital). The specific coordinating role of the public sector, and the nature of public–private partnerships, will depend on national circumstances and complementary policy measures — for example, see Box 12.

In addition to national, regional and private sector initiatives and policy support, enhanced international financial cooperation will be essential to realize the low carbon transition, given that many developing countries rely on public resources to finance energy projects (IEA, 2021c). Beyond

[6] A category entitled "[s]ources alternative to coal" is limited to gas power and heat generation.

[7] As well as some other countries not mentioned previously, such as the Dominican Republic, India and Viet Nam (FoSDA, 2021).

existing commitments to scale up public finance flows to developing countries to US $100 billion under the United Nations Framework Convention on Climate Change (UNFCCC), opportunities exist to support local capital market development, expand financing through multilateral development banks (MDBs) and specialized climate finance institutions (CFIs) and leverage private capital by increasing the use of public guarantees. The significant barriers that developing countries face in relation to financing nuclear energy projects can be partly addressed through the adoption of a technology neutral approach in the funding decisions of development and green banks for infrastructure and clean energy funds (Fowler, 2020; IAEA, 2021c).

Beyond the need for policy interventions to accelerate the deployment of low carbon technologies in the near term (to 2030), securing net zero emissions over the longer term will also necessitate continued public and private investment in R&D to support technology innovation — the IEA expects nearly half of the emission reductions for net zero to come from technologies yet to have reached the market (IEA, 2021c) — including for advanced nuclear energy systems. A key complement to inform the design of R&D and broader energy policy is the robust assessment of long term decarbonization pathways, such as those issued by the IEA and IPCC. Enhancing the representation of low carbon options in such assessments is critical to identifying critical mitigation technologies and lower cost pathways to reach net zero — Box 12 describes one of the several initiatives to strengthen such analysis.

Securing net zero emissions over the longer term will also necessitate continued public and private investment in R&D to support technology innovation.

Box 12: Contributed by UK National Nuclear Laboratory

Nuclear deployment scenarios to support assessment of net zero

In June 2021, the UK National Nuclear Laboratory (NNL) published a groundbreaking new modelling report, demonstrating the role that nuclear energy can play in delivering the United Kingdom’s net zero goals (NNL, 2021a). This modelling represents the first time that a comprehensive range of diverse, scalable and low cost applications of nuclear technologies have been fully analysed across the whole energy system. By including such a range of nuclear applications within the modelling — which in itself is innovative in that it assesses the entire energy system and not just the power sector — the work reveals potential routes to de-risk and lower the cost of achieving net zero.

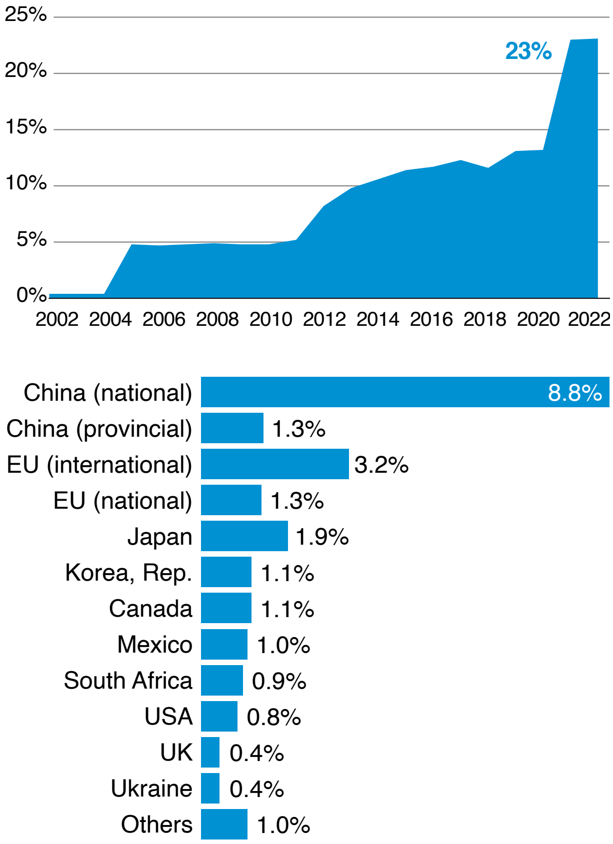
The modelling, which was conducted by independent specialists from Energy Systems Catapult and LucidCatalyst, thus considers the entire energy system on the path towards net zero. It examines the role of nuclear energy in providing not just electricity but also heat, hydrogen and synthetic fuels. This work was completed using 46 million UK pounds from the Advanced Fuel Cycle Programme (AFCP), which is led by NNL in partnership with the UK Department for Business, Energy and Industrial Strategy, as part of the 505 million UK pound Energy Innovation Programme (AFCP, 2021).

By adding to the national and international dataset that considers pathways to decarbonization, this modelling provides government and industry with crucial information to support decision making. It has already been used to underpin the AFCP’s Fuelling Net Zero: Advanced Nuclear Fuel Cycle Roadmaps for a Clean Energy Future, published in 2021 (NNL, 2021b).

Financial instruments, regulatory measures and targeted policy support

Taxonomies and other initiatives only partly address barriers to energy investment, and complementary policy measures are required to provide additional incentives and manage various project and market risks. Among these, carbon pricing — principally carbon taxes or tradable carbon emission rights — has generally been viewed as the cornerstone of any efficient climate change mitigation policy. By 2022, the share of global GHG emissions covered by carbon pricing instruments reached around 23% (World Bank, 2022f) — see Figure 49 — with the top 10 countries (including the EU) by share all using nuclear energy. It is widely recognized that such instruments alone are nevertheless unlikely to be sufficient, and thus carbon pricing needs to be part of an integrated package of complementary policies (IPCC, 2022a).

Figure 49: Share of global GHG emissions covered by regional, national, provincial, state and municipal carbon pricing initiatives.



Source: adapted from World Bank (2022f).

For the energy sector, specific complementary instruments, such as power purchasing agreements (PPAs), contracts for difference (CfDs) and regulated asset base (RAB) models have been used or are under consideration in various power markets to finance construction and operation of low carbon generation, including nuclear power plants. Equally important, however, is ensuring energy markets are designed and regulated in a way that supports the investment required for the energy transition — see Spotlight 9.

PPAs guarantee the purchase of electricity at a set price and are widely used to finance everything from natural gas plants to solar arrays, under varying terms. A PPA is supporting the financing of the Akkuyu NPP in Türkiye, which will sell 50% of its output for 15 years to the state-owned electric utility and then distribute 20% of its profits to the Turkish Treasury for the remainder of its operating lifetime (Avsar, 2019). Similarly, CfDs are another instrument to share price and revenue risks. The electricity buyer and seller agree on a strike price: if the market price is higher than the strike price, the electricity seller pays the buyer the difference. Conversely, if the market price of electricity is lower, the electricity buyer pays the seller (IEA, 2019d). In 2016, a CfD agreement with a term of 35 years was signed for the Hinkley Point C nuclear power plant in the UK.

Beyond PPAs and CfDs, which can support project development by managing pricing and revenue risks, RAB financing models also address risks related to project development by providing a regulated return during project construction —see also Spotlight 9. The RAB model thus reduces the upfront cost and risk for the developer, which translates into a lower overall project cost. The RAB mechanism has been used to finance other capital intensive infrastructure projects in the UK (UK Government, 2020b) and has been proposed for the Sizewell C nuclear power plant. So-called hybrid RAB models have also been proposed to share the risk of cost overruns (Newberry et al., 2019). Other mechanisms for addressing similar project risks range from loan guarantees through to sovereign financing.

Spotlight 9:

Designing electricity markets to drive long term investment

In liberalized electricity markets around the world today, wholesale electricity spot prices are largely determined by short run marginal generation costs — i.e. the sum of variable operation, maintenance and fuel costs of the most expensive generator needed at any given time to meet demand. While highly efficient for electricity dispatch, this arrangement has nevertheless created both volatile prices and challenges to electricity generators in recouping their full costs. Such phenomena are likely to be exacerbated in the transition towards a decarbonized system. In the EU, for example, the share of generation costs covered by electricity sales declined from 77% in 2010 to below 60% in 2017 (IEA, 2018). Without market design changes and the implementation of a robust carbon price, this share could fall below 50% within the next decade.

As a result, electricity markets are increasingly failing to mobilize the investment needed for a reliable and low carbon electricity system. Taking the EU as an example once again, the vast majority of investment in new electricity generation over the past decade has not been driven by the market, but has instead relied on other forms of support.

To reach net zero and ensure a reliable and secure electricity supply, electricity market designs and regulations need to evolve. A number of options could help to align market design with long term investment needs and climate goals, in particular the development of an additional competitive market for long term contracts. This could reduce revenue risks, and thus the cost of capital for new investment in low carbon technologies, as well as the cost of the overall energy transition, while providing consumers with confidence over the long term in terms of electricity pricing and supply. Such developments could be realized via long term capacity markets, feed-in premiums (providing a fixed subsidy per unit of generation), RAB financing models (including hybrid RABs), or CfDs and PPAs with much longer terms than traditionally used, among other options. Additional reforms to short term markets could also be considered, such as real time and nodal pricing, which would provide signals to encourage better coordination of network and generation development, particularly for investment in renewable generation capacity.

Spotlight 10:

Policy insights from robust energy modelling

Several key policies to realize an affordable power system compatible with carbon neutrality have been identified in a recent comprehensive energy modelling analysis — Energy Pathways to 2050 — by the transmission system operator in France, Réseau de Transport d'Électricité (RTE) (RTE, 2021). The analysis is based notably on a methodology incorporating a full representation of the electricity system (i.e. generation, network and consumption) and technologies, similar to the framework described in Box 12.

Given the urgent need to address climate change, the analysis identifies the necessity "to facilitate and accelerate by all means possible" the deployment of low carbon electricity, but it also notes that the revenues available in energy markets are unlikely to be sufficient to finance the renewable and nuclear electricity generation capacity required. It therefore highlights a critical role for public support, including via PPAs, CfD, feed-in tariffs or direct public investment, as well as effective carbon markets. The study notes that nuclear power can be economically competitive if a technology neutral approach to financing is adopted. The report also identifies the need to accelerate the approval processes for wind, solar and nuclear projects in line with emission reduction goals, particularly if deployment of any one of these options is prohibited.

Spotlight 1 in Chapter 2 further elaborates on the Energy Pathways to 2050 analysis.

Box 13: Contributed by the Netherlands Ministry of Economic Affairs and Climate Policy

Dutch perspective on policies supporting low carbon energy investment

A good climate policy provides opportunities to build a strong and sustainable economy and create new jobs. It is the aim of the new Dutch government, in place since 10 January 2022, to ensure that the Netherlands is ready for the future — climate neutral, fossil free and circular — with a clean energy supply and green industrial policies. The climate goal of limiting the temperature increase to 1.5°C, as set out in the Paris Agreement, should be achieved by enabling households and communities, companies and corporations, towns and villages to make the required sustainable transitions.

To become climate neutral by 2050, the Netherlands is strengthening its 2030 goal set out in the Climate Act to reduce carbon emissions by at least 55%. To ensure that this goal is achieved, the current government agreed to focus policy on greater reductions, which will amount to approximately 60% in 2030.

The parties in the new government coalition recognize that nuclear energy can complement solar, wind and geothermal energy, and can be used to produce hydrogen, while reducing the Netherlands' dependence on imported gas.

Industry

Policies to support the lowering of carbon emissions encompass all sectors, covering the built environment, agriculture, mobility and industry. Concerning industry, the level of ambition will be raised even further. To achieve higher national ambitions, the government will look first to the sectors covered by the European Emissions Trading System, alongside the 'Fit for 55' commitments.

The government plans on making binding, customized agreements with the 10 to 20 largest emitters of GHGs. These customized agreements will be based on reciprocity, with the government facilitating the new energy infrastructure and entering into agreements that stipulate ambitious sustainability goals.

Climate fund

A €35 billion fund for climate measures over the next ten years is intended for the construction of heat, hydrogen and electricity networks. It will also result in additional spending to make buildings and the transport sector more sustainable. This fund is complementary to the sustainable energy production and climate transition subsidy scheme for renewable energy, which received state aid approval from the European Commission for €20 billion in the period 2022–2025.

Nuclear power investments

The parties in the new government coalition recognize that nuclear energy can complement solar, wind and geothermal energy, and can be used to produce hydrogen, while reducing the Netherlands' dependence on imported gas. The new government of the Netherlands thus intends to take the necessary steps for the construction of two new nuclear power plants and has set aside €5 billion until 2031 to make this possible. The Borssele NPP will also be kept operational longer, with all due consideration given to safety. The new government will assist commercial operators in their exploratory studies, support innovation, carry out tender procedures, consider the contribution (financial or otherwise) to be provided by public authorities and prepare legislation where necessary. The coalition parties have also promised that a safe solution will be found for the storage of nuclear waste.

Additional targeted and regulatory measures

To capitalize on the potential of renewables and nuclear energy to support both a low carbon transition and urgent efforts to enhance energy security, the above measures, aimed at addressing investment and market barriers, should be coupled with complementary regulatory approaches to accelerate deployment — see Spotlight 10. For nuclear energy more specifically, this would include a consistent policy approach and process for approving the lifetime extensions of existing power plants, as well as more streamlined (and ideally, internationally consistent) approval processes for new plant designs that account for the size, inherent safety and emerging applications of advanced and modular reactor technologies.

Without a coherent framework combining many or all of the elements described in this chapter (taxonomies, infrastructure coordination, carbon pricing, optimal market design and regulation, risk sharing mechanisms, etc.), temporary targeted measures — e.g. the US Civil Nuclear Credit Program — may be necessary to overcome short term market failures that have the potential to undermine long term mitigation and energy security goals, particularly to avoid premature retirement of existing low carbon nuclear capacity (US DOE, 2022).

Electricity markets and regulations need to evolve to mobilize the investment needed for a reliable and low carbon electricity system.

Synthesis of key policy measures to enable investment

Mobilizing the energy investment required to address the urgent need for climate action, while capitalizing on synergies in relation to broader development objectives and enhancing energy security, requires a coherent set of policy, regulatory, infrastructure and other measures aimed at:

- **Markets and regulation:** policymakers and regulators can seek to reduce existing energy and investment market barriers and distortions, such as those related to electricity market design and regulation, poorly targeted subsidies, insufficient carbon prices and the absence of mechanisms to value and remunerate system services (including flexibility and reliability) provided by energy producers, including nuclear power plants. Approval processes for low carbon energy projects could also be more closely aligned with the need for urgent action on both climate and energy security.

- **Guiding investment:** the definitions of ESG criteria aimed at directing public and private investment towards low carbon options, including in taxonomies developed by governments, should have a strong scientific basis and avoid arbitrary barriers. By adopting objective and transparent technology neutral criteria, investment can be mobilized and guided to maximize the likelihood of realizing net zero emissions while responding to other aspects of sustainable development.

- **Management of clean energy project risks:** decision makers can adopt coherent targeted policy measures to help mitigate the risks confronting investors in relation to capital intensive, long lived, low carbon energy projects. In particular, such measures can support projects that face long lead times, complex regulatory processes and political uncertainty, as well as those providing substantial non-market benefits such as enhanced long term energy security. Policymakers can facilitate and leverage private investment through measures to manage and share risks during construction (such as via direct public financing or guarantees to debt and equity providers, including regulated asset-based approaches) and schemes to share revenue and pricing risks, such as CfDs or PPAs.

- **Coordination and cooperation:** policymakers will need to coordinate, and potentially finance, the development of hard infrastructure (e.g. energy grids and secure supply chains for critical commodities) and soft infrastructure (e.g. human capital, institutions and legal frameworks) to support the energy transition, enhance international financial cooperation and expand technology neutral financing from MDBs and CFIs — particularly to facilitate flows for energy projects in developing countries — and support local capital market development.

Developing and implementing a policy framework that incorporates the above elements will require strong political and public buy-in. Ultimately, the climate challenge cannot be addressed without this strong public engagement and support for investment in and deployment of clean energy infrastructure. In addition to the above elements, temporary targeted measures may be warranted — for example, during the development and implementation of a coherent policy framework — to avoid premature retirement of low carbon energy capacity, such as existing nuclear capacity, and to discourage investment that would lead to the lock-in of long lived energy supply infrastructure that is incompatible with a secure net zero world.

Mobilizing the energy investment required to address the urgent need for climate action, while capitalizing on synergies in relation to broader development objectives and enhancing energy security, requires a coherent set of policy, regulatory, infrastructure and other measures.

07

Nuclear energy and sustainability: Evaluating impact on a scientific basis

Key messages:

- **When assessed on a life cycle basis, the environmental impact of nuclear energy is on par with renewable energy alternatives.**

- **Energy players are increasingly deploying integrated policy and corporate strategies that work towards carbon neutrality and other sustainable development objectives, particularly biodiversity preservation and restoration.**

Sustainability and nuclear energy: The science basis for impact appraisal

As policymakers currently evaluate their options and revise plans to foster the clean energy transition, the sustainability of various technology routes is now the subject of intense scrutiny. At 12 grams of CO_2 equivalent released for each kilowatt hour generated by a nuclear power plant (median estimate), nuclear energy is indisputably among the least CO_2 intensive energy technologies, and as such is an important contributor to decarbonization (IPCC, 2014).[8] There is, however, a lack of consensus on the sustainability of nuclear technologies. Two major scientific assessments, published recently by the European Union Joint Research Centre (JRC) and the United Nations Economic Commission for Europe (UNECE), have compared energy technologies through their entire life cycle and have underlined the sustainability of nuclear energy.

Nuclear energy has been shown to be comparable with renewable energy alternatives when sustainability is assessed on a life cycle basis, as demonstrated by the two systematic and rigorous appraisals cited above. The EU taxonomy regulation (Regulation (EU) 2020/852), establishing a framework to facilitate sustainable investment in the EU, is at the heart of the European Green Deal. In order to inform the possible inclusion of nuclear energy in the EU taxonomy, the European Commission tasked its scientific and knowledge service, the JRC, to evaluate the sustainability of nuclear energy against five environmental objectives beyond its sole mitigation potential (JRC, 2022). Climate change adaptation, the sustainable use and protection of water and marine resources, the transition to a circular economy, as well as objectives related to pollution prevention and control, and the protection and restoration of biodiversity and ecosystems, were thus thoroughly assessed through numerous criteria and extensive life cycle analysis. According to the JRC, the standards of environmental control needed to protect the general public, in particular in terms of impacts of radiation on the environment, including the management of nuclear waste, are deemed sufficient to ensure that other species are not put at risk (JRC, 2022). The science based evidence confirms that nuclear energy "does not do more harm to human health or to the environment than other electricity production technologies already included in the EU taxonomy as activities supporting climate change mitigation." (JRC, 2022). As shown in Box 14 on the following page, the second UNECE study reinforces the findings of the JRC study.

The 2030 Agenda for Sustainable Development, adopted unanimously by the United Nations General Assembly, provides a framework for a comprehensive assessment of progress towards 17 cross cutting goals. Through this Agenda, 193 Member States pledged to ensure sustained and inclusive economic growth, social inclusion and environmental protection, and to do so in partnership and peace. The document lays out 17 United Nations Sustainable Development Goals (SDGs), together with 169 underlying targets to operationalize these goals (UN, 2015). The Member States must individually ensure the translation of each goal into national policies. To monitor progress, a list of SDG indicators has been drawn up. In 2021, the Global SDG Indicators Data Platform was launched, and includes four components: (i) an interface to the Global SDG Indicators Database; (ii), access to the SDG Country Profiles; (iii) SDG Analytics; and (iv) Advanced Access options (UN, 2022b).

Nuclear energy is among the least CO_2 intensive energy technologies.

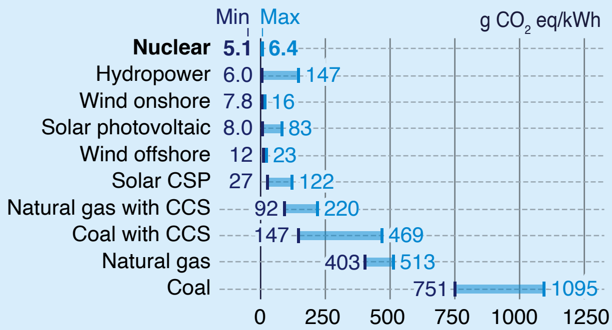
[8] By some measures, the life cycle carbon footprint of nuclear power could lie at even lower levels, in the order of 6 g CO_2 eq/kW·h, with most overall emissions generated during front end processes (UNECE, 2022).

Box 14: Contributed by the United Nations Economic Commission for Europe

Life cycle assessment of electricity sources

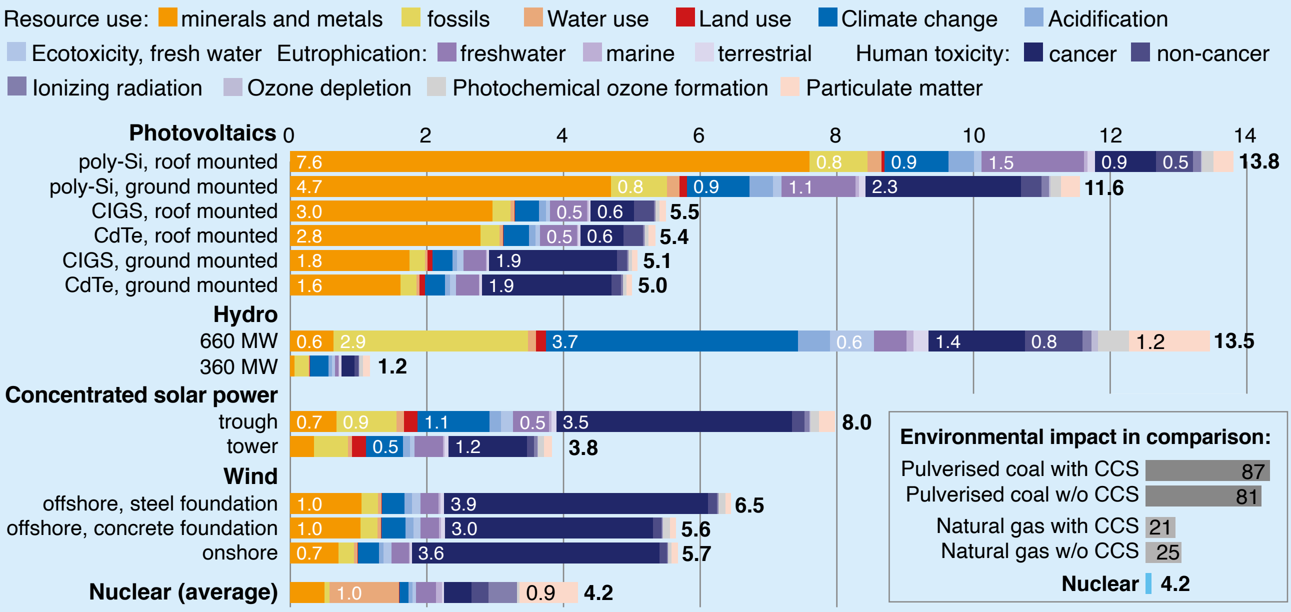
Every electricity generation technology, without exception, generates environmental impacts over its life cycle. Life cycle assessments (LCAs) are a transparent and rigorous method to provide a fair report on the environmental profiles of various energy technologies at parity to develop effective and fair policies. The UNECE conducted an LCA study to assess the life cycle environmental impacts of electricity generation options such as coal, natural gas, hydropower, concentrated solar power (CSP), photovoltaic (PV) technologies, wind power and nuclear energy. These options have been evaluated for climate change, freshwater eutrophication, ionizing radiation, human toxicity, land occupation, dissipated water and resource use. The study is part of the UNECE Carbon Neutrality Toolkit, which provides the pathway to bold, immediate and sustained action to decarbonize energy through international cooperation. Results of the study reveal that the GHG emissions from coal power show the highest scores, with 751–1095 g of CO_2 eq/kW·h. With a carbon dioxide capture facility, this score can fall to 147–469 g CO_2 eq/kW·h. A natural gas combined cycle plant can emit 403–513 g CO_2 eq/kW·h and between 92 and 220 g CO_2 eq/kW·h with carbon capture and storage (CCS). Nuclear power shows less variability with 5.1–6.4 g CO_2 eq/kW·h, as only pressurized water reactors were modelled (representative of most nuclear capacity globally). Hydropower shows the most variability ranging from 6 to 147 g CO_2 eq/kW·h. Solar technologies show GHG emissions ranging from 27–122 g CO_2 eq/kW·h for CSP and 8.0–83 g CO_2 eq/kW·h for PV. Wind power GHG emissions vary between 7.8 and 16 g CO_2 eq/kW·h for onshore and 12 and 23 g CO_2 eq/kW·h for offshore turbines.

Figure 50: Greenhouse gas emissions from electricity generation technologies.



Source: based on data from UNECE (2022). Note: CSP — concentrated solar power; CCS — carbon capture and storage.

Figure 51: Normalized and weighted life cycle impacts of renewable and nuclear technologies from the production of 1 kW·h, Europe, 2020.



Source: based on data from UNECE (2022). Note: poly-Si, CIGS, and CdTe refer to the type of solar cells.

Freshwater eutrophication

All of the technologies display very low freshwater eutrophication over their life cycles, except for coal, the extraction of which generates tailings that leach phosphate into rivers and groundwater. Average phosphate emissions from coal range from 600–800 g of phosphate equivalent per MW·h, which means that coal phase-out would virtually cut eutrophying emissions by a factor of 10, if replaced by PV, or by factor of 100 if replaced by wind, hydro or nuclear.

Radiation

The LCA for nuclear power includes the effects of ionizing radiation, which occurs as a result of radioactive emissions from radon-222, a radionuclide in the tailings from uranium mining and milling. Coal power is also a significant source of radioactivity. Non-carcinogenic human toxicity is highly correlated with the emissions of arsenic linked to the landfilling of tailings that result from mining, which explains the high score of coal power for this indicator. Carcinogenic effects are found to increase because of the emissions of chromium (VI) linked to the production of chromium containing stainless steel, which results in a moderately high score for CSP plants.

Land, water and resource use

Land occupation is highest for CSP plants, followed by coal power and ground mounted photovoltaics. Water use is high for coal, natural gas and nuclear, in the 0.90–5.9 litres/kW·h range. Moderate water inputs are required in PV cell manufacturing for silicon based photovoltaics. For PV technologies, material resources requirements are high. Wind power utilizes about 300 g of non-ferrous metals per MW·h, higher than thermal technologies, which are within the 100–200 g range, with additional metal use for carbon capture. Fossil resource depletion has been linked to fossil technologies, with 10–15 MJ/ kW·h for coal and 8.5–10 MJ/kW·h for natural gas. The UNECE LCA study will act as a first step towards agreement on a solid definition of sustainable energy as it provides a unique categorization of energy technologies and their environmental impacts. It is expected to become the basis of decision making across government, industry and finance in the UNECE region.

The latest IPCC assessment also highlights synergies, but also on trade-offs between the various climate mitigation options and the Sustainable Development Goals. The availability of abundant, clean, reliable and affordable energy — the subject of SDG 7 — is critical to the achievement of the overall Sustainable Development Agenda, as illustrated in Figure 52.

However, the interlinkages across SDGs that were compiled by the IPCC do not only translate into benefits. Possible conflicts between objectives may arise, rendering policy choices more challenging (IPCC, 2022a). This is notably the case for many mitigation options, which may act as a brake to sustainable development if not designed adequately. For example, the deployment of cleaner energy technologies may not only benefit the climate but may also improve air quality, thereby contributing to better health and overall well-being. However, in many instances, if clean energy projects are not accompanied by reforms of power markets and electricity tariffs, cleaner energy mixes may result in higher energy bills for vulnerable end users, which may in turn impact poverty alleviation objectives. Finally, methodologies to conduct systematic and objective impact assessments on the sustainability of various climate mitigation options are still in their infancy, given the complexity of interlinkages across sustainable development criteria. An example is provided in Box 15 in the context of the Egyptian nuclear construction project at El Dabaa.

Nuclear technologies, including those supporting medicine, agriculture, clean water and environmental monitoring and protection in addition to energy, can bring about numerous sustainable development benefits. In its assessment, the IPCC has thus acknowledged with a high level of confidence the relevance of nuclear energy to climate action and its synergies with several SDGs, including a reduced environmental footprint, which echoes the conclusions of the JRC and UNECE studies cited earlier. Indeed, nuclear power plants provide large scale, reliable, low carbon and climate resilient electricity to customers. Nuclear energy also has the potential to provide economy wide benefits, to boost economic activity and generate well paying jobs, including in some emerging African economies (see Chapter 5).

Figure 52: Interlinkages between Sustainable Development Goals and nuclear energy.

Benefit of abundant and reliable energy in general
Nuclear energy economic benefit
Nuclear energy environmental/health benefit

SDG3 Good health and well-being	Health services are enhanced by reliable energy for lighting, refrigeration and modern equipment.
	Considering health impacts per unit of electricity generated, including fatalities, nuclear energy is safer than nearly any other energy generating technology.
SDG7 Affordable and clean energy	Nuclear energy is a large-scale, low emissions energy source, both of greenhouse gases and particulate matter
SDG8 Decent work and economic growth	The availability of abundant and reliable energy supply enables industries to grow, stimulate economic activity and create employment in their markets and supply chains. The transition to more sustainable development patterns in general is an opportunity to stimulate economic activity, create employment and improve living conditions.
	Nuclear energy in particular provides high levels of employment, jobs that are jobs are well paid, long term and predominately local.
SDG9 Industry, innovation and infrastructure	Investments to improve energy efficiency and reduce environmental impact stimulate innovation, technology diffusion and economic activity.
	Nuclear energy can play an important role in powering industrial innovation, for instance virtual reality and robotics technology improvements in the nuclear energy industry.
SDG11 Sustainable cities and communities	Nuclear energy occupies a very small footprint of land and can supply large urban areas and megacities with electricity, heating and cooling.
SDG12 Responsible production and consumption	Nuclear energy has low resource requirements and a waste management practice of keeping arising waste outside the biosphere.
SDG 13 Climate action	Nuclear energy is among the lowest carbon producing energy technologies and can support a climate resilient energy system and economy.
SDG 14 Life below water	By replacing fossil fuels, nuclear energy can eliminate the need for ocean extraction and transport. Also, nuclear energy has a low impact on marine ecotoxicity compared to other energy technologies.
SDG15 Life on land	The low carbon and clean air character of nuclear energy results in relatively lower impacts on life on land. Also, nuclear energy is capable of replacing fossil fuels while requiring less space than other low carbon electricity sources.

Source: IAEA (2016b; 2021c).

Box 15: Contributed by Rosatom

SDG benefits from the El Dabaa nuclear power project

Main characteristics:

- **Reactor:** VVER-1200 (LWR)
- **Milestones:** site approval 2019; operation period 60+ years.
- **Capacity:** 4 units x 1200 MWe
- **Highlights:** first NPP in Egypt; latest generation III+ nuclear power reactors, fully compliant with all of post-Fukushima Daichi IAEA standards.

- In the context of this NPP project, over 1700 people will obtain **education** with the support of Rosatom (including higher education).

- **Clean energy supply:** the El Dabaa NPP will provide electricity to 20 million people (19% of the population).
- **Increased capacity of low carbon sources:** the share of electricity generation from low carbon sources will increase by 13% and up to 22% after the NPP launch.

- **Local job creation and employment:** 18 000 people have been hired for the construction period; 70% of employees are from the local population in Egypt.
- **GDP growth:** added value to Egypt's GDP will amount to over $4 billion (1% of the country's GDP) for the period of NPP construction.
- **Tax effect:** around $700 million of additional tax revenues will be added to the country's budget for the period of NPP construction.

- **Level of infrastructure development:** within the framework of NPP construction, a seaport will be built and road infrastructure will be developed in the country.
- **R&D enhancement:** internalization of high-end technologies and a boost in R&D activities is expected through the NPP project.

- **Savings in CO_2-equivalent emissions** will amount to 15 Mt/year thanks to the El Dabaa NPP (up to 7% of the country's current emissions level).

Using the SDG framework, the benefits for the Sustainable Development Agenda, of energy in general and of nuclear energy in particular, are highlighted in Figure 52, both in economic and environmental areas. It is nevertheless noteworthy that the IPCC also stresses some concerns on the part of the general public about the safety risks of nuclear power plants and radioactive materials, which may slow nuclear deployment in some countries. In addition to the contribution of nuclear energy to climate mitigation, many services offered by the IAEA to its Member States through targeted technical cooperation projects and other support instruments are drawing on nuclear isotopic techniques and are relevant to the achievement of multiple SDGs (IAEA, 2016a). These non-energy technologies make use of the key property of radioactivity that allows for relatively easy measurement, even in very small amounts.

In an effort to accelerate action towards carbon neutrality and other sustainable development objectives, policymakers and energy players alike now commonly deploy integrated policy and corporate strategies. Particular attention is being devoted to biodiversity preservation and restoration. Biodiversity is among the primary policy priorities of many governments, as shown by the dedicated Convention on Biological Diversity, another key international instrument for sustainable development (UNEP, 2021). Nuclear energy has a relatively low impact on ecosystems and biodiversity. Wildlife often thrives on nuclear power plant sites, as for instance mentioned by the US Nuclear Regulatory Commission (Sheehan, 2015). An Australian study ranked seven major electricity generation sources based on costs and benefits regarding land use, emissions, climate and cost implications, and found that nuclear and wind energy had the highest benefit–cost ratio (Brook & Bradshaw, 2015). Nuclear power plant operators can include biodiversity conservation into their company strategy, as shown by France's EDF initiatives (see Box 16).

Box 16: Contributed by Électricité de France

Biodiversity and nuclear: Acting together

A key lesson from the latest IPCC publication released as the 6th Assessment Report is that all countries are facing the same urgency and imperative to tackle both a climate and biodiversity crisis. The climate and biodiversity crises are in fact intertwined: climate change is the third most important pressure driver on biodiversity; and nature based solutions are key to mitigating and adapting to climate change, for instance through carbon sinks or wetlands.

For EDF in France, combating the erosion of biodiversity means, first of all, maximizing the contribution of its nuclear and renewables generation capacity in an effort to contribute to climate change mitigation and accelerate the transition to a low carbon economy.

EDF's ambition is to reconcile its activities with biodiversity preservation throughout the life cycle of assets, for example by:

- refurbishing existing assets to balance industrial and environmental performance;
- extending the lifetime of assets (in particular nuclear power plants), thereby limiting land use (the first driver of biodiversity loss) as much as possible;
- maximizing co-benefits for climate and biodiversity in relation to new projects;
- working with supply chain partners, in particular to address the biodiversity impacts of extractive activities;
- investing to maintain EDF's 40+ year scientific expertise regarding the link between biodiversity and industrial activities.

In 2020, EDF chose to give a new dimension to its responsibility towards the preservation of biodiversity and to go beyond its regulatory obligations. The EDF Group has committed to two voluntary schemes supported by the French state: (i) Companies Committed to Nature (Entreprises Engagées pour la Nature); and (ii) Act4nature International. EDF will report annually on the fulfilment of these commitments.

The contribution of EDF's existing nuclear generation activities to these commitments is critical.

For their operation, nuclear power plants interact with the environment.

Compact and economical in terms of land use, EDF's nuclear power plants are located in the heart of natural areas, most often rich in a biodiversity that must be studied and preserved.

On these sites, EDF is developing a proactive approach with local stakeholders for the preservation and restoration of biodiversity, which goes well beyond regulatory requirements and is part of a more global ambition for sustainable development within French territories.

A key lesson from the latest IPCC publication is that all countries are facing the same urgency and imperative to tackle an intertwined climate and biodiversity crisis.

Appendix

Table 1: Eligibility of nuclear energy under the EU taxonomy in relation to climate change mitigation.

	Pre-commercial advanced technologies with minimal waste from the fuel cycle	New nuclear plants, for electricity, heat, hydrogen; construction permit issued by 2045	Electricity from existing nuclear power plants; extension authorized by 2040
General screening criteria			
Substantial contribution to mitigation and do no significant harm	Complies with various relevant national and EU legislation, regulations and treaties; appropriate management, funding and reporting of radioactive waste disposal and plant decommissioning; resilience to natural hazards.		
	Plan for high-level radioactive waste disposal facility by 2050.		
		Accident tolerant fuels by 2025.	
Additional screening criteria			
Substantial contribution to mitigation	Life cycle greenhouse gas emissions <100 g CO_2 eq/kW·h electricity.		
Do no significant harm:			
1. Adaptation	Fulfils requirements relating to extreme natural hazards, including floods and extreme weather conditions.		
2. Water and marine resources	Addresses risks related to water quality and stress, including controlling discharge water temperature and complying with requirements for water intended for human consumption.		
3. Circular economy	Maximizes waste reuse/recycling, minimizes radioactive waste; ensures funding of decommissioning; completes EIA and implements mitigation measures.		
4. Pollution prevention	Maintains non-radioactive emissions below BAT ranges; ensures radioactive discharges and spent fuel management and storage in accordance with licence conditions and regulations/directives.		
5. Biodiversity and ecosystems	EIA; applies appropriate assessment and mitigation measures for sensitive sites.		

Source: Annex I to (European Commission, 2022b) Note: different screening criteria apply in determining the eligibility of an activity in relation to climate change adaptation (see Annex II to (European Commission, 2022b)). Note: BAT — best available techniques; EIA — Environmental Impact Assessment.

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UN Photo. (2017). Security Council Extends Yemen Sanctions Regime. Photo by Mark Garten, used under CC BY-NC-ND 2.0. Saturated from original. [Used as cover photo for Chapter 6.]

List of abbreviations and acronyms

AFCP	Advanced Fuel Cycle Programme (United Kingdom)
AR6	Sixth Assessment Report (IPCC)
ASEAN	Association of Southeast Asian Nations
AUDA-NEPAD	African Union Development Agency-New Partnership for Africa’s Development
CAPEX	capital expenditure
CCGT	combined cycle gas turbine
CCPT	Climate Change and Principle-based Taxonomy (Malaysia)
CCS	carbon capture and storage
CCUS	Carbon capture, utilization and storage
CfD	contract for difference
CFI	Climate Finance Institution
CHP	combined heat and power
CMP	Continental Power System Masterplan (Africa)
CO2 eq	carbon dioxide equivalent
COP	Conference of Parties (to the United Nations Framework Convention on Climate Change)
COVID-19	Coronavirus Disease 19
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
CSP	concentrated solar power
DNSH	do no significant harm
DOE	Department of Energy (USA)
EDF	Électricité de France
EJ	exajoule(s)
EPRI	Electric Power Research Institute
EU	European Union
EWEC	Emirates Water and Electricity Company
GBP	Green Bond Principles
GHG	greenhouse gas
GW	gigawatt(s)
HTR-PM	high temperature gas cooled reactor pebble bed module (project, China)
ICL	intermediate coupling loop
IEA	International Energy Agency
IMF	International Monetary Fund
INET	Institute of Nuclear and New Energy Technology
INIR	Integrated Nuclear Infrastructure Reviews (IAEA peer review)
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRS	Incident Reporting Systems for Nuclear Installations (IAEA)
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre (European Commission)
KANUPP	Karachi Nuclear Power Plant (Pakistan)
kW·h	kilowatt hour(s)
LCA	life cycle assessment
LEAP	Low Emission Analysis Platform (modelling)
LNG	liquefied natural gas
LTS	long term low GHG emission development strategy
MDB	multilateral development bank
MED	multi-effect distillation
MENA	Middle East and North Africa (region)

MHI	Mitsubishi Heavy Industries
Mt	megatonne(s)
MSF	multistage flash distillation
Mtoe	million or mega tonnes of oil equivalent
MW	megawatt(s)
MWe	megawatt electrical
MW·h	megawatt hour(s)
MJ	megajoule(s)
NDC	nationally determined contribution (UNFCCC Paris Agreement)
NDDP	Nuclear Desalination Demonstration Plant (Pakistan)
NEA	Nuclear Energy Agency (OECD)
NNL	National Nuclear Laboratory (United Kingdom)
NPP	nuclear power plant
NYPA	New York Power Authority
NZE	Net Zero Emissions by 2050 Scenario (modelling scenario from the International Energy Agency to achieve net zero emissions by 2050)
OCGT	open cycle gas turbine
OPEC	Organization of the Petroleum Exporting Countries
PPA	power purchase agreement
PV	photovoltaic(s)
RAB	regulated asset base
R&D	research and development
RO	reverse osmosis
SDGs	Sustainable Development Goals (United Nations)
SMR	small modular reactor
SSP	shared socio-economic pathway (IPCC)
T&D	transmission and distribution
TDS	total dissolved solids
TW·h	terawatt hour(s)
UAE	United Arab Emirates
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
VRE	variable renewable energy
WMO	World Meteorological Organization

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