UNECE

TECHNOLOGY BRIEF

NUCLEAR POWER

Cover photo: Paluel nuclear plant in France (reproduced under a Creative Commons 4.0 licence
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Disclaimer
The document does not necessarily reflect the position of the reviewers and partners listed above who helped to develop this publication.

Some environmental aspects related to nuclear energy are subject of work under and decisions of the Parties to the 1991 ECE Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) and its Protocol on Strategic Environmental Assessment.

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KEY TAKEAWAYS

Nuclear power is an important source of low-carbon electricity and heat that contributes to attaining carbon neutrality. It has played a major role in avoiding carbon dioxide (CO_2) emissions to date. Decarbonising energy is a significant undertaking that requires the use of all available low-carbon technologies. Analyses indicate that the world's climate objectives will not be met if nuclear technologies are excluded.

Beyond existing large-scale nuclear reactors, nuclear power continues to evolve with new technologies emerging including small modular reactors (SMRs) and advanced reactor technologies. These technologies will complement established large-scale reactors and open new markets, including district heating, high-temperature process heat and hydrogen production. SMRs could provide electricity for small grids or remote locations and will improve the integration of variable renewable energy sources.

In many parts of the world, nuclear power plants are a cost-competitive option for generating electricity. In other places, while new nuclear plants may be more expensive than alternatives on a levelized cost basis, they offer resilience and environmental benefits that justify these investments and will make the overall energy system more affordable and sustainable. The nuclear industry has coordinated its efforts to learn from recent projects to reduce construction costs.

Some countries may choose to pursue nuclear power with a view that it can play an important role in their energy mix as a viable decarbonisation option. Other countries have decided not to use nuclear power for a variety of reasons, some because of their endowment of natural resources and others because of their concerns relating to safety and waste. Policy-makers who wish to meet climate and sustainable development objectives using nuclear power should:

Establish a level playing field for all low-carbon technologies

Decarbonising energy is a significant undertaking that will require deployment of all available low-carbon technologies, including nuclear power.

Provide positive, long-term policy signals for new nuclear development

Consistent policies and clear market frameworks will enable investment in new nuclear power projects and support stable supply chains.

Accelerate the development and deployment of SMRs and advanced reactor technologies

Technical, financial and regulatory support are essential for the deployment and commercialisation of new nuclear technologies. International harmonisation of licensing frameworks should be promoted.

Secure the long-term operation of existing nuclear plants

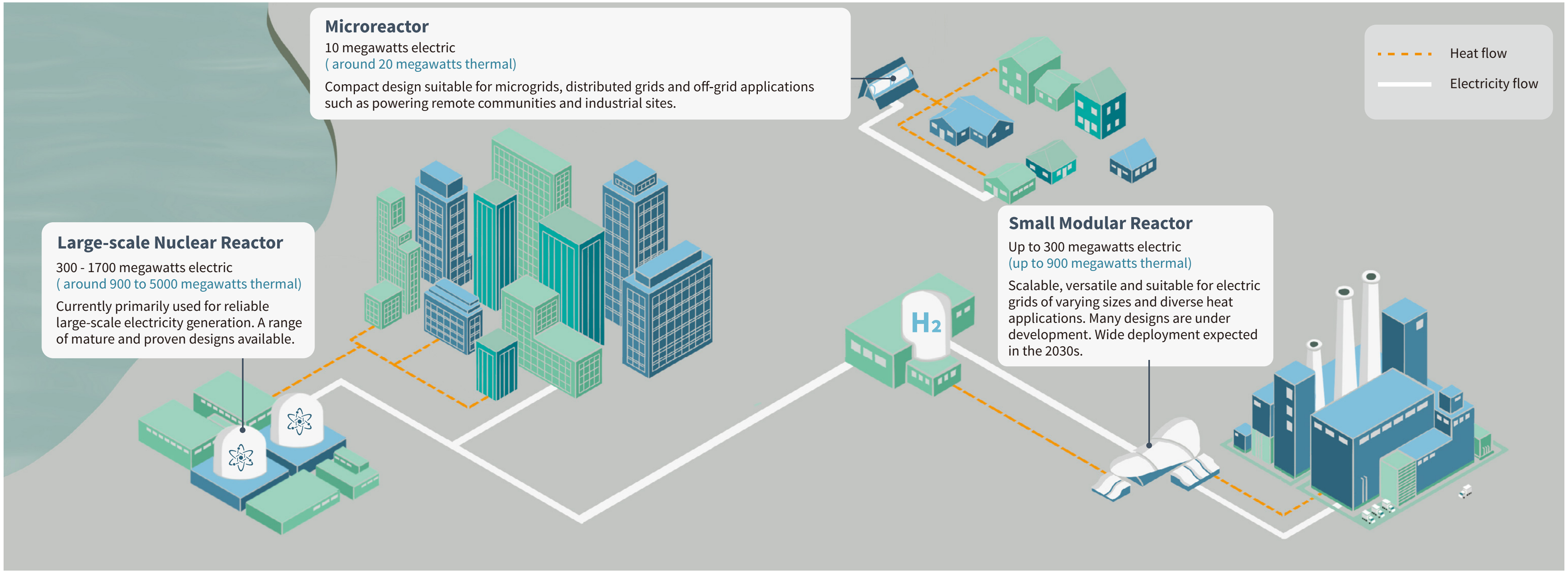
Long-term operation of existing nuclear plants will avoid unnecessary CO_2 emissions and decrease the costs of the energy transition. This must respect safety and economic parameters.

Assess the merits of low-cost financing of nuclear power projects

Green finance classifications should be based on scientific and technology-neutral methodologies. Multilateral banks and international finance institutions should consider nuclear projects as part of their sustainable lending activities.

NUCLEAR POWER

Nuclear power is an important source of low-carbon electricity and heat that contributes to attaining carbon neutrality



Microreactor

10 megawatts electric
(around 20 megawatts thermal)

Compact design suitable for microgrids, distributed grids and off-grid applications such as powering remote communities and industrial sites.

Large-scale Nuclear Reactor

300 - 1700 megawatts electric
(around 900 to 5000 megawatts thermal)

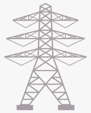
Currently primarily used for reliable large-scale electricity generation. A range of mature and proven designs available.

Small Modular Reactor

Up to 300 megawatts electric
(up to 900 megawatts thermal)

Scalable, versatile and suitable for electric grids of varying sizes and diverse heat applications. Many designs are under development. Wide deployment expected in the 2030s.

ELECTRICITY GENERATION



Nuclear power plants can produce reliable 24/7 electricity or operate flexibly as required. Dispatchable electricity sources are essential for keeping the costs of the overall system low.

HYDROGEN

Nuclear power can be used to produce low-carbon hydrogen via several process:

- Low-temperature electrolysis - using nuclear electricity
- Steam electrolysis - using nuclear heat and electricity
- Thermochemical process - using nuclear heat at above 600℃

PROCESS HEAT FOR INDUSTRY

High-temperature heat from nuclear plants can be transformative in decarbonising hard-to-abate sectors.

DISTRIC HEATING

Nuclear plants are a proven source of heat for urban district heating that have operated successfully in a number of countries.

Raising Awareness

Recognise that nuclear power is a source of low-carbon energy and heat that can help decarbonise energy systems

Promoting Acceptance

Develop policies that instil confidence and facilitate the wider application of nuclear power to decarbonise electricity and energy intensive industries

Incentivising Finance

Develop financing frameworks that instil confidence and incentivise affordable public and private investment in support of new nuclear power projects

1. INTRODUCTION

The purpose of this brochure is to provide an overview of nuclear energy technologies, both those that are available now as well as those that are under development and that are expected to be available commercially in the near future. Information is provided on the role that innovative new reactor technologies, such as small modular reactors (SMRs), could play in complementing larger reactor technologies and helping to open up new markets and applications for nuclear – such as district heating, high-temperature process heat and hydrogen production. Information is also provided on a range of topical areas including nuclear costs, socioeconomic impacts, health and environmental concerns, key innovations and enabling policies.

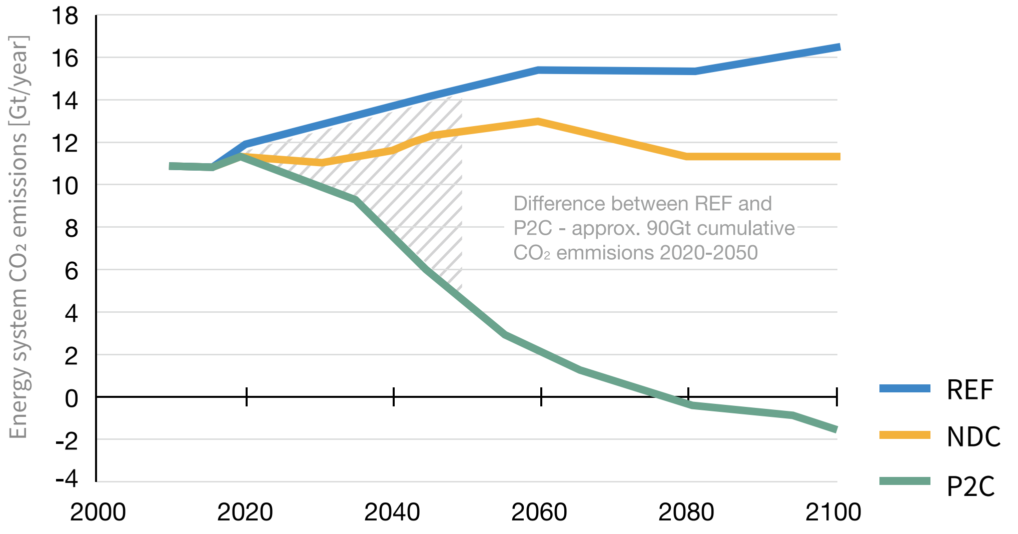
1.1 A climate emergency – all low-carbon technologies needed

Energy is critical for the attainment of the 2030 Agenda for Sustainable Development (2030 Agenda). It is the 'golden thread' that runs through all the Sustainable Development Goals (SDGs) and connects them. Achieving greater quality of life in all countries while protecting the natural world will require both expanding energy access and fully transitioning to clean energy technologies over the coming decades.

In recent years, the need for urgent climate action has become the focus of ever greater international attention. The United Nations has recognised that the world is now in a "climate emergency". Given that energy production and use is the source of around 75% of global anthropogenic CO_2 and other greenhouse gas emissions, successfully achieving this target will require a dramatic transformation of the global energy system.

Results from an earlier UNECE project called "Strengthening the Capacity of the UNECE Member States to Achieve the Energy-related Sustainable Development Goals – Pathways to Sustainable Energy" (Pathways Project) show that the countries in the UNECE region need to cut or capture at least 90 gigatonnes (Gt) of CO_2 emissions by 2050 in order to stay on a pathway that meets the 2^{0}C target (Figure 1). All available low-carbon technologies will need to be deployed to fill the gap between what has been committed and what is needed. we cannot afford to leave "off the table" any low-carbon technology.

Figure 1 **CO_2 emissions in the UNECE region by policy scenario**



The blue line reflects the level of emissions that are expected if UNECE countries continue with business-as-usual climate policies. The green line, or P2C scenario, shows what must happen for emissions in the region to stay within the 90Gt budget with net emissions going negative after 2080. The orange line shows how much emissions reduction are currently accounted for in nationally determined contributions that UNECE countries have pledged as part of the Paris Agreement.

***Source**: UNECE Pathways Project*

1.2 Nuclear power as part of the climate solution

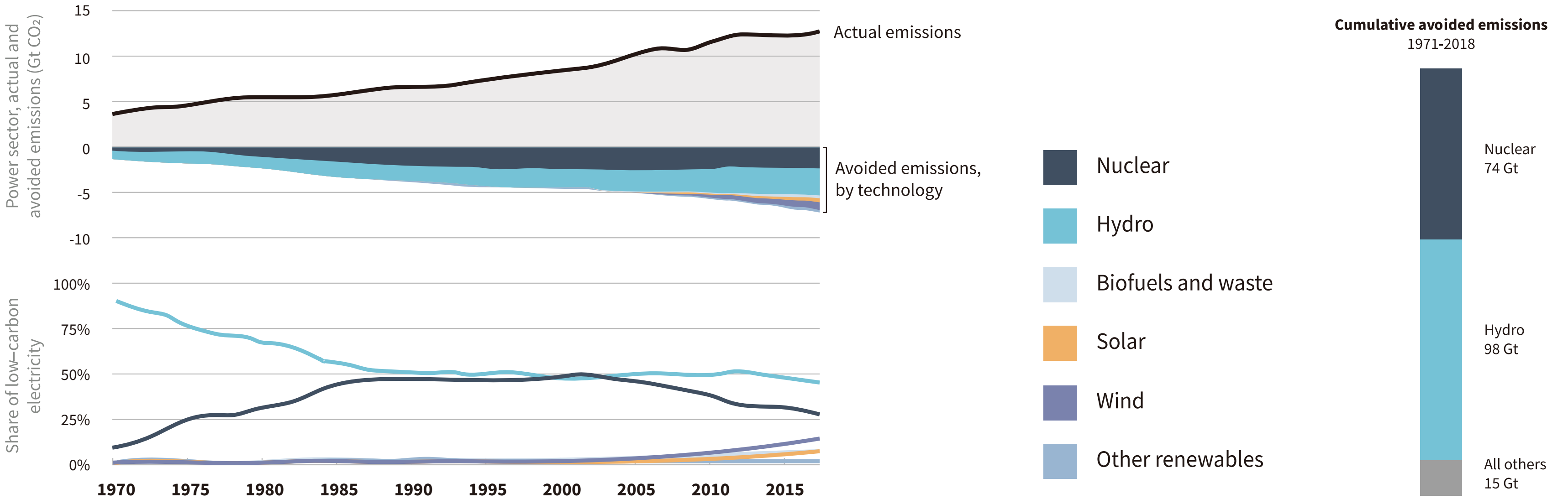
Nuclear power is a low-carbon energy source that has played a major role in avoiding CO_2 emissions. Over the past 50 years, the use of nuclear power has reduced global CO_2 emissions by about 74Gt, or nearly two years' worth of total global energy-related emissions, as shown in Figure 2. Only hydropower has played a greater role in reducing historic emissions.

Today, nuclear power provides 20% of electricity generated in the UNECE region (Figure 3) and 43% of low-carbon generation. However, fossil fuels still dominate supply and provide over 50% of electricity in the region. Nuclear power provides the source of low-carbon electricity in many UNECE countries, including Belgium, Bulgaria, Croatia, Czech Republic, Finland, France, Hungary, Slovakia, Slovenia, Spain, Sweden, Ukraine and the United States. 20 UNECE Member States currently operate nuclear power plants and 15 countries either have new reactors under construction or are actively planning to develop them. Furthermore, 7 UNECE Member States are in the process of developing nuclear power programmes for the first time. A number of UNECE countries – such as Canada, Czech Republic, Finland, France, Hungary, Poland, Romania, Slovakia, Slovenia, Russian Federation, Ukraine, United Kingdom and the United States – have explicitly stated that nuclear power will play an important role in reducing their national emissions in the future. The contribution of nuclear power in UNECE countries is presented in Figure 4 and more fully in Annex I.

Outside the UNECE region, nuclear power is growing in Asia, the Middle East, South America and Africa. There is also strong interest in nuclear power among developing countries, which are exploring pathways by which they can reach their sustainable development commitments.

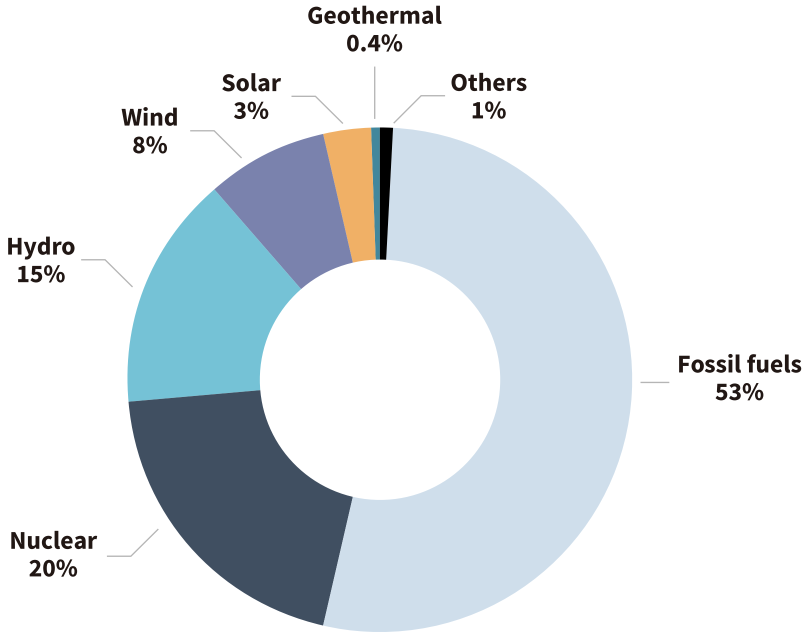
The IPCC 1.5°C report published late in 2018 presents 89 mitigation scenarios in which nuclear generation grows on average 2.5 times from today's level by 2050. In addition, the 'middle-of-the-road' illustrative scenario – in which social, economic, and technological trends follow current patterns and there are no major changes in diet and travel habits – sees demand for nuclear generation increase sixfold by 2050 with the technology providing 25% of global electricity. Nuclear power is a proven source of electricity and a vital tool for helping the world successfully mitigate the impacts of climate change. Countries that choose to pursue it will therefore need to dramatically accelerate reactor deployment in the years ahead to help prevent a temperature rise of greater than 2°C.

Figure 2 **Cumulative worldwide carbon dioxide emissions avoided by low-carbon energy sources**



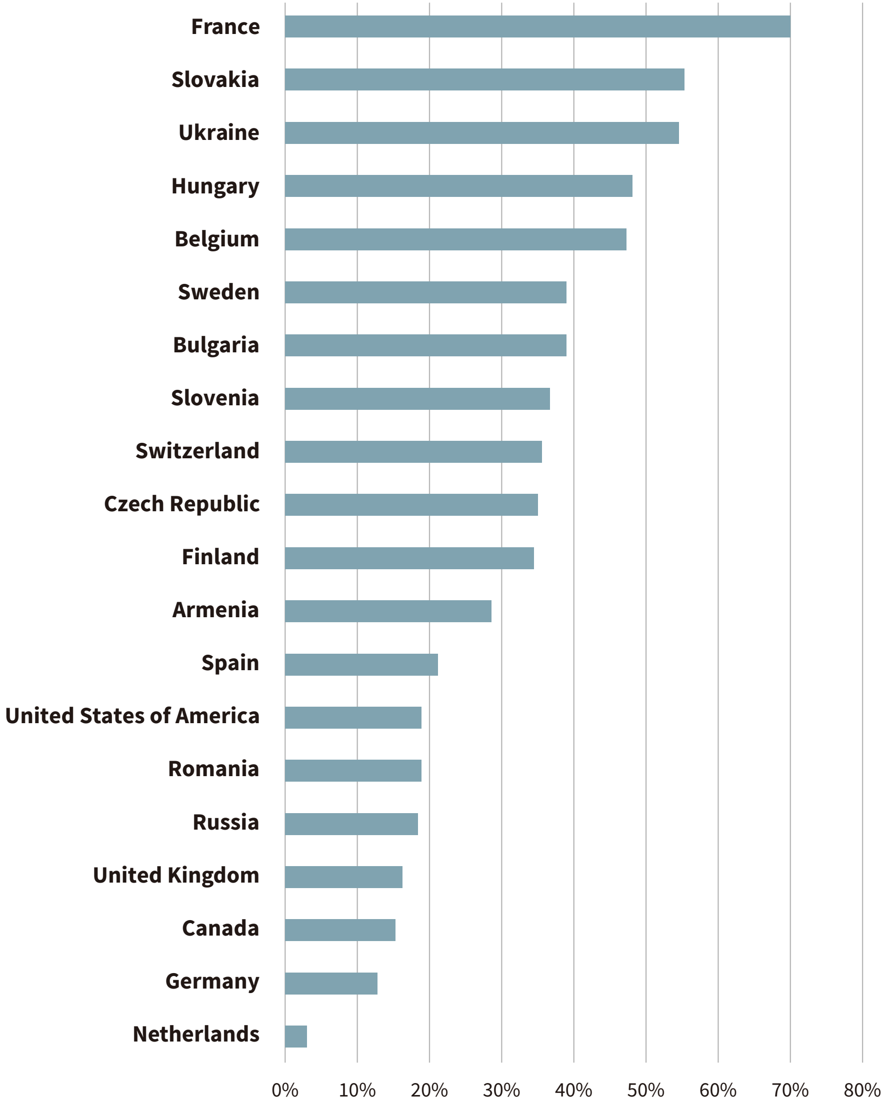
***Source**: adapted from IAEA, Climate Change and Nuclear Power 2020*

Figure 3 Electricity generation by source in the UNECE region for 2019



***Source**: Eurostat EU Electricity Generation Statistics 2020 and IEA Electricity Information 2020 data service*

Figure 4 Share of electricity generation provided by nuclear power in UNECE countries



***Source**: Eurostat EU Electricity Generation Statistics 2020 and IEA Electricity Information 2020 data service*

2. NUCLEAR POWER

Nuclear power continues to evolve with new technologies under development that will expand the envelope of nuclear power applications and increase its integration with other low-carbon energy sources, such as variable renewables and fossil with carbon capture and storage (CCS), in a future decarbonised energy mix.

Today's nuclear power plants are thermal plants that heat water to create steam to turn a turbine generator. A nuclear power plant's fuel consists of processed uranium, plutonium and (potentially) thorium, rather than hydrocarbons, and the heat is produced via nuclear fission inside a reactor instead of the combustion of hydrocarbons. The fission process is incredibly energetic and releases about a million times more energy than combustion.

There are three main classes of nuclear reactor technology: large (gigawatt-scale) reactors, small modular reactors (SMRs) and microreactors. Large reactors are commercially available today whereas SMRs and microreactors are under development with some designs rapidly approaching commercial deployment. A summary of the technology readiness levels of different reactor technologies is provided in Appendix II.

Large reactors

Over most of the history of nuclear technology development reactor sizes have grown larger to take advantage of economies of scale. A range of mature standardised reactor/nuclear plant designs that vary from about 750MW to 1800MW are currently commercially available. These designs are all based on proven technologies and are offered by well-established vendors. Today's large reactors are capable of achieving capacity factors in excess of 90% and are designed to operate for at least 60 years. Most plants are run in 'baseload mode' to take advantage of their low fuel and operating costs, however they are capable of operating in load-following mode if needed and can be adapted for district heating and hydrogen production via electrolysis.

Small modular reactors (SMRs)

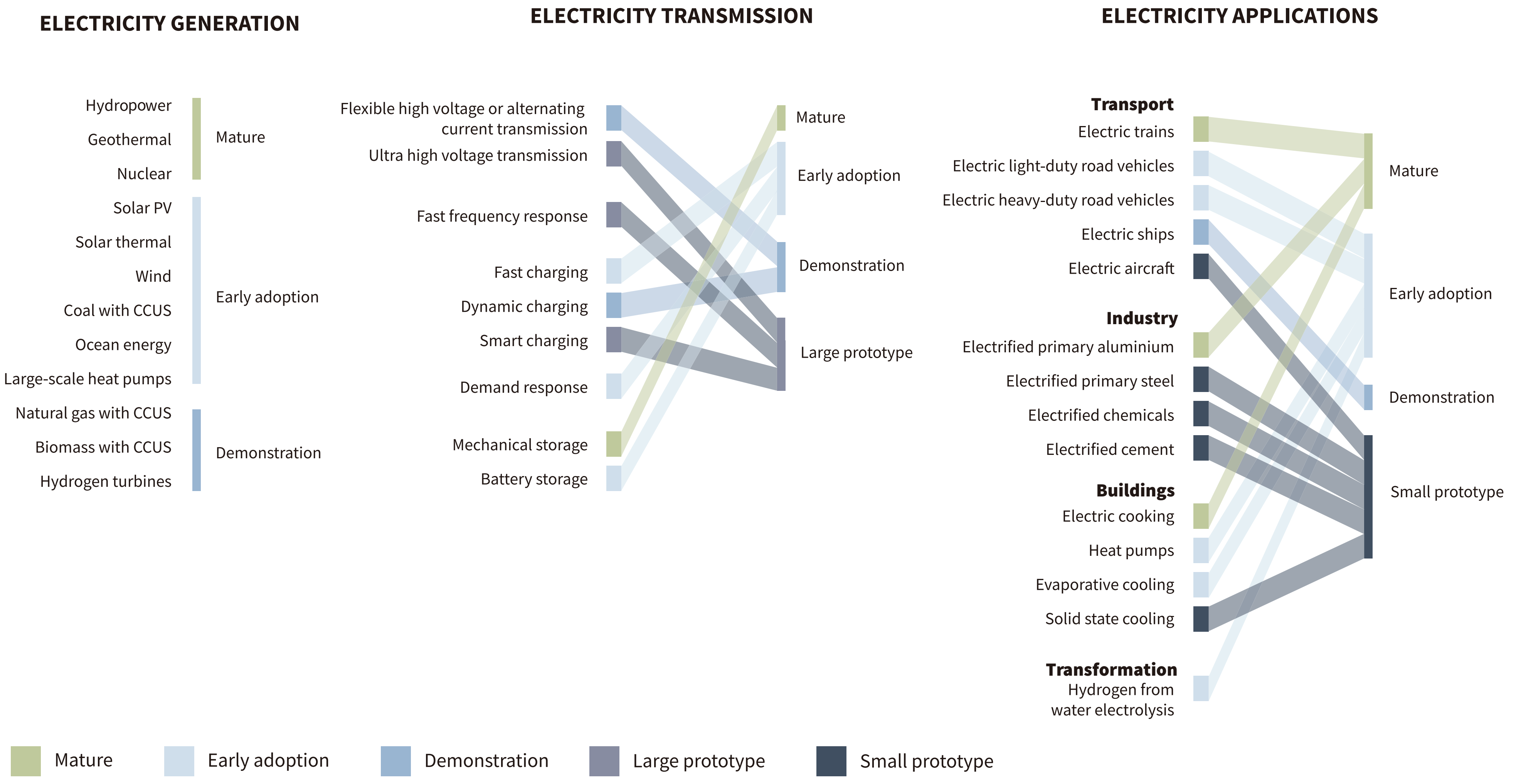
Modern SMR designs can be anywhere up to 300MW in electrical output. It should be noted that the first generation of nuclear power reactors were small, and many small reactors can be found on submarines and naval vessels today. What makes current SMRs different is a design and manufacture approach that takes advantage of their small size to integrate transformative safety features, utilise new production techniques (such as enhanced factory construction and standardisation) and open up new business models. Many SMRs are envisioned for markets where large reactors would simply be too big for either the energy demand or the existing grid capacity. SMRs could provide flexible power generation for a wide range of users and applications, including repowering fossil power plants, cogeneration, small electricity grids, and remote or off-grid areas.

There are now more than 70 SMR designs under development for different applications. Different SMR designs are at different levels of technology readiness. Some, such as the water-cooled technologies, can be considered highly mature with one such plant now built and operating off the north coast of Russia providing combined heat and power to remote communities and another design certified by the US regulatory authority. China's HTR-PM demonstration high-temperature gas-cooled reactor plant is currently under construction and is expected to start operation towards the end of 2021. Many SMR developers are expecting their first plants to begin operation in the 2020s and for these designs to be available for wider deployment during the 2030s. Designs based on novel technologies are generally further from commercialisation.

Microreactors

Microreactors are a subset of SMRs. They are expected to produce up to about 20 megawatts of thermal output (or about 10 megawatts electric) and are designed to be transported as a fully contained heat or power plant both to and from potential sites. Early designs are being tailored for off-grid applications. Some designs may be operating in vendor countries within five years, as they could be commercially viable without any reforms in the niche markets they are targeting (mostly competing with diesel generators) especially if designers and regulators pursue simplified licensing approaches.

Figure 5 Technology readiness level of low-carbon technologies

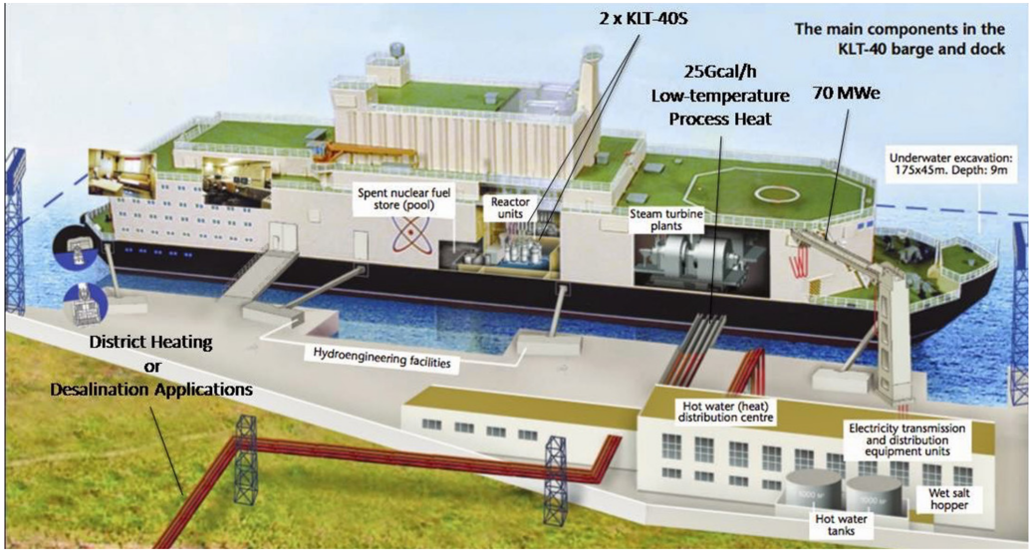


***Source**: adapted from IEA ETP Clean Energy Technology Guide*

Figure 6 Example of a larger reactor: the two-unit Diablo Canyon nuclear power plant

Source: *Tracey Adams, published under a Creative Commons licence*

Figure 7 Example of an SMR: schematic of Russia's floating nuclear power plant



Source: *Rosatom*

Figure 8 Example of a microreactor: schematic of Ultra Safe Nulear Corporation's micro modular reactor

Source: *Ultra Safe Nuclear Corporation*

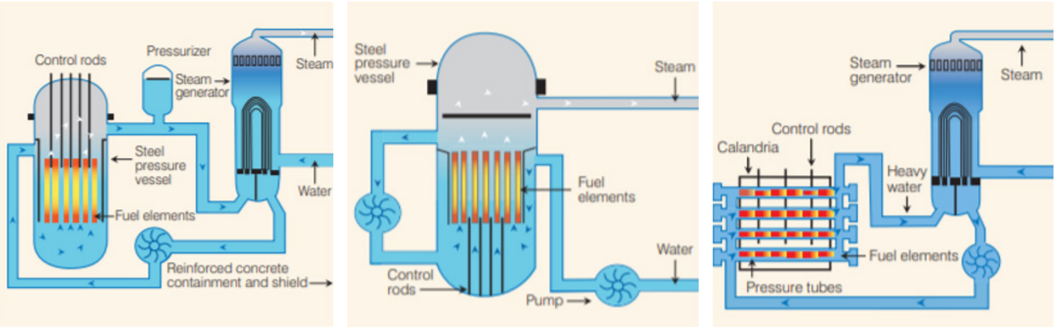
2.1 Today's reactor technologies

There are currently three main power reactor technology types: pressurised water reactors (PWRs), boiling water reactors (BWRs) and pressurised heavy water reactors (PHWRs), as shown in Figure 9. The PWR is the most common nuclear power reactor technology in the world today. It comprises two internal cooling circuits. Heat is extracted from nuclear fuel in the reactor core. From there the pressurised water goes to a steam generator where the heat is transferred to water in a secondary circuit. Here it is allowed to boil and expand, with the steam pressure used to turn turbines for electricity generation. After this, steam is converted back to water in the condenser and then pumped back to the steam generator. The BWR is the second most common nuclear power reactor technology. It contains one internal cooling circuit which integrates the functions provided by the primary and secondary circuits in PWRs. Water is heated by the fuel and boils in the upper section of the reactor vessel. In a PHWR, fuel bundles are arranged in pressure tubes, which are individually cooled. These pressure tubes are situated within a large tank called a calandria containing heavy water.

2.2 Advanced reactor designs

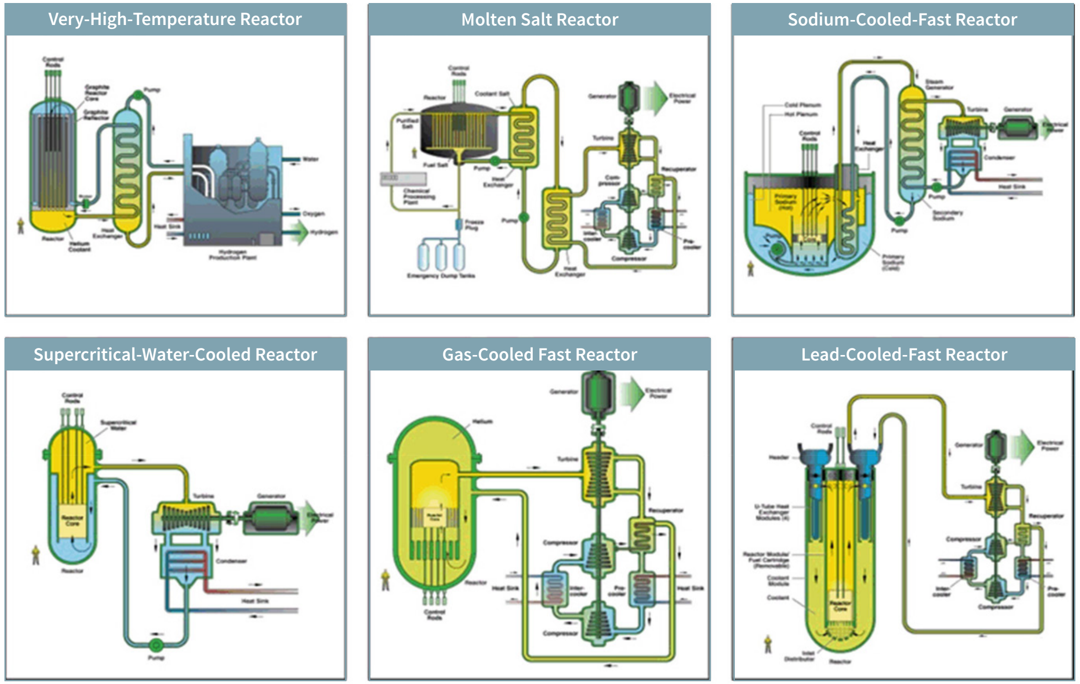
Water-cooled reactor technologies achieved dominance in the current global marketplace as a result of their early technical maturity and a commercialisation push that started in the 1950s. However, there are a multitude of reactor design variations possible with the use of different nuclear fuels, structural materials and coolants. Some of these offer distinct advantages in terms of sustainability and operating performance. An international initiative has prioritised six so-called Generation IV nuclear technology systems for further research – the gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), supercritical-water-cooled reactor (SCWR), sodium-cooled fast reactor (SFR) and very-high-temperature reactor (VHTR), as pictured in Figure 10. While advanced reactor designs have been researched for decades and several prototypes have been built, R&D has traditionally been carried out by national laboratories. However, the last ten years have seen the emergence of an advanced nuclear industry, especially within Europe and North America, which is pursuing aggressive timelines for commercialisation. Many private companies, including 'start-ups', are partnering with the laboratories and attracting venture capital in their endeavours to bring these innovative new designs out of the laboratories and into the marketplace.

Figure 9 Cutaway of most common currently available nuclear reactor technologies: a PWR, BWR and PHWR



***Source**: World Nuclear Association*

Figure 10 Generation IV reactor systems



Very-High-Temperature Reactor

Molten Salt Reactor

Sodium-Cooled-Fast Reactor

Supercritical-Water-Cooled Reactor

Gas-Cooled Fast Reactor

Lead-Cooled-Fast Reactor

***Source**: Generation IV International Forum*

2.3 Innovating the fuel cycle

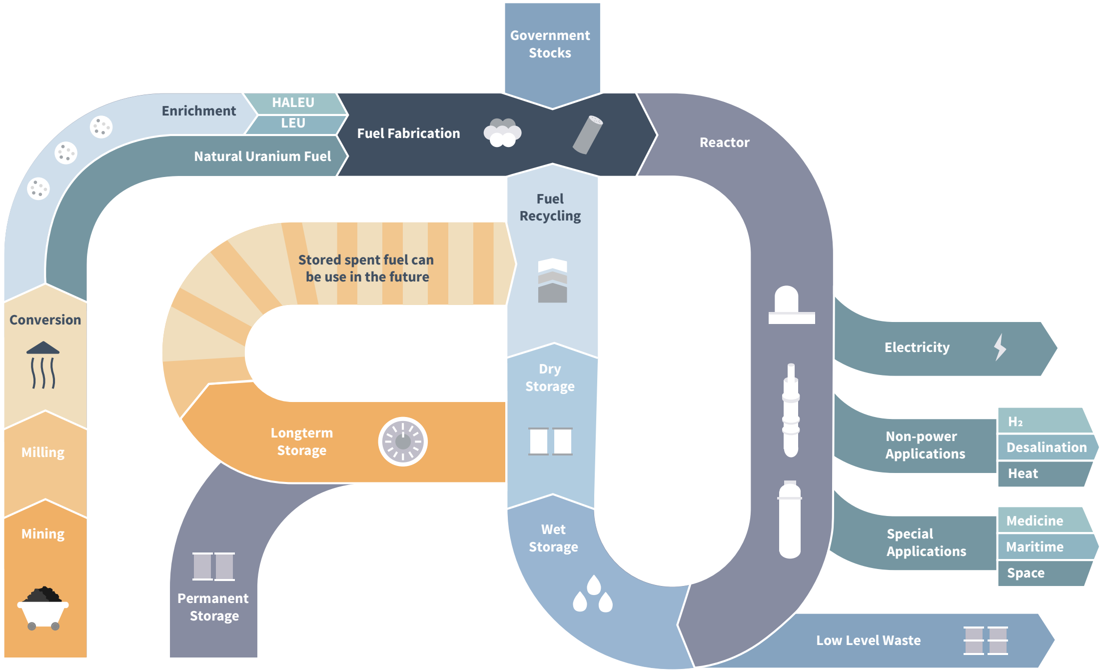
A unique characteristic of nuclear technology is that used fuel may be reprocessed to recover materials and provide fuel for existing and future nuclear power plants. In the UNECE region both France and Russia possess industrial reprocessing facilities and offer these recycling services internationally, while the UK possesses reprocessing capability as it has operated facilities for several decades. It is currently only possible to partially recycle fuel at an industrial scale which results in an energy gain of about 25% from the original mined uranium.

Fast neutron reactors could increase the energy produced from mined uranium by up to 6,000%, increasing current beyond 4,000 years. The commercialisation and potential wide availability of fast reactors would have profound implications for both uranium mining requirements and radioactive waste management. Fast reactors are currently being pursued by several countries in the UNECE region. Russia has two sodium-cooled fast neutron reactors in operation and also plans to develop a 1,200 MW sodium-cooled reactor (BN-1200) as well as a 300 MW lead-cooled design (BREST-300). There is also renewed fast reactor development in the US, where public funding for TerraPower and GE Hitachi's Natrium sodium-cooled fast reactor was recently announced. Other countries have also built and operated fast reactors in the past.

Nuclear power reactors can be used for the production of useful radioisotopes for civil applications. This can be achieved via reprocessing of used fuel to extract useful materials, for example americium-241 that can be for used as a radioisotope power source in space missions. Alternatively, useful radioisotopes can be produced through irradiation of materials placed inside the reactor core. PHWR type reactors are particularly well-suited to this with CANDU reactors in Canada being used to produce cobalt-60 and molybdenum-99 for medical purposes.

Many examples of innovation can be found throughout the broader nuclear fuel cycle. Fuel fabrication is of note since new fuel designs can be commercialised faster than new reactor designs. Recent advancements in nuclear fuel design improve the safety and economic performance of existing reactors. Advanced reactor designs also require new fuel technologies. Many need higher enrichment levels (the concentration of the uranium-235 isotope) than conventional reactors. HALEU fuel could be enriched up to 20%, up from the more typical levels of 3-5% for low-enriched uranium.

Figure 11 **The advanced nuclear fuel cycle**



***Source**: Nuclear Innovation Alliance*

The advanced nuclear fuel cycle ensures long-term management of all nuclear materials, including the production of useful radioisotopes, while recycling creates a potentially large future fuel resource.

3. NUCLEAR POWER APPLICATIONS

Nuclear plants produce both low-carbon electricity and heat, which opens up opportunities for the decarbonisation of hard-to-abate sectors beyond electricity. Potential non-electric uses for nuclear include hydrogen production, industrial process heat, district heating, seawater desalination, synthetic fuels and chemicals production, cooling and refrigeration, and cogeneration applications. While existing reactors have been demonstrated to be capable of hydrogen production, desalination and district heating, they are chiefly geared for the bulk provision of low-cost electricity. Future SMR and advanced reactor designs are expected to provide the needed performance (such as high temperatures) and flexibility (such as co-siting with industrial facilities) to truly open up these markets. This is shown in Figure 12.

3.1 Hydrogen production

Hydrogen could provide clean and versatile energy vector to support decarbonisation of hard-to-abate sectors such as industry and transport, as well as provide long-term seasonal energy storage. Nuclear technologies can be used to produce hydrogen via several low-carbon processes:

- Low-temperature electrolysis of water.
- High-temperature steam electrolysis, using heat and electricity from nuclear reactors (at 600°C).
- High-temperature thermochemical production using nuclear heat (800-1000°C).

Current nuclear reactor technologies can be used for low-temperature electrolysis and offer several potential advantages including high electrolyser utilisation factors, low operating costs and the potential to use hydrogen within nuclear plant operations. Japan operates the High Temperature Test Reactor (HTTR) with a maximum outlet temperature of 950°C for investigating hydrogen cogeneration capability. In 2019, it produced hydrogen using the iodine-sulphur thermochemical process over 150 hours of continuous operation. The US, the UK and France are all planning demonstration nuclear electrolysis hydrogen production facilities.

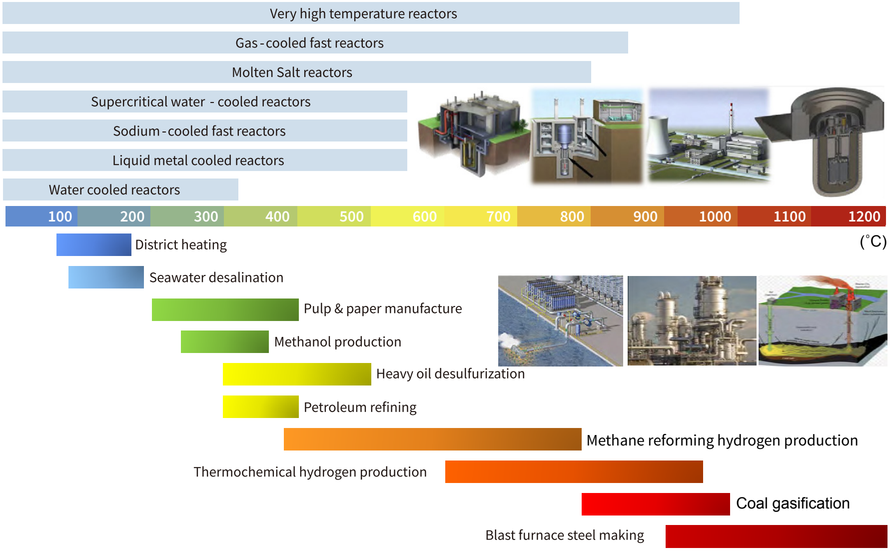
3.2 Energy intensive industries

Nuclear process heat could prove to be a viable means of decarbonising energy-intensive industries such as chemical production, pulp and paper manufacturing, and steel production. A high-temperature low-carbon technology is needed to decarbonise industrial heat supply. This is because the electrification of heat, in most cases, is thermally inefficient. When the thermal power plant is used to produce electricity then between one-half and two-thirds of the available energy is lost in the conversion, and more is lost in the transport and distribution. Even if wind and solar are at similar prices to fossil electricity sources, they would need to be over half as cheap again to compete with therm as heat sources.

3.3 District heating

The excess heat of nuclear reactors can also form a valuable resource. Russia, several East European countries, Switzerland and Sweden have all had nuclear-fuelled district heating schemes. More recently, China started a trial of the country's first commercial nuclear heating project in 2020. This provides heat to 700,000 square metres of housing. Several countries are pursuing SMR technologies that would be used primarily for district heating. Chinese researchers have also developed several bespoke heating reactor designs while Finnish researchers are assessing various concepts for their heating networks.

Figure 12 **Potential industrial uses of nuclear heat**



***Source**: IAEA, 2020, Advances in Small Modular Reactor Technology Developments*

Figure 13 A render of a microreactor. The Oklo Aurora reactor

Microreactors will be suitable for off-grid applications and remote communities where they can provide heat, electricity and other services.
***Source**: Oklo*

4. ECONOMICS OF NUCLEAR POWER AND THE COST OF DECARBONISATION

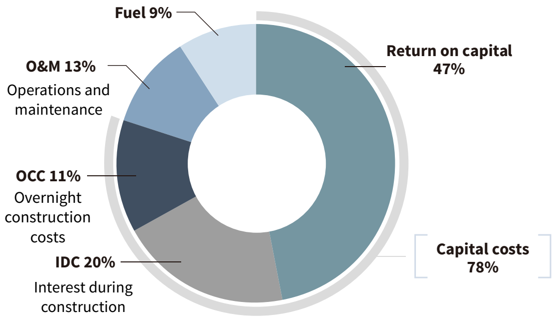
There is a range of methods for calculating and comparing the costs of energy projects, however the most widely used is the levelised cost of energy (LCOE). The largest contributing factor to the LCOE of nuclear power is the capital cost of building and financing a nuclear power plant as shown in Figure 14. The fuel, operations and maintenance costs are typically lower than for fossil plants, which is in fact the key economic advantage of nuclear power. Nuclear plants have high up-front capital costs, with the required investment ranging from 5 to 10 billion US dollars, but they provide stable low-cost electricity over many decades. Unlike other energy sources, nuclear operators are required to accumulate funds to pay for all waste and decommissioning liabilities over the life of a nuclear power plant. This is typically added to the fuel cycle category.

Nuclear capital costs can be broken down further into both construction and financing costs. Construction costs are influenced by local factors such as resource availability and labour costs, whether it is a first-of-a-kind plant or part of a fleet programme, or whether it contains any design changes from the reference plant. Industry can influence many of these factors and is best placed to handle the technical risks involved. Financing costs (often represented as discount rates or cost of capital) are influenced by interest rates, risk allocation during construction, the presence of any guarantees, the growth rate of the economy, the underlying market structure, the presence of any power purchase agreement and other factors. These factors lie mainly within government's sphere of influence. When financing costs are high, they add significantly to the LCOE of nuclear power. Access to low-cost financing is therefore key for project viability (Figure 14&15).

In many parts of the world nuclear power is one of the most cost-competitive options for generating electricity. Just like other generating technologies the cost of nuclear electricity is sensitive to a range of factors including assumed asset lifetime, capacity factors, capital costs, fuel costs and operating costs.

For nuclear power plant projects the LCOE varies significantly between regions and its cost competitiveness depends on national and local conditions. International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA) have projected the costs of generating electricity for a range of technologies assuming commissioning these plants in 2025, as shown in Figure 16.

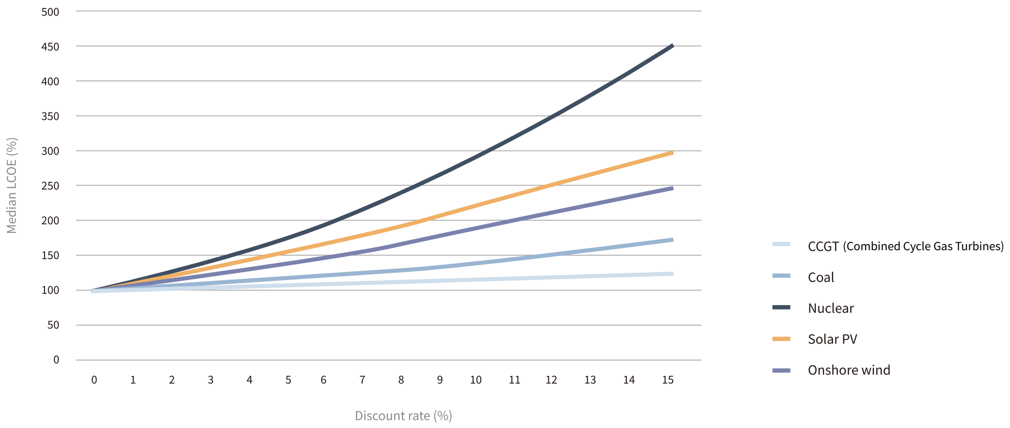
Figure 14 Breakdown of the levelised cost of nuclear power



Breakdown of LCOE for a typical nuclear project. Calculations based on overnight construction costs (OCC) of $4,500 per kilowatt of electrical capacity, a load factor of 85%, 60-year lifetime and seven-year construction time at a real discount rate of 7%.

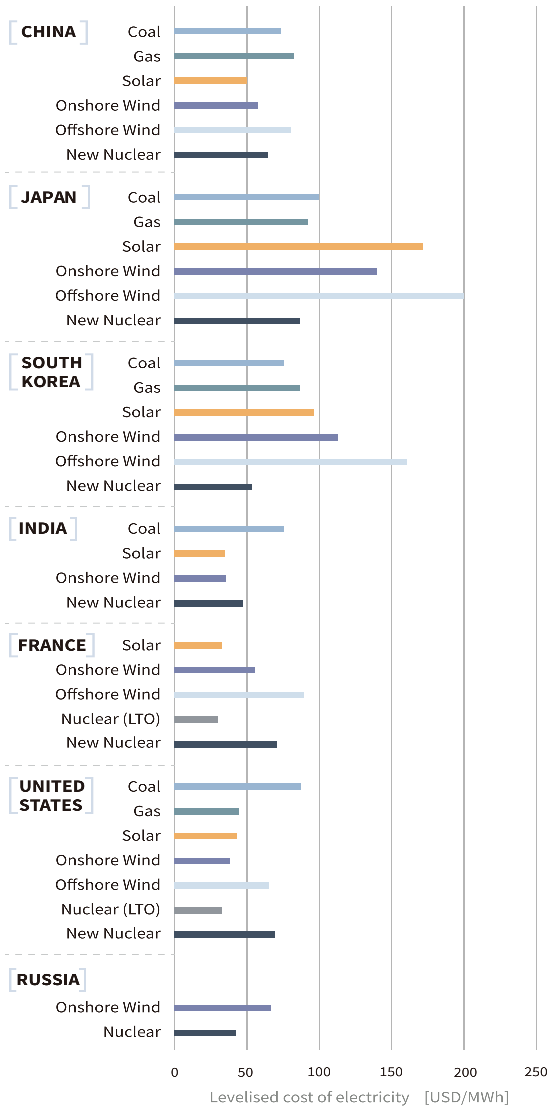
***Source**: OECD-NEA, 2020, Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*

Figure 15 Sensitivity of LCOE to financing costs for a range of technologies



***Source**: World Nuclear Association*

Figure 16 Levelised cost of electricity in different countries



Source*: IEA and OECD-NEA, 2020, Projected Costs of Generating Electricity 2020 edition*

4.1 The full costs of energy

The LCOE compares all the costs at plant level but does not take account of the value or indirect costs to the overall system and it is poor for comparing technologies that operate differently (e.g. variable renewables and dispatchable technologies). While the costs of variable renewable energy (VRE) sources are rapidly declining, these technologies also impose additional system costs which begin to increase significantly at higher penetrations. These additional system costs increase the overall cost of electricity as indicated in Figure 17. Adding firm dispatchable low-carbon generation – such as nuclear power plants, hydropower and fossil plants with CCS – to the energy system reduces the overall costs of decarbonisation while maximising the chances of a successful transition. For many countries it is clear that nuclear power will form part of an optimised quickest, least-cost and least-risk decarbonisation pathway.

Nuclear power plants also give rise to significant positive externalities which are not captured by the existing markets. They provide enhanced resilience against severe shocks that periodically affect the energy system, such as extreme weather events. For example, during the recent winter blackouts in Texas (February 2021) nuclear power plants were the least impacted form of generation.

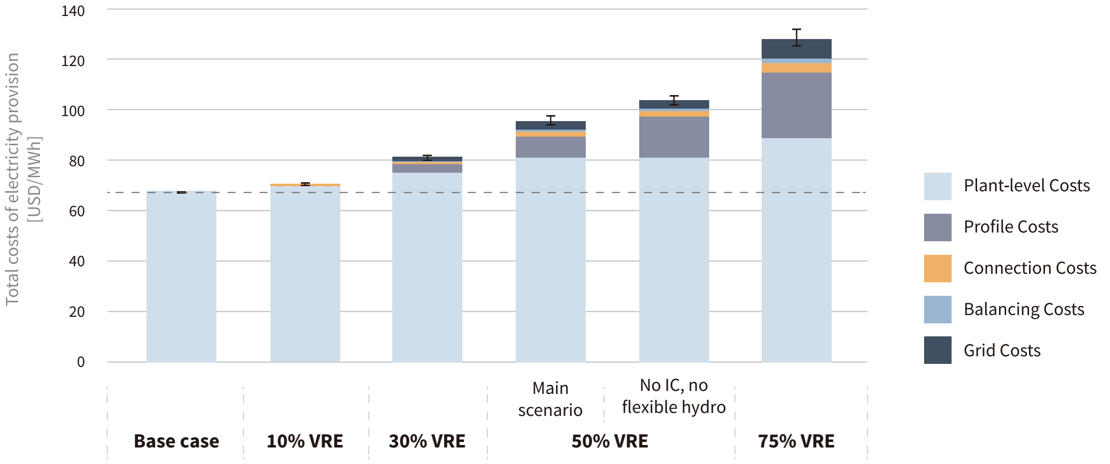
4.2 Reducing the costs of nuclear power

There have been some well-documented problems with the construction of first-of-a-kind (FOAK) and first of a generation nuclear power plant projects in some UNECE countries – notably within Western Europe and the US – but as capabilities and supply chains are reestablished industry is now transitioning from this phase. Countries that have maintained a consistent nuclear build programme; such as China, Japan, South Korea and Russian Federation, have managed to drive down the cost of nuclear new build. Therefore, there is significant potential for near-term construction cost reduction for projects in other countries as shown in Figure 18.

By capitalising on the lessons of recent construction projects from around the world, prioritising design maturity and regulatory stability, implementing a standardised reactor programme, and pursuing best practise recommendation countries can expect to significantly drive down the cost of nuclear power plant projects over the next decade. When combined with access to low-cost financing this will significantly reduce the LCOE of nuclear energy which in turn will help to cut the overall costs of decarbonisation and the low-carbon energy transition.

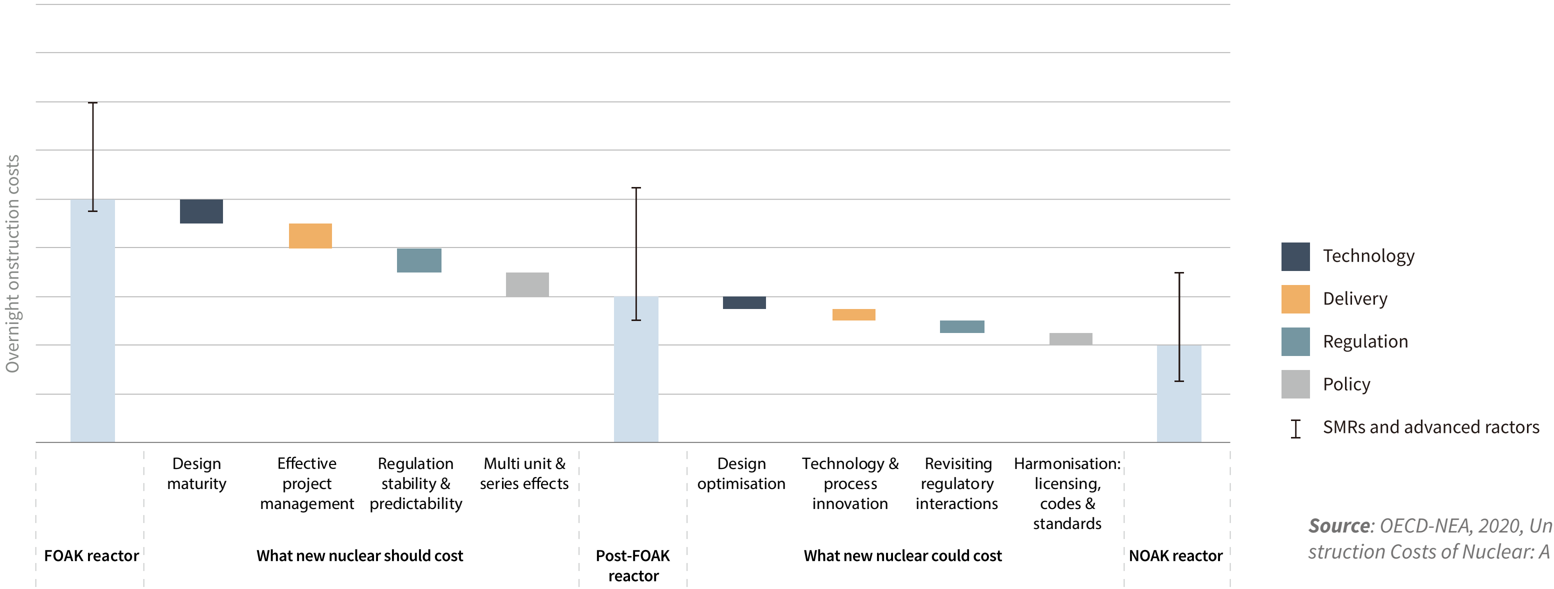
SMRs offer additional cost reduction pathways for nuclear technologies. SMRs aim to achieve their economic advantages based on economies of series production and standardisation for commercial deployment. SMR technologies could offer a wider range of energy services compared to large-scale reactor technologies, meeting the needs of grid-connected customers as well as off-grid remote communities and industrial users. Furthermore, lower capital costs, shorter construction times, and modular construction will make SMRs easier to finance, with lower investment risk. Greater deployment also means accelerated learning rates, offering additional potential for future cost reductions.

Figure 17 Growth of System costs with penetration of VRE



***Source**: OECD-NEA, 2019, The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*

Figure 18 Nuclear cost and risk reduction drivers



***Source**: OECD-NEA, 2020, Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*

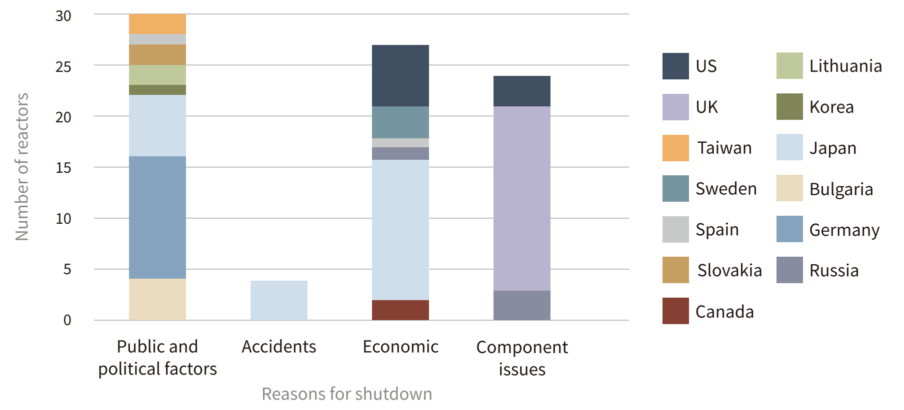
5. LONG-TERM AND FLEXIBLE OPERATION OF NUCLEAR PLANTS

Nuclear power plants were licensed originally for between 30 and 40 years of operation, but there is no fixed technical limit to the operational lifetime of a plant. Operation of nuclear plants beyond their original licence period – known as long-term operation (LTO) – is now commonplace in many countries, with plant life management programmes capable of identifying all the factors needed to maintain a high level of safety and optimise plant performance over the long-term. Amongst the many factors influencing countries' decision-making in this respect are the growing energy needs of their populations, national interests, financial factors, nuclear safety and security, climate objectives and human health, environmental and sustainability considerations. Most US nuclear plants (both PWRs and BWRs) have already been granted a 20-year licence renewal that would see them operate for a total of 60 years and many are now pursuing subsequent renewals that would permit them to operate for up to 80 years, with a number of units already having received approval. In Canada, mid-life refurbishment of PHWRs means that they will operate for at least 60 years. According to the IEA, long-term operation of existing nuclear power is one of the least-cost generating options available to many UNECE countries.

Despite this, many nuclear power plants have been shut down in the UNECE region in the last 20 years. A number of these closures are a result of political decisions shaped by incidents or accidents; others are due to economic conditions exacerbated by underlying market failure (Figure 19). Recent reactor closures have taken place in Europe – Germany initiated a phase-out in 2011 and certain Eastern European countries retired reactors as a condition for joining the European Union. In most cases, these plants have been replaced at least partly by fossil generation, therefore representing a setback for climate mitigation efforts. Many of the recent economic closures have taken place in the US where shale gas production has caused a steep decline of wholesale gas prices and hence reduced power prices. However, the underlying structure of markets and capacity auctions has also played a substantial role. In some European countries recent reactor closures are partly attributable to specific government taxes on nuclear plants. Preventing the premature closure of further nuclear power plants is seen by the IAEA and the IEA as an urgent priority for addressing climate change.

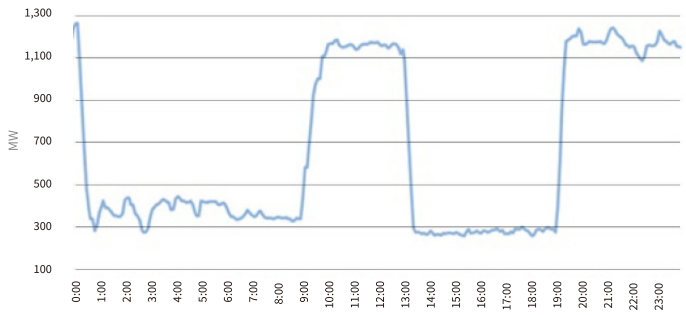
Today, most nuclear power plants around the world operate in 'baseload' mode. The low variable costs of nuclear power coupled with market structures that pay only for each unit of electricity generated incentivises operators to maximise production. The best performing nuclear plants regularly achieve average annual capacity factors of above 90% - the highest of any form of electricity generation. However, some nuclear plants can vary their power directly and operate in load-following mode if needed, while most other can be modified to be capable of this. There are no fundamental technical barriers preventing nuclear plants from operating flexibly but the power markets need to compensate plants that provide flexibility in a competitive and technology-neutral manner. Nuclear plant load following capabilities are illustrated in in Figure 20. As the amount of VRE continues to grow and constraints are put on CO_2 emitting generation, existing nuclear plants can be relied upon as a valuable source of system flexibility alongside energy storage, demand-side management and VRE curtailment.

Figure 19 Global reactor retirements from January – December 2020 (listed according to main reasons)



Source: *World Nuclear Association, June 2020, The Enduring Value of Nuclear Energy Assets*

Figure 20 Example of power variations over 1 day, Golfech 2 nuclear power plant



Source: *Nuclear Innovation Clean Energy Future, September 2020, Flexible Nuclear Energy for Clean Energy Systems*

6. HEALTH AND ENVIRONMENTAL IMPACTS

All forms of energy production pose risks and cause environmental and health impacts, and so these industrial activities are subject to monitoring and regulation to make sure impacts are managed to acceptable levels. Nuclear power presents specific risks such as radiological accidents and radioactive waste management, however comprehensive lifecycle assessments show that, when assessed across a broad range of environmental indicators, nuclear power has one of the smallest impacts of any energy source. These impacts are broadly similar to renewables as indicated in Figure 21, and many orders of magnitude lower than fossil fuels. The conclusions of a European Union Joint Research Centre investigation into whether nuclear energy should be included in the EU's green finance taxonomy "did not reveal any science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies."

One of the most important health and environmental challenges facing the world is air quality. The World Health Organization reports that ambient air pollution is responsible for 4.2 million deaths globally every year and much of this is associated with energy production and use. Household pollution in the form of exposure to smoke in cooking fires causes 3.8 million deaths per year. Nuclear power plants do not contribute to air pollution, and the historic use of the technology is believed to have helped to save over a million lives. Nuclear plants also unequivocally help to reduce CO_2 and other greenhouse gas emissions. The IPCC recognises that the whole lifecycle greenhouse gas emissions of nuclear energy are on a par with renewable sources of energy.

A nuclear power plant can produce multiple gigawatts from a single concentrated site. In terms of structural materials, a nuclear plant is mostly just steel and concrete, but it requires about ten times less of these than renewables such as wind, and hydro according to the US Department of Energy. By contrast a 2020 World Bank report notes that "Manufacturing solar panels, wind turbines, and batteries will shape the supply and demand for critical minerals for the foreseeable future." Nuclear plants also require water for cooling purposes and this needs to be managed to prevent impacts on local aquatic ecosystems. This necessitates careful siting and environmental impact assessment. The comparative analysis of space requirements of different energy sources is presented in Figure 21.

6.1 Radiation in context

Nuclear technologies present potential radiological health impacts to members of the public and workers. However, radiation occurs naturally. "Human-made" radiation is no different from natural radiation in its effects on people. Nuclear facilities are engineered with multiple protective barriers to protect people and the environment from the release of radioactive material. The regulatory justification for a proposed UK nuclear power plant estimates that the radiation dose to any member of the UK public per year to be around the same as from a return flight from the UK to New York. The nuclear energy industry is responsible for less than 0.1% of the radiation that most people are exposed to in their daily lives.

The two most serious nuclear accidents were those at the Chernobyl nuclear power plant in 1986 and the Fukushima Daiichi nuclear plant in 2011. These have been the source of much public anxiety resulted in long-term public evacuations and are the basis for the political decisions to close plants, as mentioned above. The lessons learned from these accidents and other incidents that have occurred during nuclear operations have been shared globally and incorporated into new reactor designs and operating practises.

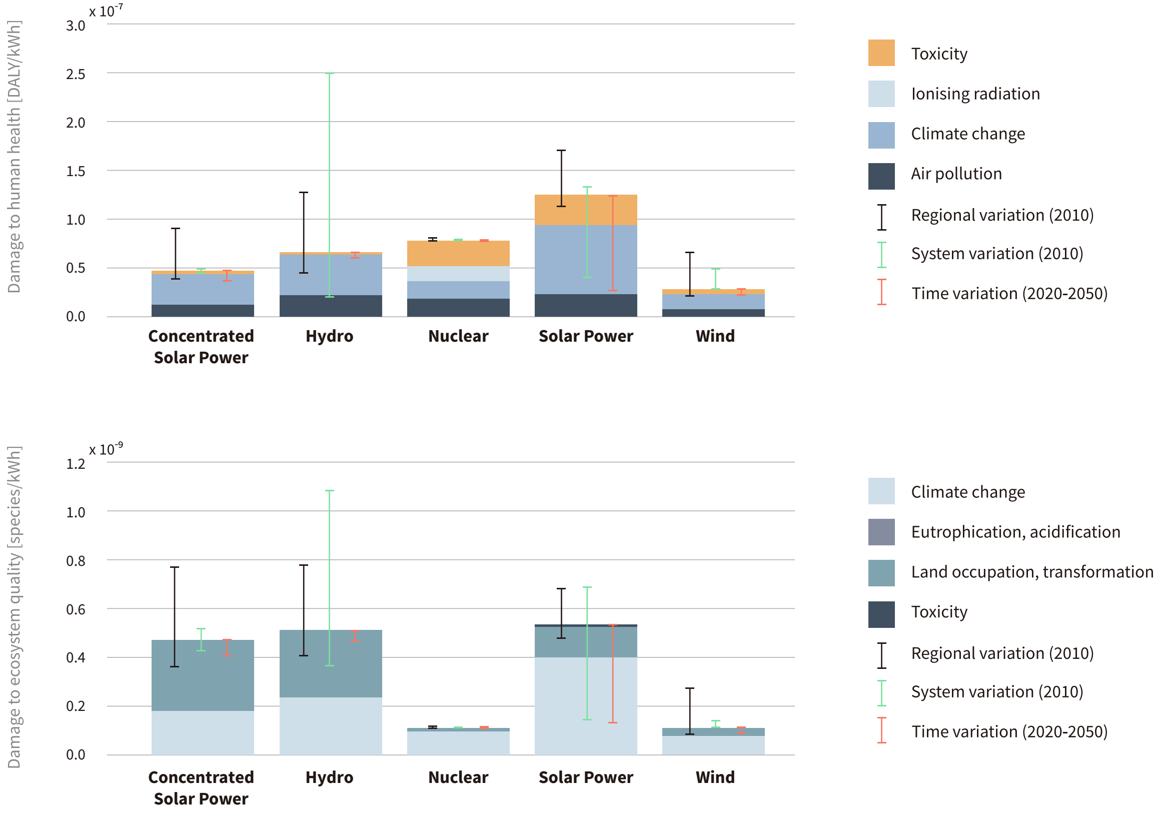
Radioactive materials are created during the production of nuclear power. Such materials demand sustainable management practices which protect workers and the environment, as well as eventual disposal in appropriately designed facilities. Radioactive waste is categorised according to the level of radioactivity present as well as the amount of time it stays radioactive, this latter being determined by the half-lives of the radioisotopes present Very low-level waste (VLLW) and low-level waste (LLW) are suitable for disposal in near surface landfill-type facilities. Intermediate-level waste (ILW) and high-level waste (HLW) including spent nuclear fuel, require disposal in deep geological repositories. ILW and HLW contain long-lived radionuclides, which necessitate disposal depths of the order of 10s to 100s of metres. About 97% of the radioactive waste generated by the nuclear industry is, after radiochemical characterisation, classified as either LLW or VLLW. HLW makes up the smallest fraction in terms of volumes (less than 0.1%), but accounts for about 95% of the total radioactivity. HLW mainly consists of spent nuclear fuel or its recycled remains. While there are no final repositories for HLW from nuclear power yet operating in the world, construction is under way on a repository in Finland which is on track to be the world's first when it starts operations in 2023.

Most materials used in the generation of nuclear electricity can be recycled and reused provided they do not become overly contaminated. Even used nuclear fuel should not automatically be categorised as a waste, since the opportunity exists to recycle it. The term 'radioactive waste' therefore only applies to radioactive materials which are considered impractical to reuse or recycle, and which are destined for disposal. In this way nuclear energy is highly aligned with the principles of a circular economy.

Public acceptance is a key factor for the future of nuclear power with many countries choosing to pursue its future development while some others have notably chosen not to do so. Public attitudes largely depend on the perception of the benefits and risks associated with nuclear power, but also of the benefits and risks of non-nuclear alternatives. Concerns about accident risks and waste management can negatively influence public acceptance. On the other hand, countries that have achieved visible progress towards operational HLW repositories are among those with the highest levels of public acceptance.

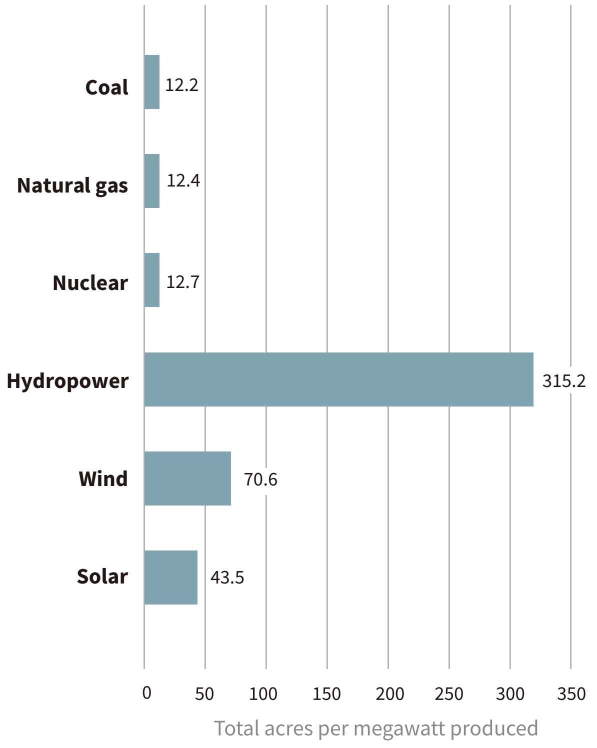
The 2020 "Guidance on the applicability of the Convention to the lifetime extension of nuclear power plants" adopted by the Parties to the UNECE Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) provides guidance on rules and procedures for domestic action and international cooperation for preventing, reducing and controlling significant adverse transboundary environmental impact from proposed activities, including in the field of nuclear energy.

Figure 21 Results of an energy lifecycle impact assessment for low-carbon energy sources



Source: Gibon et al., 16 March 2017, Health benefits, ecological threats of low-carbon electricity, Environmental Research Letters, 12, 3

Figure 22 Land requirement of different energy sources



Source: Strata, June 2017, The Footprint of Energy: Land Use of U.S. Electricity Production

ANNEX I Nuclear power plans in UNECE member countries (as of May 2021)

UNECE COUNTRIES WITH OPERATING POWER REACTORS	NUMBER OF OPERATING POWER REACTORS	INSTALLED NUCLEAR (MW)	PERCENTAGE OF ELECTRICITY (2019)	REACTORS UNDER CONSTRUCTION	CURRENT NUCLEAR PLANS
Armenia	1	375	28	0	1 new reactor proposed. Long-term operation of existing reactor
Belgium	7	5930	48	0	Phaseout by 2025
Bulgaria	2	2006	38	0	At least one new reactor currently planned. Investigating SMRs
Canada	19	13554	15	0	Actively licensing multiple SMRs
Czech Repulic	6	3932	35	0	At least 1 new large reactor currently planned. Investigating SMRs
Finland	4	2794	35	1	1 new large reactor planned. Actively investigating SMRs
France	56	61370	71	1	6 new reactors proposed. Government intends to reduce nuclear to 50% of mix
Germany	6	8113	12	0	Phaseout by 2023
Hungary	4	1902	49	0	2 new large reactors planned
Netherlands	1	482	3	0	Currently consulting on new build
Romania	2	1300	19	0	2 new large reactors currently planned. Investigating SMRs
Russia	38	28578	20	2	25 new reactors planned. Further 21 proposed (mix of SMRs and large)
Slovakia	4	1814	54	2	At least 1 further large reactor proposed
Slovenia	1	688	37	0	1 new large reactor proposed
Spain	7	7121	21	0	No new reactors planned
Sweden	6	6859	34	0	No new reactors planned
Switzerland	4	2960	24	0	All new nuclear build is currently forbidden
Ukraine	15	13107	54	2	At least 2 new reactors proposed
United Kingdom	15	8923	16	2	At least 4 new large reactors currently planned. SMR development funded
United States of America	93	95523	20	2	10 new large reactor projects authorised. Multiple SMRs being developed One SMR design now licensed

ANNEX II Readiness of different nuclear reactor technologies

REACTOR CLASS AND SIZE	LIKELY SETTING	APPLICATIONS	TECHNOLOGIES	READINESS LEVEL
Medium to large reactors (>300MWe)	On-grid	Electricity Hydrogen production Desalination District heating	**Reactor types**: PWR, BWR, PHWR, fast neutron reactor (FNR) **Conversion**: Rankine cycle	PWR, BWR, PHWR TRL: 11 SFR TRL: 8-9
SMRs (Up to 300MWe)	On- or off-grid Large developed grids Small or non-developed grids Industrial processing Off-grid agriculture	Electricity Hydrogen production Desalination District heating Industrial process heat	**Reactor types**: PWR, BWR, molten salt reactor (MSR), high temperature reactor (HTR), gas-cooled fast reactor (GFR), fast neutron reactor (FNR) **Conversion**: Rankine cycle, Brayton cycle	PWR SMR TRL: 6-9 Other SMRs TRL: 2-8
Microreactors (Up to approximately 20 MWt)	Off-grid Industrial facilities Mining operations Remote communities Oil and gas platforms Off-grid agriculture	Electricity Desalination Transport District heating Industrial process heat	**Reactor types**: fast neutron reactor, high-temperature gas-cooled reactor **Conversion**: Rankine cycle, Brayton cycle, supercritical steam, heatpipes, Stirling engines	TRL: 2-6

ANNEX III China nuclear power plant construction duration between 2010 and mid 2021

REACTOR	MODEL	CONSTRUCTION START	GRID CONNECTION	CONSTRUCTION DURATION (MONTHS)	CONSTRUCTION DURATION (YEARS)
Changjiang 1	CNP-600	25/04/2010	07/11/2015	66	5.5
Changjiang 2	CNP-600	21/11/2010	20/06/2016	66	5.5
Fangchenggang 1	CPR-1000	30/07/2010	25/10/2015	62	5.2
Fangchenggang 2	CPR-1000	23/12/2010	15/07/2016	66	5.5
Fuqing 3	CPR-1000	31/12/2010	07/09/2016	68	5.7
Fuqing 4	CPR-1000	17/11/2012	29/07/2017	56	4.7
Fuqing 5	Hualong One	07/05/2015	27/11/2020	66	5.5
Haiyang 2	AP-1000	20/06/2010	13/10/2018	99	8.3
Ningde 3	CPR-1000	08/01/2010	21/03/2015	62	5.2
Ningde 4	CPR-1000	29/09/2010	29/03/2016	66	5.5
Taishan 2	EPR-1750	15/04/2010	23/06/2019	110	9.2
Tianwan 3	VVER V-428M	27/12/2012	30/12/2017	60	5.0
Tianwan 4	VVER V-428M	27/09/2013	27/10/2018	61	5.1
Tianwan 5	ACPR-1000	27/12/2015	08/08/2020	55	4.6
Tianwan 6	ACPR-1000	07/09/2016	11/05/2021	56	4.7
Yangjiang 3	CPR-1000	15/11/2010	18/10/2015	59	4.9
Yangjiang 4	CPR-1000	17/11/2012	08/01/2017	49	4.1
Yangjiang 5	ACPR-1000	18/09/2013	23/05/2018	56	4.7
Yangjiang 6	ACPR-1000	23/12/2013	29/06/2019	66	5.5

ABBREVIATIONS

BWR	Boiling water reactors
CCGT	Combined Cycle Gas Turbine
CCS	Carbon capture and storage
FOAK	First-of-a-kind
GFR	Gas-cooled fast reactor
GHG	Greenhouse gas
HALEU	High-Assay Low-Enriched Uranium
HTTR	High Temperature Test Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCOE	Levelized cost of electricity
LFR	Lead-cooled fast reactor
MSR	Molten salt reactor
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
OECD	Organisation for Economic Co-operation and Development
PHWR	Pressurised heavy water reactors
PWR	Pressurised water reactors
R&D	Research and development
SCWR	Supercritical-water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactors
TRL	Technology readiness level
UNECE	United Nations Economic Commission for Europe
VHTR	Very high-temperature reactor
VRE	Variable renewable energy

REFERENCES

Canadian Small Modular Reactor (SMR) Roadmap Steering Committee, November 2018, A Call to Action: A Canadian Roadmap for Small Modular Reactors

European Commission Joint Research Centre, 2021, Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')

Eurostat, EU Electricity Generation Statistics

FORATOM, 25 April 2019), Economic and Social Impact Report

Gibon et al., 16 March 2017, Health benefits, ecological threats of low-carbon electricity, Environmental Research Letters, 12, 3

International Atomic Energy Agency, 2020, Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition

IAEA, 2020 Climate Change and Nuclear Power 2020

IAEA, 2018, Status and Trends in Spent Fuel and Radioactive Waste Management

International Energy Agency, Energy Technology Perspectives 2020, Clean Energy Technologies

IEA, May 2019, Nuclear Power in a Clean Energy System

IEA and OECD-Nuclear Energy Agenecy, 2020, Projected Costs of Generating Electricity 2020 edition

Kirsten Hund et al., 2020, Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition, World Bank Group

MIT Energy Initiative, 2018, The Future of Nuclear Energy in a Carbon-Constrained World

Nuclear Innovation Alliance, 2021, U.S. Advanced Nuclear Energy Strategy for Domestic Prosperity, Climate Protection, National Security, and Global Leadership

Nuclear Innovation Clean Energy Future, September 2020, Flexible Nuclear Energy for Clean Energy Systems

Pushker Kharecha and James Hansen, 15 March 2013, Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power, Environmental Science &Technology, 47, 9, p4889-4895

OECD-NEA, June 2020, Building low-carbon resilient electricity infrastructures with nuclear energy in the post-COVID-19 era, NEA Policy Brief

OECD-NEA, 2019, The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables

OECD-NEA, 2020, Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders

Oxford Economics, April 2019, Nuclear Power Pays

Sepulveda et al., 21 November 2018, The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation, Joule, 2, 11, p2403-2420

Strata, June 2017, The Footprint of Energy: Land Use of U.S. Electricity Production

UNECE, 2020, Guidance on the applicability of the Convention to the lifetime extension of nuclear power plants. Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention)

UNSCEAR, 2018, Evaluation of Data on Thyroid Cancer in Regions Affected by the Chernobyl Accident

UNSCEAR, 2020, Sources, Effects and Risks of Ionizing Radiation, Scientific Annex B

World Health Organization, Air Pollution

World Nuclear Association, Financing Nuclear Energy

World Nuclear Association, June 2020, The Enduring Value of Nuclear Energy Assets

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