A PROSPECTIVE STUDY "BLUEBOOK" ON

NUCLEAR ENERGY

TO SUPPORT

LOW CARBON

Presented by

China Institute of Nuclear Industry Strategy

EDF

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Foreword by CNNC

Climate change challenges the survival and development of humanity. Therefore, addressing climate change – and achieving green, low-carbon, and sustainable development – is the common cause for us all. China has consistently and unswervingly taken the road of ecological priority and green development, and has officially launched the strategic national goals of carbon peak and carbon neutrality. Promoting clean and low-carbon energy transition is key to addressing climate change.

Nuclear energy, a fruit of human wisdom, offers a great potential in tackling climate change as a kind of clean and low-carbon energy source. It can be used for power generation in a safe, secure, and reliable way, making it a large-scale alternative to fossil energy sources and a promising baseload power source for a new power system in the future. The multipurpose utilisation of nuclear energy for heating, process steam supply, and hydrogen production will help decarbonise carbon-intensive sectors. Promoting the use of nuclear energy is an inevitable option for China in achieving carbon peak and carbon neutrality. It is a vital component of global strategy to reduce greenhouse gas emissions from both power and industrial sectors, ensure energy security, and promote long-term sustainable development.

China attaches great importance to the development of nuclear energy and has set a policy of active, safe and well-ordered development of nuclear energy. After more than 40 years of development, China's nuclear power industry ranks among the best in the world in terms of scale, technological capability, and industrial and supply chains. As the main body of China's nuclear science and technology industry, China National Nuclear Corporation (CNNC) has played a major role in the development of nuclear energy in China. Maintaining a steady and fast pace of development, CNNC ranks first in China and second in the world in terms of total capacity of holdings, including units in operation, under construction, and approved for construction.

Adhering to the principle of safety first, none of our nuclear power units have ever had an International Nuclear and Radiological Event Scale (INES) Level 2 or above incident, and our operation performance is at the forefront of the world. With the ideal of being "innovation-driven", CNNC is actively promoting a "three-step" strategy of nuclear energy development – from thermal reactors, through fast reactors, to fusion reactors. By the end of 2023, with the successful development of Generation III nuclear power technology Hualong One (also known as HPR1000), 24 HPR1000 units had been completed or were under construction or approved. Remarkable progress has been made in the construction of Linglong One (also known as ACP100), the world's first commercial onshore small modular reactor (SMR). The research and development of fast reactors, high-temperature gas-cooled reactors (HTGRs) and closed fuel cycle systems have been stepped up.

CNNC is committed to building complete, advanced and resilient industrial and supply chains, with an ever-improving natural uranium supply and service system, a significant increase in the scale of the nuclear fuel industry and international market share, and a world-leading capacity and level of nuclear power engineering and construction. China's nuclear power industry has generated about 4000 TWh of electricity, which is equivalent to avoiding the emission of about 3.5 billion tonnes of CO_2, thereby contributing to green and low-carbon development and building a beautiful China.

Countries in the world are interdependent, and the future of humankind is closely linked. China and France are two of the major nuclear power countries, and their cooperation in nuclear energy has gone through a glorious journey for more than 40 years. A number of remarkable achievements made by China and France through cooperation in projects, technologies, human resources and industrial chains have set an example of joining hands to promote the development of nuclear energy and facilitate low-carbon development. As major participants and contributors to the development of nuclear energy in the world, CNNC and Électricité de France (EDF) have organised a joint research team carrying out a prospective study on nuclear energy to support low-carbon development. Their exchanges of ideas and practices, sharing of development experience and consolidation of consensus on development have pushed China-France cooperation to a new level.

The joint research team produced a detailed report that systematically analysed the role and advantages of nuclear energy in reducing emissions as well as the trends of the development of nuclear energy, and summarised the achievements and practical experience of promoting the development of nuclear energy. This will create a broader space for

China-France nuclear energy cooperation and provide a reference for other countries interested in developing nuclear energy and promoting low-carbon development.

I am confident that the Chinese and French nuclear industries will continue to apply their wisdom and strength to better promote the use of nuclear energy, support low-carbon development, and play a greater role in preserving the common home of humankind and building a cleaner and more beautiful world.

YU Jianfeng, Chairman of CNNC

Foreword by EDF

The recent COP28 confirmed that every decade since 1990 has been warmer than the previous one. The absolute priority is to take action for the planet to prevent climate change from getting out of hand. To avoid this, the Intergovernmental Panel on Climate Change (IPCC) states we must keep long-term warming "well below 2°C", as set out in the *Paris Agreement*.

The scientific evidence is clear: to preserve a liveable climate, we need to both accelerate the phase-out of fossil fuels and implement extremely ambitious targets for the deployment of energy efficiency and the use of carbon-free energy sources, while at the same time defining robust and prompt measures to address the increasing number of extreme weather events.

To achieve this, we need to take strong and immediate action. This leads to the electrification of many sectors – transport, buildings, and industry – as much as we can, and it requires increasing the volume of electricity generation. At the same time, we must make this electricity carbon neutral as soon as possible: all carbon-free resources, especially renewable energies and nuclear power, must be mobilised.

The use of a combination of renewable energies and nuclear power is essential, as it provides economic benefits and reduction in CO_2 emissions. Nuclear power and hydropower guarantee that prices remain affordable for the general population and the industry on the long run, while maintaining a secure supply in the face of the necessary high pace of development of variable renewable energies. In a way, they are the needed insurance to achieve carbon neutrality.

France has a long and unique history of developing nuclear energy. For over 60 years, France has been engaged in the research and development of nuclear energy and has built many nuclear power stations around the world. Today, France's installed nuclear capacity holds a major position in the nation's energy supply and ranks among the highest globally. EDF, as the exclusive operator of the large nuclear power fleet in France, has a strong record of ensuring safety and reliability in nuclear operations.

Nuclear energy will enable us to act quickly and on a large scale. At COP28, France pledged to work towards an ambitious global target of tripling nuclear power generation capacity between 2020 and 2050: by studying the extension of the lifespan of existing nuclear power plants (NPPs), and by building new power plants. EDF is fully dedicated to this effort, with three EPRs under construction in France and the United Kingdom, a major programme to build 6 and possibly 14 EPR2 reactors in France, and other projects at an advanced stage, including the development of the Nuward SMR.

Beyond these actions, EDF is engaged in actively promoting international cooperation and sharing its technology, experience, and best practices with global partners. EDF has been firmly established in China for more than 40 years and is now one of the largest foreign investors in power generation and energy services. EDF has forged partnerships with leading Chinese utilities and key players in the Chinese nuclear industry, including its peers CNNC and CGN. EDF also chairs the France-China Partnership for Electricity (PFCE), made up of qualified nuclear suppliers, the Chinese AFCEN Users Group, and the Low-Carbon Group of the Franco-Chinese Business Council together with CNNC.

Today, as Europe, and especially France, experiences a revival of nuclear energy, and as the Chinese industry achieves unprecedented growth and innovation, this Bluebook represents a pioneering and unique initiative. Supported by the nuclear industries of our two countries, it aims to highlight the properties of nuclear technologies for a successful energy transition, while underlying the overriding imperative of safety.

This common piece of work is of great importance for the two major nuclear energy companies of France and China as they join forces to promote the sustainable development of nuclear energy. EDF and CNNC will work together in the pursuit of fighting climate change and, by sharing experiences and fostering stronger cooperation, aim to pave the way for a greener and more sustainable future. I can only welcome the formalisation of this shared vision, which brings mutual enrichment and opens common partnership perspectives!

Luc RÉMONT, Chairman of EDF

Preface

For the first time in history, the nuclear power industries of China and France have come together to jointly write a book highlighting the benefits of nuclear energy in terms of the fight against climate change, as well as in terms of economic advantages and the security of supply.

Above all, the creation of this book has been an exceptional adventure. Not only have the two nations' editorial teams got to know each other through the process of working together, they have also become acquainted with dozens of technical experts with expertise in various areas of nuclear energy. This Bluebook would never have come to fruition without their hard work, dedication, and involvement.

Despite many challenges posed by our different cultures, geographical distance and the intricate task of translating among Chinese, English and French, we are now very pleased to be able to announce the on-schedule publication of this Bluebook. Two on-site missions – one to France and the other to China – enabled the teams to meet each other, to visit both French and Chinese industrial sites together, and to forge strong links that helped to resolve many of the challenges inherent in a project of this magnitude.

In order to stick to the ambitious timetable that we had set ourselves, and as this is the first exercise of its kind, EDF and China Institute of

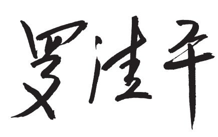
Nuclear Industry Strategy (CINIS) have decided to share responsibility for writing the book's sub-chapters with this allocation of duties being explicitly outlined in the report. Of particular note, each section detailing "Chinese practice" was written and validated by CINIS and each section detailing "French practice" was written and validated by EDF.

Nevertheless, we considered it essential to write at least a few sections together. There was complete agreement on the structure of the report and its reading grid, and – most significantly – the jointly and unanimously written Executive Summary demonstrates a remarkable alignment in the delivery of our key messages.

Having met these challenges together, we are delighted with this achievement. With a shared approach based on commitment, transparency and friendship, this mutual involvement in writing the CINIS & EDF Bluebook lays the foundations for future cooperation in various areas of nuclear energy.

Finally, during the compilation of this Bluebook, we have received tremendous support and valuable insights from experts and scholars from many Chinese and French government departments, nuclear-related enterprises, universities, and research institutes, without whom this would have been impossible, and we would like to express our sincere gratitude for their contributions.

Bertrand MARTELET
EDF Bluebook Strategic Pilot



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Executive Summary

The executive summary reflects the common understanding of China National Nuclear Corporation (CNNC) and Électricité de France (EDF) on the role of nuclear energy in supporting global carbon neutrality and sustainable development goals (SDGs). It provides an overview of the report, covering the following aspects: the role of nuclear energy in addressing climate change, the development trend of nuclear energy, the advantages of nuclear energy, the key topics and approaches in developing nuclear energy, the directions for scientific and technological innovation, and the need for international cooperation.

The role of nuclear energy in addressing climate change

Climate change is a common challenge to the survival and development of humankind. The United Nations (UN) has declared that the world is in a state of climate emergency. In recent years, the need for urgent climate action has increasingly received global attention. The

IPCC states that to meet climate targets, global long-term warming must be kept "well below 2°C", as outlined in the *Paris Agreement*. However, if the current governmental policies around the world remain unchanged, global long-term warming could exceed 3°C. China and France have both committed to achieving carbon neutrality, by 2060 and 2050 respectively.

Excessive CO_2 emissions, primarily from the energy sector, are the main cause of climate change. Therefore, accelerating the transition to low-carbon energy is key to tackling climate change, mainly through electrification of uses in various sectors. This requires a significant increase in electricity production, alongside energy efficiency measures. A fundamental transition is needed for the global energy system. All available low-carbon technologies must be deployed to bridge the gap between current policies and what is necessary. The world should remain open to adopting mature low-carbon technologies.

Nuclear energy is a safe, efficient, sustainable, and competitive energy source with very low emissions, making it a significant contributor to mitigating climate change. From 1971 to 2022, global nuclear power generation has led to a cumulative reduction of around 70 Gt in CO_2 emissions. Without nuclear power, total emissions from electricity generation would have been almost 20% higher over the last fifty years[1]. In the transition to low-carbon energy, nuclear energy is one of the most practical options to achieve economic and stable transformation. Its contribution and role should not be overlooked. In

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[1] IEA, *Nuclear Power and Secure Energy Transitions*, 2022.

recent years, nuclear energy has accounted for around 10% of total global electricity production and more than a quarter of the world's low-carbon electricity production.

A growing number of countries have recognised that nuclear power, as a proven source of low-carbon electricity, is now a vital tool for mitigating climate change and providing the dispatchable electricity needed, alongside fast-developing power generation from non-dispatchable renewable energy sources such as wind power and solar PV. In most of the world's energy studies[2], nuclear power plays a significant role in future energy mixes.

Development trend of nuclear energy

In almost all countries with NPPs, the role of nuclear energy has been confirmed, revived, or highlighted. In addition to France and China, many countries, including Canada, India, Japan, the Republic of Korea, Russia, the United Kingdom, the United States, and several European countries have recently unveiled energy strategies that emphasise nuclear power. These efforts mainly focus on nuclear plant lifetime extensions, and also include introducing new programmes to secure energy transition.

International energy organisations have forecast an increase in installed nuclear capacity. In alignment with the growing consensus among countries to address climate change, many international organisations, including the International Atomic Energy Agency

2 Including the IPCC, the IAEA, the WNA, the IEA, and the IRENA.

(IAEA), the International Energy Agency (IEA) and the OECD Nuclear Energy Agency (OECD/NEA), have developed scenarios that project a substantial increase in installed nuclear capacity worldwide. For instance, the IEA report *Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems*, released in 2022, estimated a doubling of global installed nuclear capacity by 2050 based on a net-zero emissions scenario.

China and France are strong supporters of sustainable nuclear energy development. France, with 61.37 GWe in operation and 1.63 GWe under construction, and China, with 53.15 GWe in operation and 23.72 GWe under construction, are making significant contributions to this momentum. In 2022, the French President took the decision to extend the lifetime of all nuclear reactors that can be extended as long as safety is ensured, to launch a programme of at least 6 new large EPR2 reactors, possibly 14, and to develop SMRs. In China, the *Report on the Work of the Government 2021* pointed out that the nation will "take active and well-ordered steps to develop nuclear energy on the basis of ensuring its safe use". In addition to its 21 reactors under construction, China approved the construction of 10 reactors in 2022 and 2023 respectively, the largest number since 2008.

In the future, most of the incremental increase in nuclear power will come from China, India, and other emerging countries. This is mainly due to the rising demand for clean, low-carbon energy in these countries as a result of economic and social development. A growing number of countries are envisaging, planning, or launching nuclear power programmes, including Bangladesh, Egypt, Poland, Türkiye, and many other countries in Africa, South America, Southeast Asia and the Middle East.

Pressurised water reactors (PWRs) are expected to remain the most widely used technology for large third-generation reactors until the 2050s. PWRs have long served as the mainstream technology for the construction of nuclear power plants worldwide, as they have advantages in terms of safety, cost-effectiveness, and technological advancement. According to the IAEA, at the end of 2023, more than 300 PWR units were in operation worldwide, accounting for over 70% of the total, and around 50 were under construction, accounting for over 85% of all reactors under construction. PWR units account for close to 91% of units in operation and under construction in China, and 100% in France[3]. PWRs seem to remain the preferred option for new large nuclear power units in many countries into the 2050s.

In recent years, remarkable progress has been made in renewable energy sources such as wind power and solar PV, resulting in a considerable reduction in costs, and accelerating decarbonisation of electricity worldwide. Given the long construction period of nuclear plants and the dispatchable nature of nuclear energy, leading energy companies with nuclear assets are proactively developing renewable energy sources. This coordinated approach seeks to leverage the strength of different energy sources, thereby establishing a well-balanced global energy system that supports collective decarbonisation efforts.

[3] Data source: IAEA PRIS database, December 2023.

Advantages of nuclear energy: environmental and economic benefits, and security of supply

Environmental benefits

Greenhouse gas (GHG) emissions from nuclear power production are zero. Estimates from many international research institutes indicate that the full lifecycle carbon intensity of nuclear power is one of the lowest of all energy sources. According to the IPCC, based on median values, nuclear power emits only 12 gCO_2/kWh, which is similar to the lifecycle carbon emission intensity of wind power, about a quarter of that of distributed solar PV, 1/41 of natural gas and 1/68 of coal power. In France, thanks to the high share of nuclear and renewables in the electricity mix, this figure is around 4 gCO_2/kWh.

The environmental impact of nuclear power is comparable to that of other green energies[4]. In terms of indicators, such as pollutants, health, ecotoxicity and the footprint of non-energy raw materials, nuclear power shows similar or lower values than other low-carbon technologies. Considering the fuel cycle, nuclear energy produces a relatively small amount of nuclear waste, which is perfectly manageable over the long term without any harmful impact on the public.

Economic benefits

The large-scale development of nuclear energy reduces the economic cost of transition to a low-carbon energy system, and offers advantages in

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4 https://publications.jrc.ec.europa.eu/repository/handle/JRC125953.

terms of external costs, such as social and environmental costs. The joint use of renewables and nuclear energy delivers economic benefits and reduces CO_2 emissions. In France, a recent study conducted by Réseau de Transport d'Électricité (RTE) shows that an electricity mix with a significant nuclear base has considerably lower system costs than one with little or no nuclear power. A Chinese study based on the OECD/NEA[5] data shows that nuclear energy is highly competitive when the costs of the whole system are considered.

Extending the life of nuclear power units is essential to maximising their contribution to the clean energy transition. According to IEA estimates, the investment required to extend the operational life of a light water reactor (LWR) unit typically ranges from 500 million to 1.1 billion USD per GWe, which is significantly lower than the cost of new construction.

Both China and France are taking actions to reduce costs for new nuclear builds. Several factors are involved, including the learning effect, scale-up construction, standardisation, digitisation, and modularisation. China has demonstrated a strong capability in further lowering construction costs, while France is taking measures to improve the cost-effectiveness of future reactors. Both countries have succeeded in boosting the economic efficiency of nuclear energy and shall continue to do so by learning from each other.

Lastly, nuclear empowers economic growth. An International Monetary Fund (IMF) study published in 2021 showed that the multiplier effect of nuclear power was two to three times higher than

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[5] https://www.oecd-nea.org/jcms/pl_14998/the-full-costs-of-electricity-provision.

that of other energy sources. Developing nuclear power drives domestic growth, creates more high-level jobs, and fosters innovation in the multipurpose use of nuclear, which is a major trend of nuclear energy development.

Security of supply

Nuclear energy provides a stable and secure supply of electricity. With various advantages, such as high energy density and stable output, nuclear power is resilient to cyclical, regional, and seasonal fluctuations. As a dispatchable baseload power source, nuclear energy ensures a consistent and secure supply of electricity while maintaining grid stability.

A single 1,000 MWe nuclear power reactor requires 20-25 tonnes of nuclear fuel annually, which is 1/100,000 of the weight of coal needed for equivalent electricity production. As fuel costs represent only a small portion of the total operating costs of nuclear power, fluctuations in fuel prices have limited impact on the overall costs. Furthermore, although new mines will have to be developed, there are abundant recoverable uranium resources worldwide. In addition, nuclear energy is less reliant on essential raw materials than other energy sources, which enhances the security of its supply chain.

Key topics in developing nuclear energy and approaches in China and France

To achieve such advances in nuclear energy, the following issues need to be addressed:

Build a robust nuclear safety regulatory system

Ensuring safety is the top priority for any nuclear operator. Through long-term exploration and practice, both China and France have established effective nuclear safety regulatory systems tailored to their domestic conditions. Measures have been taken to strengthen nuclear safety regulations and standards, as well as to implement a comprehensive system of laws, administrative regulations, regulatory requirements, and technical standards, thus achieving extensive nuclear safety coverage.

China's National Nuclear Safety Administration (NNSA) oversees the entire process of the site selection, construction, operation and decommissioning of nuclear facilities. It has also implemented a safety licensing system. Chinese nuclear power enterprises are committed to fostering a culture of nuclear safety, aiming to further enhance operational safety. Over the past three decades, China has not experienced any nuclear safety incidents or accidents at Level 2 or higher on the International Nuclear and Radiological Event Scale (INES), placing Chinese nuclear units among the top performers globally in the evaluation by the World Association of Nuclear Operators (WANO).

France has safely deployed a civil nuclear programme with no major incidents that could bring the technology into question. The safety and radiation protection of civil nuclear installations is regulated by the French Nuclear Safety Authority (ASN), which is independent of the operator and has been duly qualified to monitor the installations. EDF reinforces the safety culture in each nuclear plant. Continuous improvement is being made, and feedback on operating experience is integrated. Nuclear licensees regularly receive international assessments, notably from Operational Safety Review Team (OSART) and IAEA missions. Additionally, reviews are conducted by WANO on a regular basis.

Enhance the competitiveness of nuclear energy

China is continuously boosting the economic efficiency of its nuclear energy sector by rolling out initiatives and learning from previous experience. The highlights include achieving breakthroughs in 3D model design and construction technology for the integration of the two phases; optimising nuclear power design in various aspects, such as general layout, modularisation, and fuel management; and stepping up the construction of "digital nuclear power", including the phased implementation of an intelligent system for operation, maintenance, technical support, supply chain management, security, and training.

In the context of the EU's electricity market, while the short-term wholesale market ensures optimal dispatch and use of transmission networks within Europe, new tools such as long-term Power Purchase Agreements (PPAs) or Contracts for Difference (CfDs) are necessary to send price signals that incentivise long-term investments.

Improve public communication on nuclear energy

Adequate information transparency and effective public communication are essential to improving social acceptance of nuclear power. China and France have adopted comprehensive measures to facilitate public access and participation in nuclear power projects, including legislation, establishment of specialised institutions, popularisation of nuclear science, as well as public consultation and debate.

Nuclear Safety Law of the People's Republic of China and the *Nuclear Transparency and Security Act* in France are the two countries' fundamental laws in the field of nuclear safety, which require disclosure of information related to nuclear power and encourage public participation. China's NNSA and the Local Information Commissions (CLIs) and National Public Debate Committee in France provide important channels for public participation and communication, including disclosure of government information, publication of annual reports, public consultation, and public debate.

The governments and nuclear energy companies of both countries, including CNNC and EDF, have intensified efforts to innovate in nuclear communication, utilising new technologies and new media to share knowledge about nuclear energy and support public participation.

Build strong and resilient supply chains

Nuclear power construction and development require a large number of supply chains and supporting industrial chains. To develop the necessary skills for these projects, effective human resource strategies must be implemented.

China has set up a comprehensive nuclear power industry ecosystem, which provides services for engineering design, construction, equipment manufacturing, and O&M. Meanwhile, China has established a full-fledged supply chain for the nuclear fuel cycle, which covers the production and supply of natural uranium and nuclear fuel components, spent fuel reprocessing technology and waste management.

With around 500 companies, the French nuclear industry is complete and autonomous, covering all steps of the supply chain. With more than 2,100 reactor years of experience, it benefits from international experience and serves nearly 250 reactors worldwide. It also works with players whose mission is to ensure the implementation of regulations, issue certifications and provide skill training, striving for the highest levels of industrial performance.

Build a safe, cost-effective and sufficient system for securing uranium resources

China and France attach great importance to ensuring adequacy of uranium resources, focus on security of supply, economics, and diversification, and continuously improve the reliability of their own uranium supply in order to support their medium-term and long-term sustainable development of nuclear power.

China has intensified its efforts in the exploration and development of uranium resources. Through ongoing technological innovation, China seeks to raise the standards of uranium exploration and extraction. Priority has been given to the support system of uranium supply and capacity building. China has been advancing domestic uranium development while fully leveraging global uranium resources. A reserve system has been established with the aim of better securing the diversified supply of uranium.

Since 1960, France has successfully developed a complete industrial value chain, from uranium production to spent fuel recycling. Furthermore, EDF aims to guarantee its nuclear fuel procurement through supplier diversification, so as to be robust to all types of risk that may affect the availability of suppliers' production, with long-term contracts with primary producers, such as Orano, that own, develop and operate their facilities. This also helps to establish an in-depth, industrial and mutually beneficial partnership with suppliers, and build reserve stocks to cope with major disruptions to the supply chain.

Implement a closed fuel cycle and minimise radioactive waste

Resource sustainability and environmental friendliness are crucial factors for the sustainable development of nuclear energy. China and France recognise the importance of a closed nuclear fuel cycle in achieving sustainable development of nuclear energy with the highest standards. Both countries have reduced their dependence on uranium through reprocessing and recycling of spent fuel, thus minimising the amount of waste requiring disposal.

In pursuit of closed fuel cycles for nuclear energy, China has conducted R&D on reprocessing and recycling technologies and equipment, built a pilot plant for spent fuel reprocessing and kept it in operation. Now the country is advancing demonstration and commercial projects for spent fuel reprocessing within NPPs.

In France, a total of 22 PWR units use MOX fuel[6]. In addition, the use of enriched reprocessed uranium is resuming in 2024 with the aim of extending its use to about 15 reactors over the next few years. The French experience shows that plutonium and uranium recycling can reduce the overall demand for natural uranium by 20% to 25%. Meanwhile, the volume of waste is decreased by 80%. Orano has benefited from the practice of reprocessing 40,000 tonnes of spent fuel over more than 30 years.

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[6] The plutonium extracted from the spent fuel is mixed, as an oxide, with the depleted uranium oxide produced by enrichment plants to make MOX (Mixed Oxides) fuel.

Adapt nuclear reactor fleets to climate change

China and France have taken measures to enable nuclear power to better cope with extreme climatic disasters.

China is enhancing the operational security of its energy infrastructure to better withstand extreme weather events such as storm surges, high temperatures, and freezing. All of China's existing NPPs in operation or under construction are located on the coast, making them particularly vulnerable to the gradual rise in sea levels due to climate change. China has taken steps to enhance the ability of its NPPs to cope with climate change, withstand extreme weather events such as hurricanes and tsunamis, and mitigate risks associated with cold-source safety.

In France, building on long-standing work, EDF has launched the ADAPT project, which aims to make power generation from thermal and nuclear sites secure by anticipating the consequences of climate change. A similar approach is taken for the new reactors by considering the impact of climate change in their design and construction processes.

Consider nuclear energy as a flexibility tool

As the share of intermittent energy sources in electricity mixes continues to grow, there will be a need for an increase in flexible, dispatchable power generation sources.

China is gradually shifting away from an energy mix dominated by fossil fuels, and is projected to fully utilise nuclear energy to achieve a stable, low-carbon power supply. To improve the compatibility of nuclear power with the grid, China has taken active measures, such as the integrated operation of NPPs and pumped storage power stations. During holidays, some NPPs are still in operation, though with reduced power, to ensure grid stability.

French nuclear reactors were designed for flexibility from the beginning, as nuclear accounts for 70% of the power mix, and the new reactors will also be flexible. Today, up to 20 GWe can be ramped up or down within 30 minutes, twice a day. Alongside other low-carbon flexibility tools, flexible nuclear power can support the growing share of intermittent sources while keeping electricity available and affordable.

Develop the multipurpose use of nuclear energy

Currently, nuclear energy is mainly used for power generation. In the future, nuclear energy will play a bigger role, not only in power generation but also in serving other purposes. There are broad prospects for the application of nuclear energy in various fields, such as heating and cooling, industrial steam, seawater desalination and hydrogen production. The potential of nuclear energy will be further explored, especially for the decarbonisation of industrial sectors such as steel, petrochemicals, and other carbon-intensive sectors.

Directions for scientific and technological innovation

The sustainable development of nuclear energy and related innovation can be achieved by transitioning from thermal reactors to fast reactors and then to fusion.

China and France have made significant strides in scaling up the development of thermal nuclear reactors, paving the way for large-scale construction. The two countries have also promoted the R&D and deployment of SMRs and fourth-generation reactor technologies to enhance safety, cost-effectiveness, and proliferation resistance. Furthermore, both China and France are engaged in the research and development of controlled fusion technology and are active participants in the International Thermonuclear Experimental Reactor (ITER) project of the International Big Science Program.

Optimise the R&D, design and engineering construction management of PWRs, and enhance the R&D of advanced fuels

France has fully incorporated the experience gained from the construction and operation of the first batch of EPR units into the newly improved nuclear power models, EPR2 and EPR1200. Similarly, China stays committed to developing safer, more economical and advanced follow-up HPR1000 series, and is continuously optimising this model.

Both China and France prioritise learning from existing mature nuclear power technologies and construction practices to minimise the time of construction, enhance safety and improve cost-effectiveness of nuclear power units. This is achieved through optimising reactor design, adopting modern information technology, digitisation, additive manufacturing, modularising and standardising construction, applying advanced nuclear fuels, and seeking innovative financing solutions.

In terms of advanced fuels, China has been a firm supporter of accident-tolerant fuel (ATF) research and pilot assembly testing since the Fukushima nuclear accident in Japan. China and France are also promoting the R&D of MOX fuel and fast reactor fuel. The MOX fuel used in the French PWRs has been successfully applied, fully validating its safety and reducing the consumption of natural uranium. China has acquired the key technologies of MOX fuel assemblies for fast reactors and is preparing to test them in reactors, while actively conducting the R&D of metallic fuels.

Develop small reactors based on modular design and multipurpose use as an important direction for nuclear innovation

Advanced reactors, such as SMRs, are emerging as an alternative or a complement to large-scale reactors. They are expected to account for an increasing share of new nuclear capacity after 2030, provided that continued progress is made in technology, extensive application and cost-effectiveness. There are over 80 varieties of design under development worldwide, including water-cooled, gas-cooled, liquid metal-cooled and molten salt-cooled reactors, among other underlying technologies, as well as different fuel cycles.

China is carrying out a variety of SMR projects, including a multipurpose SMR technology demonstration project in Changjiang, Hainan Province. The ACP100 (Linglong One) technology, developed by CNNC is employed in the project. The 125 MWe project, scheduled for completion by 2026, is expected to be the first commercial SMR, and to demonstrate multipurpose applications such as combined power generation, refrigeration, and seawater desalination. Aside from ACP100, China is endeavouring to advance the R&D and deployment of other SMR models. Major progress has been made in the R&D of SMRs for offshore SMRs, nuclear heating reactors and low-temperature heating reactors.

Following its strategic choice early in 2023, EDF established a subsidiary dedicated to the development of its SMRs. Nuward has been developed through the contributions of strategic partners, namely CEA, TechnicAtome, Naval Group, Framatome, and Tractebel. It targets the 300-400 MWe segment of the SMR market and supports potential usages beyond electricity production, such as hydrogen production, district heating, desalination, heat & electricity cogeneration, and CO_2 capture and processing. Other SMR projects, including Generation IV reactors, are also under development in France.

Promote the utilisation and development of Generation IV reactors

To fully exploit uranium resources and ensure the sustainable development of nuclear energy, it is necessary to develop fast-neutron reactors and closed fuel cycles. Both China and France have stepped up the R&D of the Generation-IV nuclear energy systems, working towards the goals of sustainability, safety, cost-effectiveness and nuclear non-proliferation.

China has built the China Experimental Fast Reactor (CEFR), promoted the demonstration and commercialisation of the sodium-cooled fast reactor (SFR) project, and started the R&D of the Integral Closed Cycle Advanced Fast Reactor Nuclear Energy System to form an advanced closed fuel cycle system. China has also built the high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration project, which is the world's first commercial demonstration plant with Generation IV features, along with a supporting nuclear fuel supply system. The development of ultra-high temperature gas-cooled reactor power plants is actively conducted. France, with the involvement of the CEA, is continuing its R&D work on key SFR technologies to ensure it has the necessary technological capabilities.

Conduct fusion reactor engineering research based on the ITER project

Fusion reactor is an ultimate solution for the sustainable development of humanity. Currently, numerous fusion reactor technologies are under study, and related technologies are being developed at an accelerated pace.

As major participants in the ITER project, China and France have undertaken a large number of scientific research tasks. The two countries have gained rich experience in the R&D, design and construction of Tokamak devices, and carried out corresponding studies on their own to improve the cost-effectiveness and verify the feasibility of fusion reactor projects.

China has made significant breakthroughs in the R&D of fusion technology. In 2023, the HL-3 device at CNNC's Southwestern Institute of Physics achieved a plasma current exceeding 1 million Ampere. In addition, the Experimental Advanced Superconducting Tokamak (EAST), the world's first experimental non-circular cross-section full superconducting Tokamak nuclear fusion device, built by the Institute of Plasma Physics of Chinese Academy of Sciences, achieved 403 seconds of steady-state H-mode plasma in 2023.

Strengthen international cooperation

Promote multilateral cooperation under the framework of international organisations such as the IAEA

Multilateral cooperation is crucial for the development of nuclear energy. Intergovernmental international organisations such as the IAEA, the OECD/NEA, the ITER Organisation and the Generation IV International Forum (GIF), as well as non-governmental international organisations such as the WANO and the World Nuclear Association (WNA), play a vital role in promoting the safe, secure and peaceful development of nuclear power and nuclear applications worldwide.

Bilateral cooperation is also essential for the peaceful development of nuclear energy. Many countries have recognised the key role of bilateral cooperation in the peaceful development of nuclear energy. France's cooperation with the United States has facilitated the standardisation of the French nuclear power programme. In China, the Daya Bay Nuclear Power Station has opened a new chapter in China-France nuclear cooperation, while the Taishan NPP, built in collaboration with France, has become the world's first operational EPR project. In partnership with China General Nuclear Power Corporation (CGN), EDF is building two new nuclear units at Hinkley Point in the United Kingdom, based on the EPR technology.

All countries have equal opportunities to develop nuclear power. Nonetheless, countries starting to develop nuclear power from scratch need to build comprehensive infrastructures, including a system of laws and regulations, and a human resources system, so as to provide favourable conditions for the safe construction and operation of nuclear power. It is also difficult for any country to form a completely self-sufficient development model. This is why countries with advanced technology in nuclear power could offer comprehensive technical services to emerging countries adopting nuclear energy. It is also crucial to provide financial support for NPP projects launched in target countries, especially in developing countries.

Cooperation should be conducted through the platform of international organisations, such as IAEA's technical cooperation programme, coordinated research projects and collaborating centres. More efforts should be made to promote initiatives such as IAEA's Atoms4NetZero and the Nuclear Harmonization and Standardization Initiative (NHSI). CNNC and EDF have taken an active part in the NHSI to set international standards for SMRs, coordinate regulatory requirements, and promote the safe and reliable deployment of SMRs in the world.

Enhance international cooperation on major projects and support the development of new technologies

Promote the R&D of nuclear energy and renewables. Nuclear energy, combined with renewables, can play a bigger role in achieving decarbonisation and building a safe and reliable power system. Countries should formulate public policies focused on low-carbon growth, including accelerating the development of renewables like hydropower, wind, solar PV and geothermal power, extending the life of existing NPPs and launching new programmes. Such efforts help achieve climate goals while optimising the cost of energy transition.

China and France have engaged in extensive and efficient cooperation on nuclear energy. Both countries are beneficiaries and promoters of bilateral cooperation, and strongly support international cooperation and exchanges to advance the peaceful utilisation of nuclear energy.

Promote the R&D of advanced nuclear technologies such as

SMRs, Generation IV reactors and fusion. SMRs have a key role to play in adapting to and mitigating climate change and ensuring energy security, but their timely and widespread deployment remains a tough challenge. Nuclear energy can also be generated through fusion, which has become an emerging research field worldwide. Despite remarkable progress in recent years, it is necessary to further strengthen international cooperation in this area, given the need for large, complex, and expensive devices to address the problems related to reactor physics and technology.

1 Introduction

Climate change – recognised as a common challenge to humanity's survival – demands concerted efforts from all countries. This global issue is primarily propelled by the emission of GHGs, with the energy sector playing a substantial role, contributing to about 3/4 of the total. Therefore, the key to addressing the problems of climate change lies in adopting clean and low-carbon energy solutions.

1.1. Challenges of Climate Change

Primarily driven by a steep increase in atmospheric CO_2 concentration resulting from the burning of fossil fuels, extensive deforestation, agricultural expansion, and industrial development, there is no doubt that the Earth's surface temperature has risen over the past century. An IPCC Assessment Report (AR6) underscores that human activities, primarily through GHG emissions, have led to global warming, and the report warns that, without immediate action, the planet's surface temperature is projected to continue rising over the next 30 years.

According to the IPCC's assessment, highly adverse events such as hot extremes, cold extremes, agricultural and ecological drought, extreme precipitation, and volcanic eruptions, have become more frequent over the past 40 years. In 2019, some scientists warned that "more than half of the climate tipping points identified a decade ago are now 'active'". Setting off a chain reaction in the planetary system, weather extremes are now expected to occur more frequently. Through natural disasters, diseases, and other catastrophes, this – in turn – will both directly and indirectly affect human survival and sustainable development.

Addressing climate change has become one of the most pressing issues of our time. Many countries are intensifying their efforts. Adopted in December 2015, the *Paris Agreement* sets the goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".

1.2. Energy Transition

As the energy sector is responsible for approximately three-quarters of GHG emissions, solving its problems is a crucial way of influencing climate change. Reaching 41.3 Gt of CO_2-eq, global energy-related GHG emissions increased by 1.0% in 2022. Among them, global CO_2 emissions from energy combustion and industrial processes reached a new high of 36.8 Gt, accounting for 89% of total energy-related GHG emissions.[1] Projections from the IEA in the Stated Policies Scenario (STEPS) indicate that global energy demand is expected to increase by 0.8% per year by 2030.[2] Faced with this growing energy demand and the imperative for carbon peak and carbon neutrality, the transition to clean and low-carbon energy emerges as the optimal path forward.

1.3. Role of Nuclear Power

Nuclear power – as characterised by its technical maturity, safety, and security – has proven itself, when compared to others, to be a more effective energy source in reducing carbon emissions. For instance – in addition to outperforming same-capacity coal-fired power plants in curbing atmospheric pollutants like SO_2 and NOx – a 1,000 MWe NPP can avoid the emission of more than 6 million tonnes of CO_2 (equivalent to reforestation of 18,000 hectares). The advantages of nuclear power in emissions reduction are evident. Making it a viable option for large-scale replacement of fossil energy sources, nuclear's high stability and reliability makes it well-suited for serving as a grid's baseload and balancing the grid. Moreover, nuclear power can be integrated with other renewable energy sources to enhance grid absorption, contributing significantly to grid balancing and scheduling. This integration ensures the security, stability, and reliability of the energy system. The versatility of nuclear energy also extends to providing cleaner alternatives for heating and steam supplies in other energy-intensive sectors. Over the past 70 years, nuclear energy has made substantial contributions to

[1] IEA, CO_2 emissions in 2022.

[2] IEA, *World Energy Outlook*, 2022.

global energy supply security and carbon emissions reduction and – in addressing climate change and advancing the UN's SDGs – its role is poised to expand even further in the future.

1.4. Contributions from China and France

As of the end of December 2023, France's installed nuclear capacity was 61.37 GWe, ranking second worldwide, with a further 1.63 GWe under construction. In parallel, China's installed nuclear capacity was 53.15 GWe, ranking third worldwide, with a further 23.72 GWe under construction[3]. Both countries play pivotal roles in the global development of nuclear energy. In their respective processes of developing nuclear energy for their countries, CNNC and EDF, as significant contributors to this development, exhibit numerous strengths in nuclear power construction, operation, maintenance, and fuel supply, and have accumulated ample experience. Looking to the future, both companies acknowledge nuclear energy as a realistic and feasible option for transitioning to a modern energy system characterised by cleanliness, low-carbon emissions, safety, and efficiency. Especially with the expansion from single use (power generation only) to multipurpose applications (such as heating, steam supply, and hydrogen production), they also anticipate an accelerated decarbonisation of high-emission industries.

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[3] Data source: IAEA PRIS database, 31 December 2023.

2 Global Nuclear Energy Development

Over nearly 70 years of development, nuclear has demonstrated its safety, reliability, and efficiency as an energy source. Coupled with the increasing global emphasis on carbon reduction, the continuous advancement of nuclear power technology has led to a growing number of countries planning, deploying, and developing nuclear energy. To promote their collaborative support for a clean and low-carbon energy transition, these countries are integrating nuclear energy as a significant source of electricity working in synergy with other new energy sources such as wind power and solar power.

2.1. Brief History, Current Situation and Trends

A brief history of nuclear development

Nuclear energy emerged from scientific work in the first half of the 20th century. The 1950s saw intensive research, development and demonstration of reactor design and operation. Small experimental reactors were first developed in France, Russia, the United Kingdom and the United States. In the 1960s, ten other countries (Belgium, Canada, Germany, India, Italy, Japan, the Netherlands, Spain, Sweden, and Switzerland) commissioned nuclear reactors. By the end of the decade, nuclear power accounted for just 1% of global electricity generation.

These early prototypes and the subsequent reactors that were commissioned during the 1960s are often referred to as "Generation I". By today's standards, their generating capacity was relatively small, usually between 10 and 500 MWe. More than 90% of these first-generation reactors were deployed in advanced economies and have all since then been decommissioned.

During the 1960s, a strong effervescence in reactor types, skills, and research, led to an acceleration of the development of nuclear power, particularly with the first oil shock in 1974

Nuclear plant construction started to accelerate during the 1960s and peaked after the oil price shock of 1973-1974. During that time, Europe and the United States accounted for most of new nuclear builds.

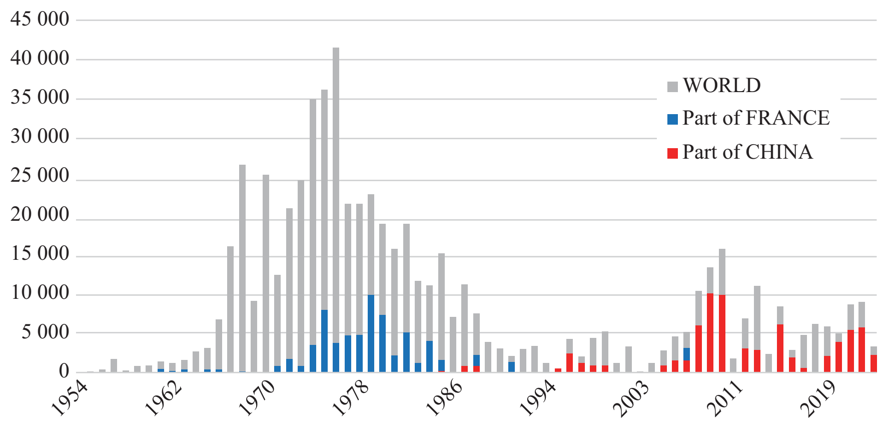
The 1970s and 1980s saw the strongest growth of nuclear reactors worldwide, with almost 400 reactors commissioned during these two decades, and almost all of them belonging to "Generation II". The average size of these reactors increased by a factor of around 7 compared with the previous generation, with total installed capacity worldwide increasing more than 20-fold in twenty years. As with the previous generation, the vast majority of additions took place in advanced economies. France's nuclear fleet was built during this period, with most reactors commissioned in the 1980s.

Following the accident at the Three Mile Island in 1979 and at Chernobyl in 1986, the nuclear industry entered a downturn and construction starts fell sharply, particularly in the United States and in Europe. The slowdown had already begun in previous years due to multiple factors, including slower electricity demand growth in advanced economies, and financing issues.

The 1990s and early 2000s saw little new nuclear reactor construction outside of China, Japan, and the Republic of Korea. In many OECD countries, gas prices were low and were expected to remain so, and investment in new nuclear plants became less attractive than investment in alternatives, particularly combined-cycle gas turbines (CCGTs). Moreover, slow electricity demand growth and over-build in the previous decade meant that many OECD countries had excess capacity. A large number of projects were suspended or cancelled. On the other side, China started to develop its fleet with great success in the 1990s and 2000s, with independent innovation and the support of Canadian, French and Russian technologies.

There was a resurgence in new nuclear builds in the late 2000s, mainly driven by China – seeking to meet fast-growing electricity demand and to reduce air pollution. Construction starts of new reactors in most OECD countries remained very limited. Activity focused there on existing plants: raising capacity factors, increasing capacity through power uprates and extending lifetimes. The accident in Fukushima in March 2011 impacted the nuclear policy and new nuclear programmes in several countries, including China, where a clear shift from Generation II to Generation III was put in place.

Some countries accelerated or adopted plans to phase out nuclear power, though most did not change their views on its long-term role in their energy systems. Overall, almost two-thirds of the capacity that came online over the period 2000-2019 was added between China and Russia, and only 5% in North America and Europe, in stark contrast to the previous thirty years (1970-1999).



（Source: IAEA PRIS database, 2023）

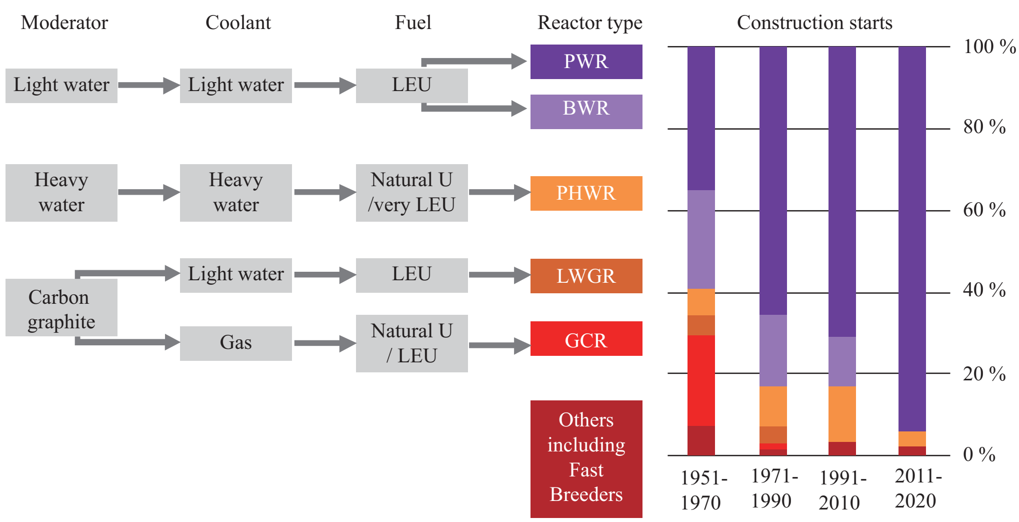
Figure 2-1 Part of China and France in Reactor Construction Starts (MWe per year)

Technologies have experienced a sustained evolution to increase safety and economics, with PWRs being now the dominant technology

Reactor technologies have continued to evolve based on operational experience. There is no universally shared definition of reactor generations, but, in broad terms, so-called Generation I reactors were built in the 1950s and 1960s. Generation II reactors, which comprise the majority of the reactors in operation today, were mostly built after 1970.

Early models of Generation III reactors first became commercially available in the 1990s. Compared to the preceding generation, this generation of reactors aims to enhance safety, by incorporating design changes that lower the risk of a severe accident and, should a severe accident occur, by using appropriate mitigation systems to limit its impact on the population and the environment. Improvements may include more redundancy (back-up systems), greater use of passive systems (which rely on natural forces such as gravity) or fewer components.

Three major reactor types exist: pressurised water reactors (PWRs), which account for 68% of installed nuclear power capacity, boiling water reactors (BWRs) for 14%, and pressurised heavy water reactors (PHWRs) for 11%. Graphite-moderated reactors account now for less than 6%. Each basic type may include several unique designs built by different entities at separate times, in accordance with customer needs and the prevailing state of technological development.



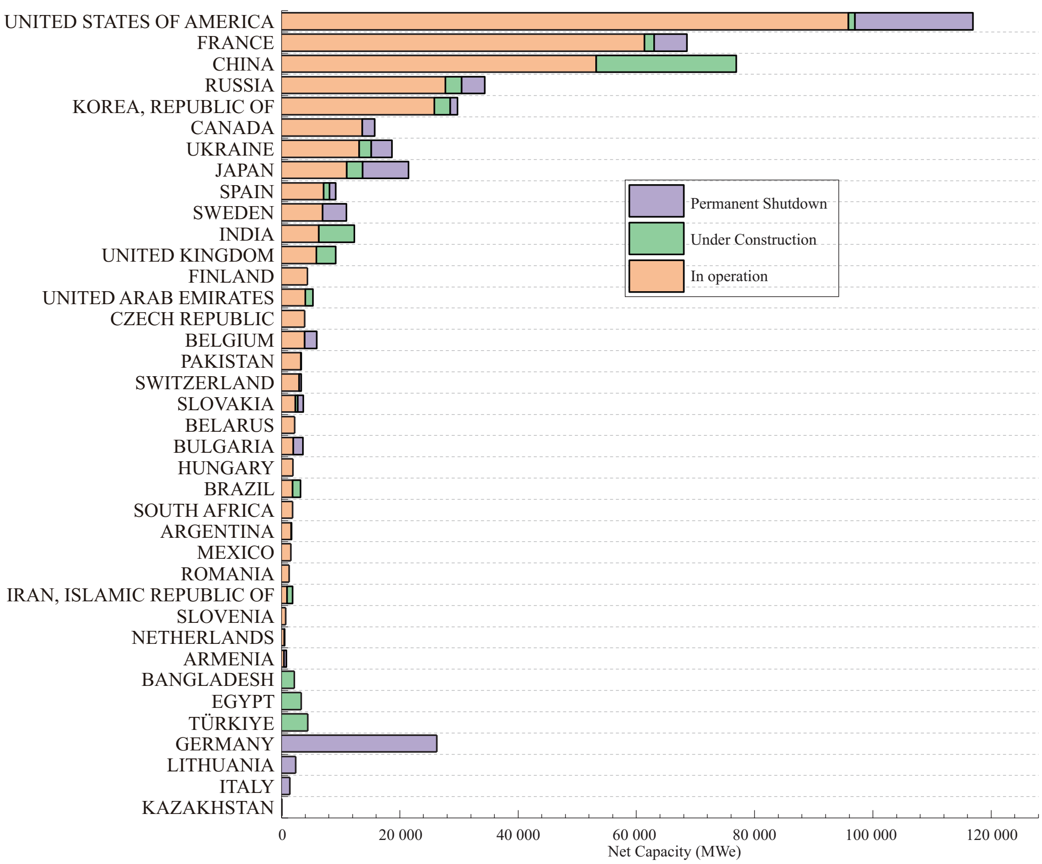
(Source: IAEA PRIS database, 2023)

Notes: LEU = low enriched uranium; Natural U = natural uranium; PWR = pressurised water reactor; BWR = boiling water reactor; PHWR = pressurised heavy water reactor; LWGR = light water graphite-moderated reactor; GCR = gas-cooled reactor.

Figure 2-2 Nuclear Reactor Technologies and Their Share in Construction Starts

PWRs are now the dominant technology. They account for 94% of the new construction launched in the last ten years. The remaining 6% consists of two PHWRs in India, and China's Generation IV pebble-bed module high-temperature reactor and two fast neutron reactors.

As of 31 December 2023, world nuclear net capacity accounted for 371 GWe, provided by 413 operational reactors in 31 countries.

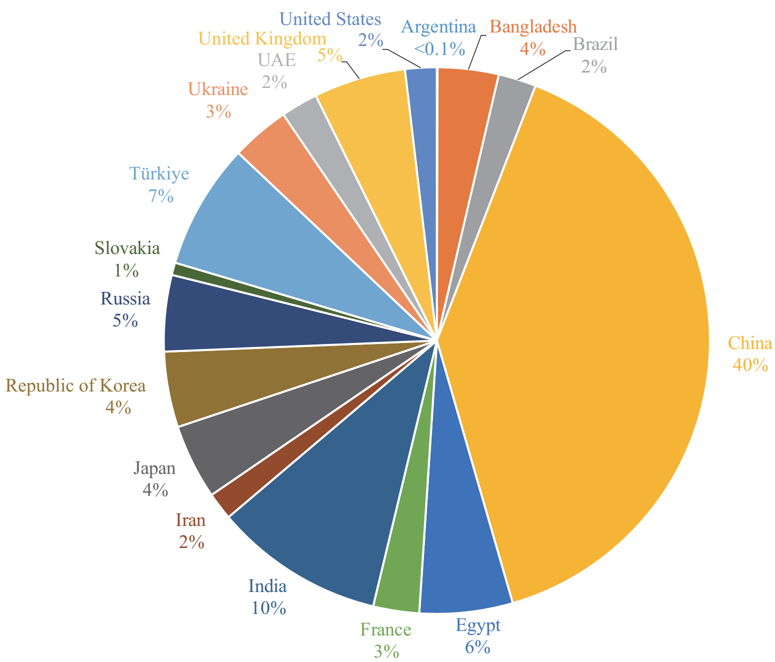


(Source: IAEA PRIS database, December 2023)

Figure 2-3 Net Capacity in Operation, Under Construction, and Permanently Shutdown as of December 2023

57 reactors are under construction in 17 countries, and many other countries express a strong interest

As of 31 December 2023, a total net capacity of 59 GWe (57 reactors) was under construction in 17 countries. Installed nuclear capacity under construction has remained broadly stable in recent years, except for continued growth in Asia.



(Source: IAEA PRIS database, 2023)

Figure 2-4 Nuclear Capacity Under Construction per Country as of 31 December 2023

In almost every country with nuclear plants, nuclear is confirmed, revived, or amplified, and a growing number of non-nuclear countries plan or consider new nuclear programmes

Energy is critical for the achievement of the *2030 Agenda for Sustainable Development* (2030 Agenda). It is the "golden thread" that runs through all the 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 UN 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. All available low-carbon technologies shall be deployed to close the gap between what has been promised and what is needed. The world cannot afford to "leave out" any low-carbon technology.

The IPCC 1.5°C report published late in 2018 brings forward 89 mitigation scenarios in which nuclear generation grows on average 2.5 times from today's level by 2050.[1] In addition, the "middle-of-the-road" illustrative scenario, in which social, economic, and technological trends follow current patterns and in which there are no major changes in diet and travel habits, sees demand for nuclear generation increase fivefold by 2050 with nuclear providing 25% of global electricity.

A growing number of countries recognise that nuclear power, a proven source of low-carbon electricity, is now a vital tool for helping to successfully mitigate the impacts of climate change and providing the dispatchable electricity needed, alongside rapidly developing power generation from non-dispatchable renewable energy sources such as wind and solar PV.

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1 IPCC, *Global Warming of 1.5℃*, 2018.

There is a general acknowledgement, among countries with nuclear, that lifetime extensions are a very cost-effective source of low-emission electricity

Lifetime extensions are estimated at less than 50 USD/MWh for a 10- to 20-year extension, the cheapest way to provide dispatchable zero carbon electricity in major markets.[2] With long lead time for nuclear construction, lifetime extensions also provide time to build new nuclear plants and other low-emission sources fast enough to meet new electricity demand and displace fossil fuels.

A new momentum is building in many countries, with series of new reactors relaunched or accelerated

With the need to meet growing zero carbon electricity demand, many countries with nuclear plants have taken measures to implement new nuclear programmes. Main examples include Canada, China, most European countries, India, Japan, the Republic of Korea, Russia and the United States. In addition, many countries are considering, planning or launching nuclear power programmes (see Sub-chapter 2.4).

By 2040, almost all the increase in global nuclear capacity is expected to come from large reactors. In addition to the optimisation of these reactors for greater economic efficiency, safety and sustainability, other longer-term factors support the global drive for nuclear power, such as the emergence of SMRs and the promise of nuclear fusion.

The emerging trend of SMRs

The urgent need to reach net zero emissions and growing concerns

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[2] IEA, *Nuclear Power in a Clean Energy System*, 2019.

about the security of the electricity supply are prompting governments to consider and support new technological solutions. Advanced reactors, which are small and easy to build, are an alternative or a complement to large-scale reactors. One category of reactors, known as SMRs, is particularly promising. SMRs could account for a growing share of new nuclear capacity after 2030, provided that continued progress is made in developing and proving the technology, and that costs are reduced.

SMRs are generally defined as nuclear reactors with an electrical capacity of less than 300 MWe per module, although some models under development may be larger. The various designs currently under development worldwide, of which there are around 80, include different underlying technologies, such as water-cooled, gas-cooled, liquid metal-cooled and molten salt-cooled reactors, as well as different fuel cycles.

Political and institutional support is very strong, with government subsidies for R&D and demonstration projects having increased by an order of magnitude in recent years in some countries. This is attracting significant private investment and introducing new players and new approaches to project development into the nuclear industry. Some countries also see this as an opportunity to assert their technological leadership.

If investment decisions are taken this decade, the period beyond 2030 will open up opportunities for large-scale deployment of SMRs, including reactors of currently less mature design and reactors associated with spent nuclear fuel recycling strategies. These reactors could be deployed more widely in the 2040s to supply low-emission electricity, heat and hydrogen.

The potential of fusion reactors

Nuclear energy can also be produced by fusion reactions of light nuclei. Worldwide research has made impressive progress in the field of fusion and plasma physics. Many scientific questions have been resolved in recent years. Research into controlled nuclear fusion and plasma physics is currently being carried out in more than 50 IAEA member states.

The challenge is to prove that fusion as an energy source is scientifically feasible. Since this will require large, complex and expensive devices to meet the physical and technological challenges of reactors, international collaboration on fusion research and development is needed.

The world's largest and most advanced fusion experiment is the ITER project, which brings together seven members (China, the European Union (EU), India, Japan, the Republic of Korea, Russia, and the United States). Based on the tokamak concept (which uses a device that confines plasma through a magnetic field), ITER is currently being built in Cadarache, France. The reactor is designed to produce 500 MWe of fusion energy. It will also be used to test the key technologies required for a fusion reactor.

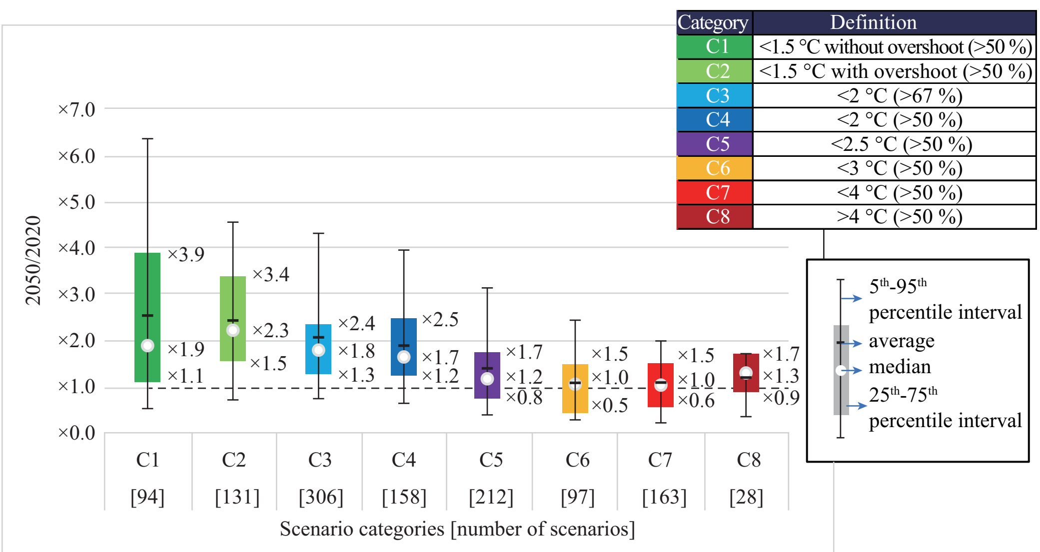
This trend is supported by the role of nuclear power in the fight against climate change, as highlighted by the main reference studies

Nuclear is a significant part of future energy mixes in most prominent global energy studies from the IPCC, the IEA, the International Renewable Energy Agency (IRENA), the World Energy Council (WEC), the Institute of Energy Economics (Japan), Enerdata (France), Statoil

(Norway), Shell (Netherlands), and Det Norske Veritas Group (Norway).

We examine the IPCC Sixth Assessment Report (AR6), and more specifically the report of Work Group III published in April 2022. Four key messages can be drawn from the analysis of this data:

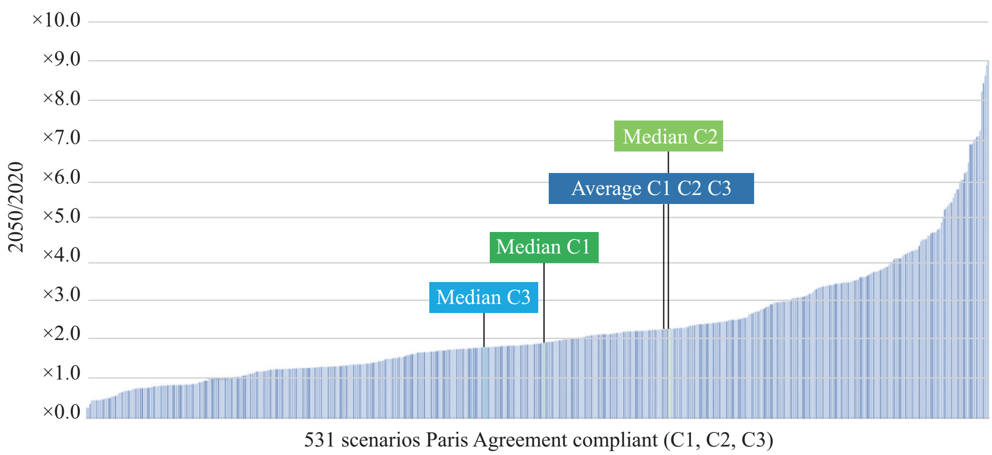
- On average, the more ambitious the goal for limiting warming, the greater the increase in nuclear generation. Between 2020 and 2050, generation is roughly constant on average for the scenarios limiting warming to 3°-4°C (scenario families C6 and C7). Generation is multiplied by 2 to 2.5 for scenarios limiting warming to 1.5°-2°C (scenario families C1, C2, C3 and C4).
- In detail, the scenarios showing the largest increases in nuclear generation have the most ambitious reduction goals. Between 2020 and 2050, the generation growth factor is of the order of 2 (doubling) at 4°C, 2.5 at 3°C, 3 at 2.5°C, 4 at 2°C and 6.5 at 1.5°C.



(Source: IPCC)

Figure 2-5 Nuclear Electricity Generation in Different Scenarios

• Scenarios compatible with the *Paris Agreement*, which aims to limit global warming to a level well below 2°C, preferably to 1.5°C, compared to the pre-industrial level (families C1, C2 and C3), increase nuclear power generation on average by a factor of 2 to 2.5 in 2050 compared to 2020, going up to 9 in some scenarios.

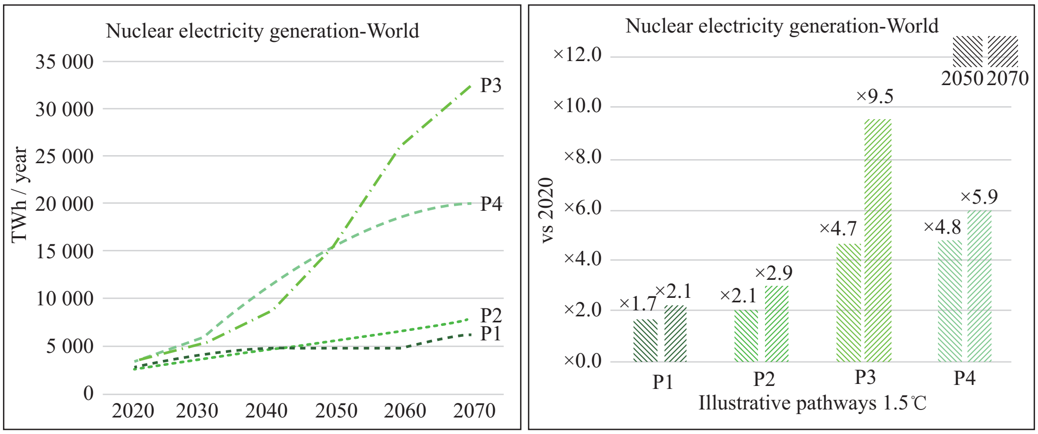


(Source: IPCC)

Figure 2-6 World Nuclear Electricity Generation from 2020 to 2050

• Regarding the scenarios limiting warming to 1.5°C, the four illustrative scenarios P1, P2, P3 and P4 presented by the IPCC in its 2018 "1.5°C" special report, and whose data is included in the AR6 databases, project a multiplication of nuclear generation by 1.7 to 4.8 in 2050 and by 2.1 to 9.5 in 2070 compared to 2020 (see Figure 2-7).

According to the scenario of the IEA, in quantitative terms, under the NZE scenario (Global Net Zero Emissions in 2050) which allows for a median global temperature rise in 2100 of 1.5°C, nuclear increases by a factor of 2.1 from 2021 to 2050. In the announced Pledges Scenario, which allows for a median global temperature rise in 2100 of 1.8°C, nuclear increases by a factor of 1.8 from 2021 to 2050.



(Source: IPCC)

Figure 2-7 World Nuclear Electricity Generation Under 4 Scenarios at 1.5°C

2.2. China: History, Current Situation and New Policies

In 2016, China signed the *Paris Agreement*. On 22 September 2020, President Xi Jinping – in his speech at the general debate of the 75th session of the UN General Assembly – emphasised China’s dedication to enhancing its Nationally Determined Contributions. This commitment involves implementing stronger climate-friendly policies and measures with the aims of having CO_2 emissions peak before 2030 and achieving carbon neutrality before 2060. In alignment with these objectives, China has expedited its planning for the construction of a new energy system and outlined its policy of developing nuclear power in an active, safe and orderly manner. In the future, nuclear power is poised to play a more significant role in contributing to China’s goals of achieving carbon peak and carbon neutrality.

2.2.1. Brief history

China initiated its nuclear energy research in the 1950s and began to substantially develop its nuclear energy programmes in the 1970s. The development process may be described as follows:

(1) Startup (1970s-1994)

In the early 1970s, China began considering the construction of NPPs to address energy shortages experienced by cities in the eastern region. In 1983, the Chinese government set up the State Council Leading Group on Nuclear Power and agreed on *Key Policy Points for Developing Nuclear Energy Technology*. These policy points outlined the technical route emphasising PWRs for nuclear power development, and set forth a combined approach of imported technology and indigenous development. In 1984, China became a member state of the IAEA. Marking the beginning of nuclear power generation on China's mainland, the Qinshan-1 project – which would be successfully connected to the grid on 15 December 1991 – saw its first tank of concrete poured on 20 March 1985. In 1987, construction at the Daya Bay NPP began on two 1,000 MWe-class three-loop PWR units, known as M310 reactors. They were imported from France and respectively achieved commercial operation in February and May 1994.

(2) Moderate development (1994-2003)

During this period, the policy of "moderately developing nuclear power" was implemented, leading to the construction of eight units under four projects. These projects included Qinshan NPP Phase II Units 1&2, Ling'ao NPP (Guangdong Province) Units 1&2, Qinshan NPP Phase III Units 1&2, and Tianwan NPP (Jiangsu Province) Units 1&2. The cumulative installed capacity of these projects reached 6.6 GWe and great improvements were made in the design, construction, and O&M of Chinese NPPs.

(3) Large-scale development (2003-2011)

Prompting the large-scale and batch construction of NPPs, nuclear power was incorporated into the national plan for power development. In 2003, the State Leading Group for Self-reliant Development of Nuclear Power Technology was established to promote the accelerated development of nuclear power, as well as to start the bidding process for the introduction of Generation III technology from abroad. In 2006, the Chinese government released the *Medium- and Long-Term Development Plan for Nuclear Power (2005-2020)*, which outlined the policy of "proactively developing nuclear power" and set the goals of 40 GWe of installed nuclear power capacity in operation and 18 GWe under construction on China's mainland by 2020. From 2005 to 2011, 13 nuclear power projects were approved at various sites in Fujian, Guangdong, Guangxi, Hainan, Liaoning, Shandong, and Zhejiang provinces.

(4) Safe and efficient development (2011-2020)

After the Fukushima-Daiichi nuclear accident in Japan, China temporarily suspended the approval of new nuclear power projects, including those in the preliminary stages. China also conducted comprehensive safety inspections of existing domestic nuclear installations. In October 2012, issued the *Nuclear Power Safety Plan (2011-2020)* and *Medium- and Long-Term Development Plan for Nuclear Power (2011-2020)*. As per these plans, new nuclear power projects were mandated to adhere to the highest international safety standards, and newly approved nuclear power units had to comply with nuclear safety standards for Generation III technology. Facilitating steady progress in nuclear power development, a number of projects including Tianwan NPP Phases II & III, Shidaowan

HTR-PM Demonstration Project, Yangjiang NPP Phase III, Hongyanhe NPP Phase II, Fuqing NPP Phase III, Fangchenggang NPP Phase II, Zhangzhou NPP Phase I, Huizhou NPP Phase I, San'ao NPP Phase I, and the demonstation NPP of National Science and Technology Major Project for Advanced Large PWRs have received approval since 2012.

(5) Active, safe and orderly development under dual carbon goals (2020 until now)

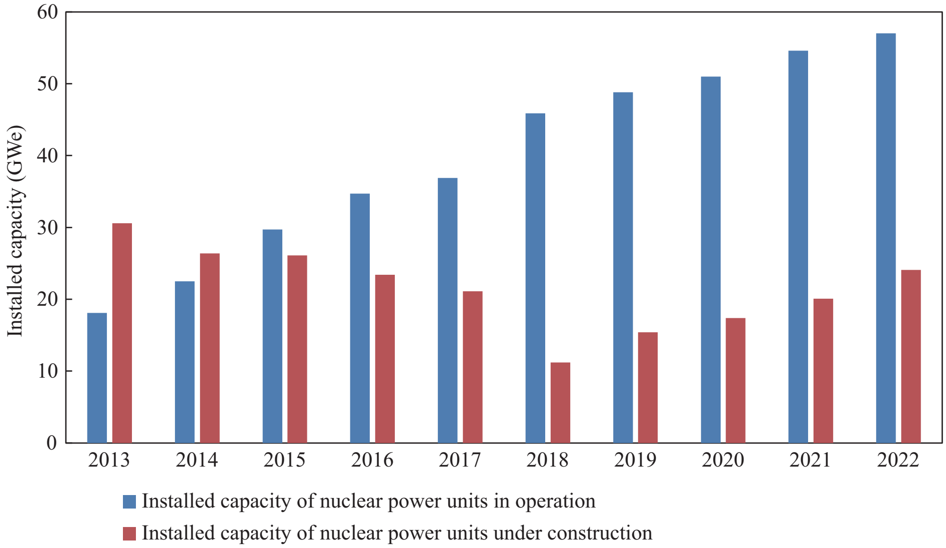
The carbon peak and carbon neutrality goals set by China in 2020 have ushered in new opportunities for the development of nuclear power. China's National Energy Administration issued several policy documents emphasising the importance of "developing nuclear power in an active, safe and orderly manner".

Since 2020, a total of 25 units (including Changjiang NPP Phase II units, Changjiang SMR Demonstration Project, Tianwan NPP Units 7&8, and Xudabu NPP Units 3&4) have received approval. In 2022 – comprising 10 units in total – an additional 5 projects (including Sanmen NPP Units 3&4, Haiyang NPP Units 3&4, Lufeng NPP Units 5&6, Zhangzhou NPP Phase II Units 3&4, and Lianjiang NPP Phase I Units 1&2) received approval. Compared to the 14 units approved in 2008, this notably marks a significant increase in the number of approved units. China has maintained the pace of nuclear power development and approved the construction of another 10 nuclear power units in 2023.

2.2.2. Current status

As of the end of 2023 – securing its global position as the third-largest nuclear power producer – China's mainland has 55 units (with a total installed capacity of 53.15 GWe) in operation. These units are distributed across 18 nuclear sites. With a commitment to minimising operational safety risks, stringent measures have been implemented to ensure the safe operation of NPPs in China. No operational events at INES Level 2 or above have occurred. Over the past decade, China has continuously improved safety standards for NPPs, designing new facilities which meet Generation III safety standards and incorporate comprehensive measures for the prevention and mitigation of severe accidents. Simultaneously – and marking a leap from Generation II to Generation III – significant efforts have been invested in advancing nuclear power technologies. Intensive R&D has led to the successful development of advanced Generation III large PWR technologies (such as HPR1000 and CAP1400) along with HTGR technology featuring Generation IV characteristics. Laying a solid foundation for the development of advanced Generation IV nuclear technology in China, the 200 MWe HTGR demonstration plant has been successfully connected to the grid. Figure 2-8 and Table 2-1 illustrate the installed capacity and geographical distribution of units in operation and under construction on China's mainland between 2013 and 2022.

Equipping itself to offer a range of services (including NPP design, construction, equipment manufacturing, nuclear fuel supply, and O&M) across the entire NPP lifecycle, as well as technologies and equipment for nuclear fuel cycle, waste treatment and disposal, and nuclear facility decommissioning, China has established a comprehensive nuclear energy industry system with solutions for all aspects of nuclear energy development and depoloyment.



(Source: website of China Nuclear Energy Association)

Figure 2-8 Installed Capacity of Units in Operation and Under Construction on China's Mainland, 2013-2022

Table 2-1 Operational Nuclear Reactors on China's Mainland

Name	Reference Unit Power (MWe)	Name	Reference Unit Power (MWe)
CHANGJIANG-1	601	NINGDE-2	1,018
CHANGJIANG-2	601	NINGDE-3	1,018
DAYA BAY-1	944	NINGDE-4	1,018
DAYA BAY-2	944	QINSHAN-1	326
FANGCHENGGANG-1	1,000	QINSHAN 2-1	623
FANGCHENGGANG-2	1,000	QINSHAN 2-2	623
FANGCHENGGANG-3	1,000	QINSHAN 2-3	623
FANGJIASHAN-1	1,012	QINSHAN 2-4	623
FANGJIASHAN-2	1,012	QINSHAN 3-1	677
FUQING-1	1,000	QINSHAN 3-2	677
FUQING-2	1,000	SANMEN-1	1,157
FUQING-3	1,000	SANMEN-2	1,157
FUQING-4	1,000	SHIDAO BAY-1	200

Name	Reference Unit Power (MWe)
FUQING-5	1,075
FUQING-6	1,075
HAIYANG-1	1,170
HAIYANG-2	1,170
HONGYANHE-1	1,061
HONGYANHE-2	1,061
HONGYANHE-3	1,061
HONGYANHE-4	1,061
HONGYANHE-5	1,061
HONGYANHE-6	1,061
LING AO-1	950
LING AO-2	950
LING AO-3	1,007
LING AO-4	1,007
NINGDE-1	1,018
TAISHAN-1	1,660
TAISHAN-2	1,660
TIANWAN-1	1,000
TIANWAN-2	1,000
TIANWAN-3	1,060
TIANWAN-4	1,060
TIANWAN-5	1,060
TIANWAN-6	1,060
YANGJIANG-1	1,000
YANGJIANG-2	1,000
YANGJIANG-3	1,000
YANGJIANG-4	1,000
YANGJIANG-5	1,000
YANGJIANG-6	1,000

(Source: IAEA PRIS database, February 2024)

(1) NPP production and operation

In 2023, nuclear electricity production in China reached 433.37 TWh[3], of which 406.71 TWh of accumulated power had been supplied to the grid. Nuclear power generation accounted for 4.86% of the country's total power generation, both lower than the global average and that of countries such as France and the United States. The potential and scope for China's nuclear power development are vast. The average utilisation of NPPs stood at 7,661.08 hours, with an average capacity factor of 91.25% for units. Annual utilisation hours are shown in Figure 2-9, and

3 Data source: China Nuclear Energy Association: www.china-nea.cn. Accessed 10 March 2024.

annual electricity generated and electricity supplied to the grid are shown in Figure 2-10.

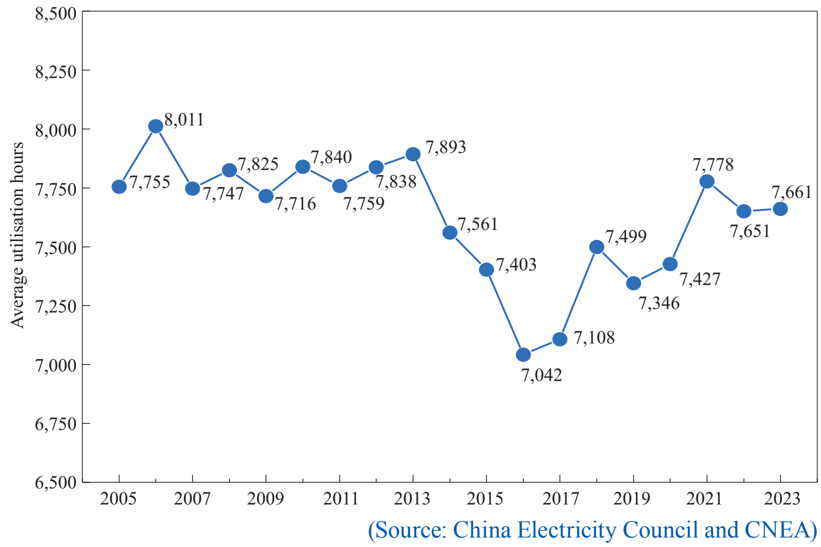


Figure 2-9 Utilisation Hours of NPPs in China, 2005-2023

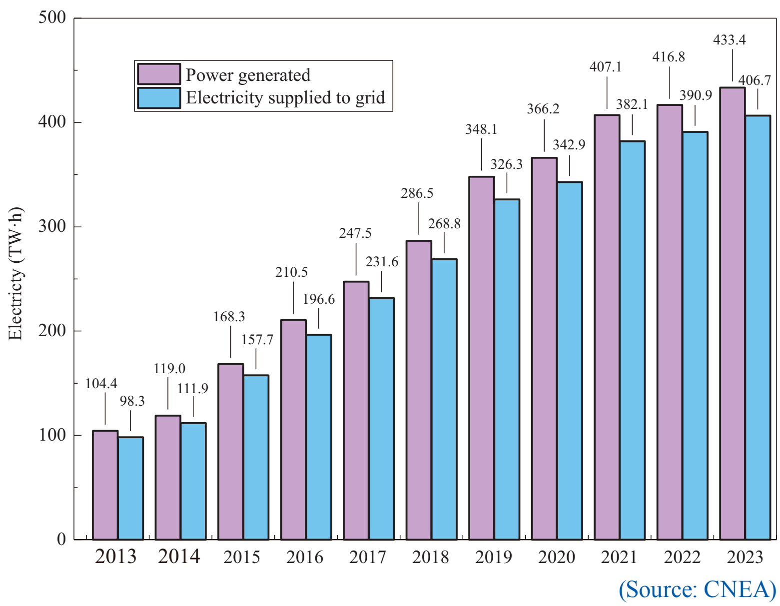


Figure 2-10 Electricity Generated and Electricity Supplied to the Grid in China, 2013-2023

According to WANO’s 2022 performance indicators statistics – when the WANO composite index was calculated for a total of 51 nuclear power units on China’s mainland – 37 units achieved the maximum score of 100 points. As shown in Table 2-2, the percentage of Chinese nuclear units with 100 index points surpasses the global average.

Table 2-2 WANO Composite Index Points for Units in Operation Worldwide, 2022

Points (Range)	Number of Units Worldwide	Number of Units on China’s Mainland
100	74	37
90-100	121	10
80-90	93	4
70-80	48	0
0-70	51	0
Percentage of 100-point units	19%	75%

In addition to the increased utilisation of nuclear energy for electricity generation, initiatives for nuclear-based district heating and industrial heating have been successfully implemented at NPPs in Shandong, Zhejiang, Jiangsu, and Liaoning provinces to promote the multipurpose utilisation of nuclear energy.

(2) NPP construction

As of the end of 2023, China leads globally with 23 nuclear power units under construction, with its total installed capacity reaching 23.72 GWe. Continuous efforts at building new NPPs have been underway since the initiation of the Qinshan NPP in 1985. China’s current nuclear equipment manufacturing capacity annually allows for the supply of main equipment for 10-12 GW-class units and can facilitate the simultaneous construction of up to 40 units. Through self-reliant innovation, introduction and absorption of technology, and continuous innovation over the past four decades, China has successfully designed and constructed various NPPs, including 100 MWe, 300 MWe, 600 MWe, 1,000 MWe and larger PWR NPPs. Professionally structured – with a balanced mix of knowledge and age – the workforce in China has formed a strong team for nuclear power project research, design, and construction, and has put in place well-established procedures for design and interface control, and quality management systems. The world's first demonstration project for HPR1000, Fuqing NPP Unit 5, is illustrated in Figure 2-11.

(Source: CNNC)

Figure 2-11 Global First HPR1000 Reactor Demonstration Project – Fuqing NPP Unit 5

2.2.3. Needs and strategy

In the context of carbon peak and carbon neutrality, nuclear energy is poised to assume an increasingly pivotal role in China's new energy system. According to predictions from CINIS, the installed capacity of China's NPPs in operation is expected to surpass 150 GWe by 2035. Doubling its share from the figures recorded in 2022,[4] this would result in nuclear power accounting for 10% of the country's total electricity generation. Additionally, as part of its commitment to clean and low-carbon energy, China plans to undertake the construction of several nuclear-based heating demonstration projects. With nuclear power serving a crucial role in achieving China's dual carbon goals, these initiatives aim to bolster the integrated utilisation of nuclear energy, ensure energy security, maintain power system stability, and deliver clean and low-carbon electricity.

Since 2021, "developing nuclear power in an active, safe and orderly manner" has been a focal point of various policies introduced, and one of the key tasks in the *Action Plan for Peak Carbon by 2030* (which emphasises the importance of "the orderly development of nuclear power, ensuring safety and security, maintaining a steady construction pace, promoting advanced reactor demonstration projects, including HTGRs, Fast Reactors, SMRs, and offshore floating reactors, and carrying out the demonstration of integrated utilisation of nuclear energy"). Throughout the years 2021 to 2025 and in the medium and long term, the emphasis on "developing nuclear power in an active, safe and orderly manner" serves as a guiding principle for nuclear power development, and

4 CNEA, *Report on the Development of China's Nuclear Energy (2022).*

solidifies the status and role of nuclear power in China's commitment to constructing a clean, low-carbon, safe, and efficient energy system.

2.3. France: History, Current Situation and New Policies

2.3.1. History of the development of nuclear energy

The development of the French nuclear power programme began at the end of 1945 with the commitment of the French State to undertake research and industrialisation of nuclear energy in France (electricity production, medicine, radiation protection, safety, etc.).

This programme was based on the three objectives of the French government:

• Guaranteeing France's energy independence.
• Developing a French technological and industrial sector.
• Ensuring competitive and stable electricity cost over the long term, to support the economic growth of France and its industry.

(1) 1950-1970: Testing of different technologies

The organisation of the research and development of the first French reactors was initiated by the creation of the CEA, the Commissariat à l'Energie Atomique (Atomic Energy Commission), a public research institute.

Ten years later, in 1955, the CEA commissioned the first experimental nuclear reactor at Marcoule, with a very modest power output of 2 MWe. It was the first reactor using the French technology known as UNGG (Uranium Naturel Graphite Gaz) with natural uranium moderated by graphite and a gas heat transfer fluid. Two other experimental reactors (G2 and G3), each delivering a power output of 40 MWe, were commissioned in 1958 and 1960. A total of nine "first-generation UNGG" reactors were built in France; the last one, Bugey 1, with a capacity of 540 MWe, was connected to the grid in 1972. At the same time, EDF assessed the various existing technologies, in particular heavy water reactor (HWR), with natural uranium and gas-cooled, with the construction of the Brennilis plant (70 MWe, commissioned in 1967), and PWR, with the commissioning of the first 300 MWe PWR at Chooz A in 1967.

This first phase laid the foundations for the French nuclear system, with:

- EDF, a public company and project architect for the construction of NPPs.
- Private sector companies, stakeholders both as manufacturers and assemblers. Among them, the Franco-American atomic construction company, Framatome, established in 1958, which was involved in the construction of the French-Belgian power plants Chooz A and Tihange.
- An authority responsible for monitoring the safety of the design and construction of Basic Nuclear Installations (BNIs), established in 1960 as the Commission de Sûreté des Installations Atomiques (CSIA). In 1973 it became the Service Central de Sûreté des Installations Nucléaires (SCSIN), and in 2002 it evolved into the Direction Générale de la Sûreté Nucléaire et de la Radioprotection (DGSNR). It became an independent authority (ASN) under the Law of 13 June 2006 relating to transparency and safety in nuclear matters.

At the end of this phase of testing and development of expertise the government decided in 1969 to abandon graphite-gas technology, on the basis of a technical-economic and industrial inter-comparison between technologies. The graphite-gas reactors were all shut down after 20 years of operation (the last one in 1994). Similarly, the BWR at Brennilis was shut down in 1985.

(2) 1970 to mid-1990s: Industrialisation and construction of the French nuclear fleet

The first oil crisis led to a fourfold increase in the price of a barrel of oil. In order to ensure its energy security and guarantee a stable energy price over the long term, the French government decided, in 1974, to begin a large-scale nuclear construction programme: 58 PWRs with a cumulative power output of 63 GWe were built and commissioned between 1977 and 1999.

Three series of nuclear reactors were developed, moving progressively towards higher power reactors based on three key principles:

- Industrial standardisation, a lever of economic and industrial performance; with a head of series and a batch run for each series, based on the same design and on the reuse of the main equipment.
- Strengthening safety, by incorporating changes in requirements, codes and standards.
- Incorporating operating experience from the operation of reactors in service and events in the global nuclear fleet.

In parallel with the construction of the French nuclear fleet, the fuel cycle industry sector was developed:

- Mining exploration, extraction and enrichment of uranium with the Tricastin-Pierrelate and Georges Besse plants.

• The manufacture of fuel assemblies, with the FBFC plants (Franco-Belge de Fabrication du Combustible, French-Belgian Fabrication of Fuel) of the Framatome group in the Drôme and Melox in Marcoule.

• Spent fuel reprocessing at La Hague and recycling at Melox.

• Management of radioactive waste.

This led to the establishment, in 1976, of the COmpagnie GEnérale des MAtières nucléaires (COGEMA) to carry out all these activities, which are today performed by several private and public companies.

• Orano (previously Areva) for the extraction and enrichment of uranium.

• Framatome for the manufacture of fuel assemblies and Orano for the manufacture of MOX fuel, enriched with plutonium.

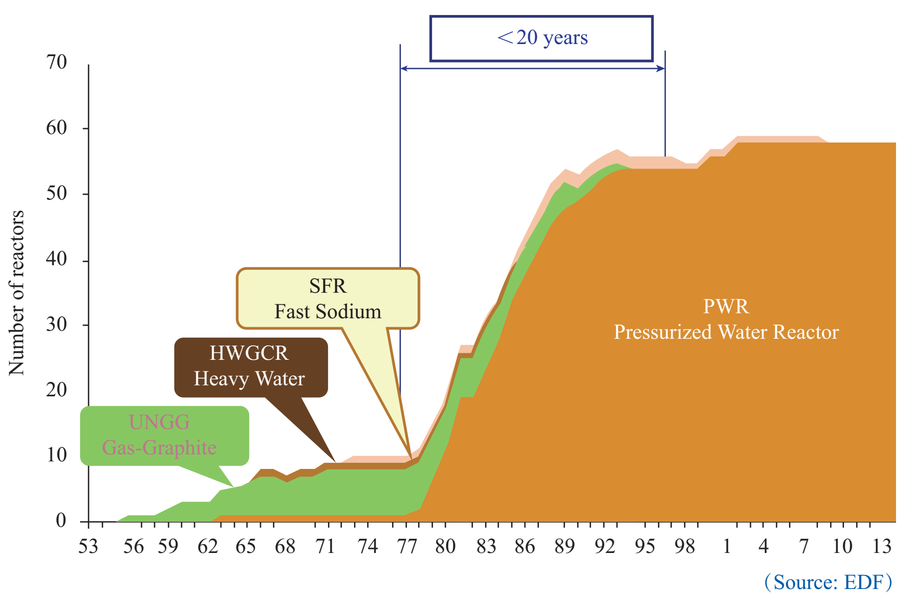


Figure 2-12 Construction of the French Fleet

- Andra (Agence Nationale pour la gestion des Déchets RAdioactifs – the national agency for radioactive waste management, established in 1979).

Alongside the development of the French programme, interest remained in more advanced models, and particularly in fast-breeder reactors.

At the same time, the CEA continued the work undertaken historically on fast-breeder reactors, which could close the nuclear cycle by exploiting the full energy potential of uranium and offering a possible use for some isotopes from PWR plants.

In 1968, the decision was made to build a fast neutron reactor at Marcoule, Phénix, using liquid sodium as a coolant. Phénix was connected to the electricity grid in 1973 and operated until 2010. With a 250 MWe capacity, this prototype was connected to the grid in order to demonstrate the viability of an industrial series of fast neutron reactors and the ability of EDF and CEA to operate them. Above all, Phénix became a research and development centre which provided France with a technological lead for thirty-five years. A larger 1,200 MWe sodium-cooled fast neutron reactor, Superphénix, in Creys-Malville, built and operated by NERSA (a company bringing together several European partners and of which EDF was the main shareholder), was commissioned in 1984 and shut down in 1999 for political reasons.

In its Generation IV development programmes, France has already conducted a study for a new fast neutron reactor model, the ASTRID programme conducted by the CEA which ended in 2019 on political grounds. Research on this technology continues with research and development activities on the reactor itself, as well as on the fuel cycle processes.

The French industry has also been active internationally. In 1976, the Société française d’ingénierie électronucléaire et d’assistance à l’exportation (SOFINEL), a subsidiary of EDF and Framatome, was set up to develop NPPs for export. Framatome took part in the construction of the Koeberg reactor in South Africa and the Ulchin reactor (now called Hanul) in the Republic of Korea, with EDF providing staff training and technical assistance. The 1980s saw the startup of the Daya Bay project in China, where EDF acted as an assistant to the owner and future operator, CGN, and provided training and know-how transfer to CGN engineers. From 1995, Areva and Alstom Power took part in the construction and commissioning of the first two Ling’ao reactors under CGN’s responsibility.

(3) Mid-1990s to present: Preparing for the future

During the period from mid-1990s to present, France’s nuclear strategy has mainly focused on:

- The development of the so-called third-generation model, EPR (European Pressurised Reactor), as part of a French-German industrial collaboration, embodied in particular by the merger of Areva and Siemens KWU (see Section 5.2.1).
- The development of French nuclear power in international markets; a centre of excellence and recognised expertise. In addition to its strong presence in China, but also in the United Kingdom with nine reactors in operation and two EPRs under construction at Hinkley Point C (and possibly two additional ones at Sizewell C), EDF is very active in new nuclear development and is in discussions

with many countries including the Czech Republic, Finland, India (Jaitapur project), the Netherlands, Poland and Sweden.

- The prospect of extending the existing fleet beyond 40 years.

As early as the 2000s, the question of extending the operation of the French nuclear fleet beyond 40 years was raised, considering, on the one hand, the uncertainties regarding the energy focus and the opportunities for new technologies (Combined Cycle Gas, Renewable) and, on the other hand, the extensions approved by the regulatory authorities of several countries (Belgium, the United States, etc.).

The Grand Carénage (major overhaul programme) was officially launched in 2015, based on significant economic and industrial investment aimed at strengthening the safety of the units, replacing some critical large components at the end of their life, and dealing with obsolescence. This programme, currently underway on the 900 MWe series units, is an industrial opportunity contributing to the maintenance of expertise and redeployment of the sector's industrial capabilities.

2.3.2. Current status of nuclear power development in France

(1) Nuclear power operation

France currently has 56 units in operation, classified into series:

- 32 reactors 900 MWe:
    - CP0 series: 4 riverside reactors (Bugey NPP).
    - CPY series: 28 reactors
        - 22 riverside reactors (Blayais, Dampierre-en-Burly, Tricastin, Chinon, Cruas-Meysse and Saint Laurent des Eaux NPPs).
        - 6 seaside reactors (Gravelines NPP).

Table 2-3 Operational Nuclear Reactors in France

Name	Reference Unit Power (MWe)	Name	Reference Unit Power (MWe)
BELLEVILLE-1	1,310	DAMPIERRE-3	890
BELLEVILLE-2	1,310	DAMPIERRE-4	890
BLAYAIS-1	910	FLAMANVILLE-1	1,330
BLAYAIS-2	910	FLAMANVILLE-2	1,330
BLAYAIS-3	910	GOLFECH-1	1,310
BLAYAIS-4	910	GOLFECH-2	1,310
BUGEY-2	910	GRAVELINES-1	910
BUGEY-3	910	GRAVELINES-2	910
BUGEY-4	880	GRAVELINES-3	910
BUGEY-5	880	GRAVELINES-4	910
CATTENOM-1	1,300	GRAVELINES-5	910
CATTENOM-2	1,300	GRAVELINES-6	910
CATTENOM-3	1,300	NOGENT-1	1,310
CATTENOM-4	1,300	NOGENT-2	1,310
CHINON B-1	905	PALUEL-1	1,330
CHINON B-2	905	PALUEL-2	1,330
CHINON B-3	905	PALUEL-3	1,330
CHINON B-4	905	PALUEL-4	1,330
CHOOZ B-1	1,500	PENLY-1	1,330
CHOOZ B-2	1,500	PENLY-2	1,330
CIVAUX-1	1,495	ST. ALBAN-1	1,335
CIVAUX-2	1,495	ST. ALBAN-2	1,335
CRUAS-1	915	ST. LAURENT B-1	915
CRUAS-2	915	ST. LAURENT B-2	915
CRUAS-3	915	TRICASTIN-1	915
CRUAS-4	915	TRICASTIN-2	915
DAMPIERRE-1	890	TRICASTIN-3	915
DAMPIERRE-2	890	TRICASTIN-4	915

(Source: IAEA PRIS database, February 2024)

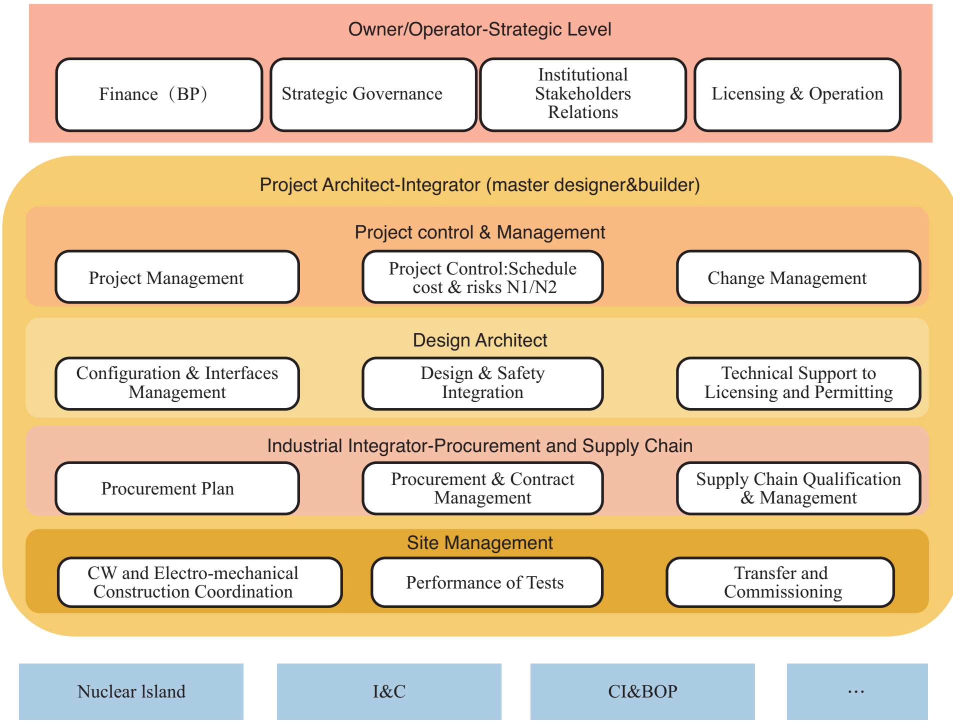
- 20 reactors 1,300 MWe:
    - P4 series: 8 reactors
        - 2 riverside reactors (Saint-Alban NPPs).
        - 6 seaside reactors (Flamanville and Paluel NPPs).
    - P'4 series: 12 reactors
        - 10 riverside reactors (Belleville, Cattenom, Golfech, Nogent-sur-Seine NPPs).
        - 2 seaside reactors (Penly NPP).
- 4 reactors 1,450 MWe:
    - N4 series: 2 riverside reactors at Chooz NPP and 2 at Civaux NPP, the last of which was connected to the electricity grid at the end of 1999. These are the newest operating reactors.
- One EPR 1,650 MWe reactor is currently being built at Flamanville (seaside reactor) and will be in operation in 2024. It is an evolutionary reactor of the third generation.

(2) Nuclear design and construction

Typical industrial organisation scheme for Nuclear New Build projects

Effective project management requires the implementation of an efficient industrial organisation scheme for each project. The Architect-Integrator project management structure has at least four main departments: Project Control & Management, Design Architect, Industrial Integrator and Site Management.

The success of a construction project depends on many factors including an Owner/Operator, who can challenge strategic guidance,



（Source: EDF）

Figure 2-13 Typical Industrial Organisation Scheme for Nuclear New Build Projects

design maturity and industrial control and present the Licencing and Permitting to the Regulatory Authorities.

Transforming nuclear engineering to boost competitiveness

EDF nuclear engineering launched a transformation plan in 2015, which aims to improve performance (optimise costs) and achieve operational excellence in the control of industrial quality.

System engineering and the deployment of the PLM integration tool make design engineering management more robust, with a proven record in the aerospace and shipbuilding industries. They encourage cooperative inter-disciplinary organisation (safety, operation, mechanical and electrical, etc.) around the definition and optimisation of each product making up a unit. This "product centric" organisation is embodied in the Product Technical Architect function, which provides the control and coordination of the design.

Manufacturing & construction: strengthening the industrial sector and improving constructions

To prepare for the construction of a new French nuclear programme with a minimum series of six EPR2 units and eight EPR2 optional units, the nuclear sector has regrouped within GIFEN (Groupement des Industriels Français de l'Énergie Nucléaire), a trade association for the French nuclear industry with EDF at the head, in order to be aligned on industrial goals and deploy a common action plan – the Excell Plan.

With the aim of controlling and reducing construction time, several areas of improvement have been implemented for ongoing nuclear projects, including two major projects concerning the setting-up of efficient industrial organisation for on-site construction and the development of modularity.

2.3.3. New policies and needs of nuclear energy

France represents a characteristic illustration of the contribution of nuclear power to a country's supply security, to its industrial competitiveness, and to its growing need for decarbonised electricity.

This structured view of nuclear power was developed at length by the President of the Republic during a policy speech entitled "Reprendre en main notre destin énergétique" (Regaining control of our energy destiny), on 10 February 2022 in Belfort.

The main points of the speech about energy policy and nuclear power are as follows:

- There is no stable industrial production if there is no stable energy at the most competitive prices. There is no energy and climate transition if there is no decarbonisation of the energy generated. There is no real sovereignty, if there are no choices that the nation can make and keep in terms of energy.
- To reduce our greenhouse gas emissions by 55% by 2030 compared to 1990, and achieve carbon neutrality by 2050, reduce our dependence on foreign countries for our energy needs, ensure the industrial development of our country, and control the energy bills for the French public, we have an obligation to commit to structural and historic projects to prepare for the future:
    - The first major project is to consume less energy.
    - The second structural project to be carried out in the coming decades, is to produce more decarbonised electricity. We will have to be able to produce up to 60% more electricity than we do today.
- To increase national electricity generation by 2050, in addition to the main categories of renewable energy, we need to resume the great civil nuclear adventure in France. On the basis of the work of RTE and the IEA, the French President has taken two major decisions:
    - To extend the lifespan of all nuclear reactors that can be extended without compromising safety.
    - To start a programme of new nuclear reactors, including

the construction of six EPR2 units, and studies on the construction of eight additional EPR2 units. In addition, a call for project proposals will be launched to develop SMRs as well as for innovative reactors allowing the fuel cycle to be closed.

- To implement these decisions, the regulatory, financial, and organisational conditions for the sector and the State must be in place. EDF will build and operate the new EPRs. Massive public funding of several tens of billions of euros will be committed to finance this new programme, which will safeguard EDF's financial situation and develop the entire sector.

2.4. Other Countries and Regions: Nuclear Energy Development and Policy

2.4.1. Africa

In its *National Infrastructure Plan 2050 Phase I*, published in March 2022, South Africa outlined a comprehensive strategy for the development of nuclear, wind, and solar energy to replace fossil fuel power generation. The plan includes the implementation of new nuclear power projects and the promotion of advanced nuclear energy technologies, including SMRs. Egypt set a goal for nuclear power to account for 9% of the country's total power generation capacity by 2030. To realise this goal, Egypt has entered into an agreement with Russia for the construction of four nuclear power units with a combined installed capacity of 4.8 GWe. Construction of the first two units commenced in 2022. Other countries (including

Nigeria and Algeria) are also in the planning stages for NPPs, and for incorporating nuclear energy into the energy mix as a way of ensuring the security of national energy supply.

2.4.2. ASEAN

Countries such as Indonesia and Vietnam are prepared to build large PWR NPPs, SMRs, and Generation IV nuclear reactors.

2.4.3. Canada

Viewing SMRs as a new impetus towards nuclear power, Canada developed an SMR roadmap in 2018 in consultation with economic and civil society stakeholders, including several provinces, territories and utilities, to define what the role of SMRs could play in Canada's energy mix. At the same time, Canada has introduced regulations that have helped attract new small reactor concepts. The *2020 SMR Action Plan* outlines the steps for SMR deployment and calls for the first units to be commissioned in the late 2020s. In addition to SMRs, Canada is now also considering the construction of large reactors in the near future.

2.4.4. European Union

(1) A new momentum in Europe

Europe is the region with the highest share of nuclear power in the electricity mix. Of the 14 countries in the world with a nuclear share above 20%, 12 are European countries. About half of the countries that use nuclear power in the world are in Europe.

The European nuclear fleet is the largest electricity generating source, meeting one-quarter of its demand, supplying a significant contribution to energy security, stability of power systems, economic development and industry systems.

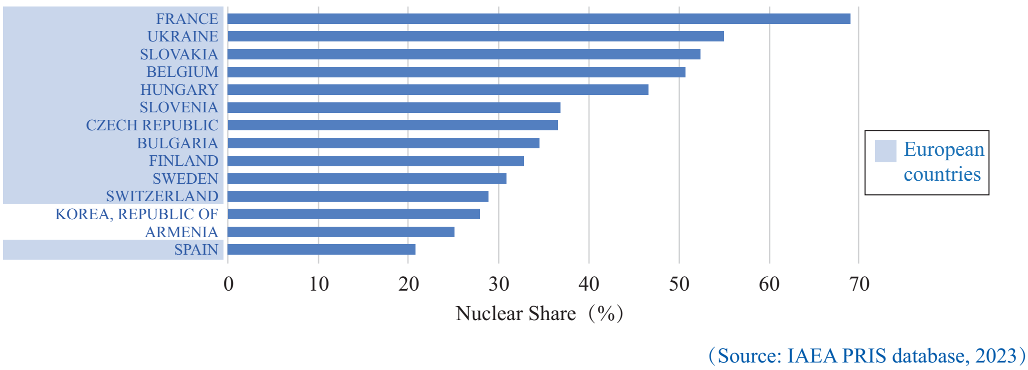


Figure 2-14 Largest Countries per Nuclear Share in 2023

(2) Significant progress in nuclear power for many EU countries

In the EU, climate policies, high fossil fuel prices and efforts to reduce dependence on imports are combined to reduce demand for fossil fuels.

Despite the closure of German reactors, which has been the main factor in the decline in nuclear generation in the EU since the mid-2000s, there is growing interest in nuclear power in a large number of European countries. In February 2023, energy ministers from 11 EU member states (Bulgaria, Croatia, the Czech Republic, Finland, France, Hungary, the Netherlands, Poland, Romania, Slovakia and Slovenia) called for strengthening European cooperation in the field of nuclear energy.

They agreed to foster closer cooperation between their national nuclear sectors to ensure the best cooperation across supply chains and to explore joint training programmes and industrial projects, in order to support new projects, notably based on innovative technologies, as well as the operation of existing power plants. They also discussed the possibilities for increased scientific cooperation and the coordinated deployment of best practices in the field of safety.

In March 2023, the European Commission (EC) decided to include nuclear by referencing SMRs and advanced reactors under its *Net Zero Industry Act* and has acknowledged nuclear technology as a means to decarbonise the energy mix.

Belgium: delays the phasing out of existing NPPs

Belgium has delayed the phase-out of the five nuclear reactors currently in operation, which supply around 50% of the country's electricity. The government has also decided to study other technologies which could contribute by 2050. In 2022, the Belgian government allocated funding for SMR research.

Bulgaria: energy strategy includes four new nuclear reactors

In January 2023, Energy minister has set out an energy strategy from 2023 to 2053 for Bulgaria, which sees the continued use of coal to 2030 before reducing its use to zero by 2038. The aim is for Bulgaria "to remain a leader in the production and export of electricity in the region". It includes plans for two new reactors at Kozloduy and two at Belene.

Czech Republic: life extensions, a new reactor planned at Dukovany, and Temelín site designated for SMRs

Czech energy company ČEZ is making investments at both its Dukovany plant – aimed at ensuring operation until at least 2047 –

and Temelín plant to prepare it for at least 60 years of operation. A contract with Framatome will see the modernisation of the existing instrumentation and control (I&C) Spinline testers for safety systems at the four units at Dukovany. ČEZ is currently evaluating bids for the construction of a new reactor at Dukovany and potentially three others at Dukovany and Temelín. An area Near Temelín has been designated the South Bohemia Nuclear Park and earmarked for small reactors to operate in the early 2030s.

Finland: start of the first EPR, life extension granted, and one SMR planned

In February 2023 the Finnish government granted Fortum an extension to the operating license for the two-unit Loviisa NPP, allowing the plant to continue generating power until the end of 2050. The first EPR began producing electricity at Olkiluoto in 2022. In December 2022, EDF and Finnish utility Fortum signed a framework agreement to seek opportunities for cooperation to develop nuclear reactor projects in Finland and Sweden, both with conventional large reactors (EPRs) and small- and medium-sized reactors.

Hungary: life extension and ongoing construction of Paks II

The existing four VVER-440 reactors at Paks produce about half of the country's electricity. In 2022, the Hungarian Parliament approved a proposal to further extend their lifespan, meaning that preparations can begin on operating the NPP into the 2050s. Hungary is pushing ahead with constructing new nuclear power facilities.

Italy: launch of the National Platform for Sustainable Nuclear Power

In September 2023 the Italian government launched the National Platform for Sustainable Nuclear Power, which in nine months will draw up guidelines for the possible reintroduction of nuclear power as a national energy source. The government is studying new technologies such as SMRs and fourth-generation nuclear reactors (AMRs).

Netherlands: a preferred site for two new reactors, and life extension studied for the existing one

In December 2021, the Netherlands' new coalition government placed nuclear power at the heart of its climate and energy policy. In December 2022, the Dutch Council of Ministers designated the existing Borssele NPP site as the preferred location for two new reactors. It has also called for a feasibility study into extending the operation of the existing Borssele plant beyond 2033.

Poland: a significant nuclear programme for both large and small reactors

Poland planned the construction of large reactors with a total capacity between 6 GWe and 9 GWe in 2020. According to the adopted schedule, the construction of the first NPP in Poland will start in 2026. The first reactor, with a capacity of 1-1.6 GWe, will be commissioned in 2033. The following units will be commissioned every 2-3 years. There are also plans to build SMRs.

Romania: new law approving government support for Cernavoda Units 3&4, and plans for SMRs.

In March 2023, a new adopted law approved a support agreement with Romania's government for the two units. The commitments given by the law include the government taking the necessary steps to finance the construction of the two reactors. Romania also has plans for SMRs.

Slovakia: completion of the two reactors under construction, and new reactor planned

Slovakia has four nuclear reactors – Mochovce Units 1&2 and Bohunice Units 3&4 – in commercial operation, generating half of its electricity. In February 2023, the third unit at Mochovce was connected to the grid. Generation from Mochovce Unit 3 will increase the share of nuclear energy in the total electricity mix from 52% to 65%. The startup of the fourth unit of the Mochovce NPP could be put into operation in the spring of 2024.

Slovenia: Energy permit granted for second Slovenian reactor

Krško, a 696 MWe PWR, is Slovenia's only NPP and generates about one-third of its electricity. In July 2021, Slovenia's Ministry of Infrastructure issued an energy permit to GEN Energija for a proposed second reactor at Krško, referred to as the JEK2 project.

Sweden: a roadmap for the development of new nuclear power

In November 2023, the Swedish government announced a roadmap outlining its objectives and establishing sustainable conditions for the development of new nuclear power. The new policy will enable the development of new nuclear power with a total capacity of at least 2,500 MWe by 2035. Given the long-term need for non-fossil fuel until 2045, further expansion is also required.

2.4.5. India

The Indian government has pledged to increase its nuclear capacity as part of its massive infrastructure development programme.

In November 2022, the *Long-Term Low-Emission Development Strategy* submitted by India to the UN Framework Convention on Climate Change (UNFCCC) includes a threefold increase in nuclear energy capacity by 2032 and explores the potential deployment of SMRs. It therefore aims to explore a greater role for nuclear energy and to enhance support for R&D into future technologies such as green hydrogen, fuel cells, and biofuels.

2.4.6. Japan

In addressing climate change, the Japanese government actively promotes the reopening of its nuclear power units, clarifying that nuclear power is an important way to ensure power supply. It proposes to maximise the use of nuclear energy and to support the construction of Generation IV reactors. The Japanese government has officially launched a revision of nuclear energy regulations to extend the operating life of existing NPPs and allow existing nuclear power units to operate for more than 60 years.

2.4.7. Republic of Korea

The Republic of Korea plans to become carbon neutral by 2050. The government has established a policy of actively developing nuclear power and a plan to increase the share of nuclear power in the domestic electricity mix to 30%.

2.4.8. Middle East

In the Middle East, Saudi Arabia has outlined plans to diversify its energy mix by incorporating nuclear power.

2.4.9. Russia

Nuclear energy is recognised as a crucial option for facilitating a low-carbon transition and addressing climate change. To support the research and development of advanced nuclear technology and professional training, various policies have been implemented. In alignment with these efforts, the President of the Russian Federation has signed the decree *On Announcing the Decade of Science and Technology in the Russian Federation*. This initiative spans multiple areas, including nuclear energy, and outlines the fundamental tasks for the development of nuclear science and technology over the next decade. Russia has developed the VVER series Generation III reactors, nuclear-powered icebreakers and floating NPPs. With regard to Generation IV nuclear technologies, Russia has successfully constructed the BN-600 and BN-800 sodium-cooled fast reactors (SFRs), with the BREST-OD-300 lead-cooled fast reactor (LFR) currently under construction and plans for the BN-1200 in progress.

2.4.10. South America

Both Brazil and Argentina have launched national energy plans. Brazil proposed to increase its installed nuclear power capacity by 8-10 GWe by 2050, while Argentina has set an ambitious target to double its current total installed nuclear power capacity through collaborations with China and Canada.

2.4.11. United Kingdom

All but one of the reactors are set to be retired by 2030. There is an urgent need to replace them and a strong commitment from the UK government is needed. EDF is building two EPR reactors at Hinkley Point, together with CGN. The start of power generation by unit 1 is expected towards the end of this decade. In 2022, the government published its *Energy Security Strategy*, which sets ambitions for eight new large reactors, as well as SMRs, to achieve a nuclear generation capacity of 24 GWe by 2050, or around 25% of forecast electricity demand in the United Kingdom.

2.4.12. United States

Today the United States nuclear fleet provides about 20% of its electricity needs. The average availability factor was broadly constant until the year 2000 and has since increased, reaching 91% in 2020. In January 2024, net capacity in operation was 95.8 GWe (93 reactors), net capacity under construction 1.1 GWe (one AP1000 reactor), and net capacity shutdown 20 GWe (41 reactors).

Life extension is a strengthened priority. The United States has to date issued 20-year extensions of the original 40-year operating licenses for 88 of the country's 93 reactors currently in operation, while 13 reactors have applied for a further 20-year extension, including six reactors with an 80-year operation license already approved[5]. In total, these extensions have already prevented the closure of nearly one-quarter of total capacity that would otherwise have occurred by 2020, a share that will rise to almost 40% by 2030[6].

For new domestic construction, SMR is on the front line. In the United States, a few recent major initiatives involving federal government support have provided concrete momentum for SMRs. The federal *Infrastructure Investment and Jobs Act of 2021* includes numerous nuclear-related provisions, such as funding for the United States Department of Energy's Advanced Reactor Demonstration Program. This programme is designed to accelerate the demonstration of advanced reactors through cost-sharing partnerships with the United States industry.

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5 Turkey Point Units 3&4, Peach Bottom Units 2&3, Surry Units 1&2.

6 IEA, *Nuclear Power and Secure Energy Transitions*, 2022.

3 Advantages of Nuclear Energy

As a clean and low-carbon energy source, nuclear energy has been a pivotal contributor to mitigating rising carbon emissions over the past 70 years. Poised to assume an even more substantial role in the global fight against climate change in the future, the development of nuclear energy will bring significant economic and social benefits, and hold the potential to reduce the overall cost of the power system, stimulate industrial development, and bring more jobs. As a baseload energy source, nuclear power offers stability and reliability with minimal susceptibility to weather changes and unique advantages in ensuring energy supply security.

3.1. Environmental Benefits

3.1.1. Clean and low-carbon

Nuclear power produces virtually no carbon emissions. The minimal amount of carbon emissions associated with nuclear power stems from the consumption of fossil fuels during nuclear fuel production, NPP construction, and spent fuel reprocessing.

(1) Low carbon intensity throughout the lifecycle of NPPs

Full lifecycle carbon emissions are a crucial consideration in assessing environmental benefits. For NPPs, the entire lifecycle of carbon emissions predominantly results from the consumption of construction materials, raw materials, and energy (electricity and fuel) during the construction, operation and decommissioning of facilities in the nuclear power industry chain. From the perspective of the industry chain, sources of carbon emissions encompass a number of activities such as the mining, milling, purification, conversion and enrichment of uranium; fuel fabrication; the construction, operation and decommissioning of NPPs; reprocessing of spent fuel; and disposal of radioactive waste.[1]

Since the 1990s, research institutions in Europe, the United States, and Japan have conducted extensive studies on the lifecycle carbon emissions of NPPs. After reviewing the findings of 23 relevant reports from 1997 to 2011, the WNA has obtained the mean and range of full lifecycle carbon emission intensity of various electricity generation technologies, as shown in Figure 3-1.

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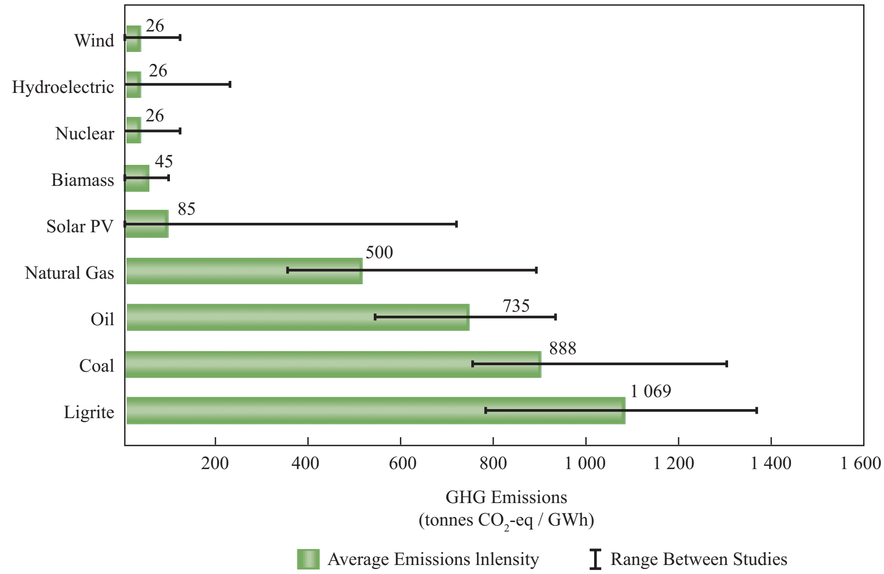
[1] IPCC, *Climate Change 2014: Mitigation of Climate Change.*



(Source: WNA Report)

Figure 3-1 Lifecycle GHG Emissions Intensity of Electricity Generation Methods[2]

The assessment report of the UN IPCC reveals that nuclear power generates only 12 gCO_2/kWh when considering carbon emissions along the entire industry chain (from uranium mining and milling to the decommissioning of NPPs). This carbon emission intensity is comparable to the full lifecycle carbon emission intensity of wind power, and is approximately 1/4 of distributed solar PV, 1/68 of coal power, or 1/41 of gas power. Similar results were found by United Nations Economic Commission for Europe (UNECE).

The Chinese Academy of Engineering has also conducted specialised studies on the full lifecycle carbon emission intensity of different electricity generation technologies[3]. Taking 1,000 MWe-class

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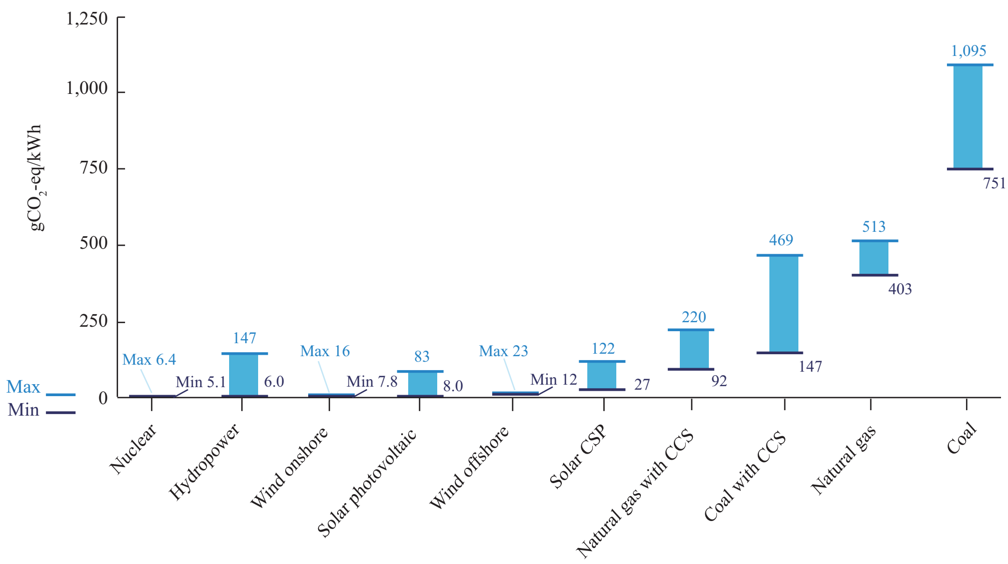
[2] WNA, *Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources*, 2011.

[3] Consulting research report of Chinese Academy of Engineering, *Greenhouse Gas Emissions by Power Generation Source in China*, China Atomic Energy Press, Beijing, 2015.



(Source: UNECE)

Figure 3-2 Full Lifecycle Carbon Emission Intensity by Power Generation Technology

nuclear power units of Daya Bay NPP as an example, their research indicates that the full lifecycle carbon emission intensity of nuclear power (including the front and back ends of nuclear fuel cycle and the construction and operation of NPPs) was 11.9 gCO_2/kWh. Another study by CINIS reveals a figure of 10.02 gCO_2/kWh for a Hualong One on a lifecycle basis. These findings underscore that nuclear power holds a substantial advantage in carbon reduction over power from other technologies.

(2) Significant contribution of nuclear power to reducing global CO_2 emissions

According to research by the IEA, nuclear power is the largest source of low-carbon energy in developed economies. Contributing half of all low-carbon electricity over the past half-century, it has played a crucial role in reducing CO_2 emission growth rates. In 2022, after hydropower with 15.2%, nuclear power – at 9.2% of global electricity generation – was the second-largest low-emission power source[4]. Remaining one of the primary sources of electricity in developed economies, nuclear power has significantly contributed to carbon reduction in Europe and the United States. In 2022, nuclear power accounted for 62.6% of total electricity in France, 30.4% in the Republic of Korea, 18.1% in the United States, 14.3% in Canada, and 14.2% in the United Kingdom.

Globally, NPPs have annually contributed to averting 1.5 billion tonnes of CO_2-eq emissions and reduced the demand for natural gas by 180 billion cubic meters. From 1971 to 2022, NPPs have cumulatively avoided approximately 70 billion tonnes of CO_2-eq emissions worldwide. Without nuclear power, total CO_2 emissions from the energy sector would have increased by nearly 20% during this period, and carbon emissions from electricity generation in some countries such as Canada and the Republic of Korea, would have increased by about 50%[5]. In China, nuclear power has played a vital role in carbon reduction. Since 1994 when the country's first NPP was commissioned, China's NPPs have generated a cumulative 3,500 TWh of electricity. This is equivalent to avoiding the combustion of approximately 1.05 billion tonnes of standard coal equivalent (SCE) and the emissions of approximately 2.75 billion tonnes of CO_2.[6]

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4 Data source: Statista, *Distribution of electricity generation worldwide in 2022*.

5 IEA, *Nuclear Power and Secure Energy Transitions: From today's challenges to tomorrow's clean energy systems*, 2022.

6 Data source: China Nuclear Energy Association, www.china-nea.cn, accessed 10 March 2024.

3.1.2. Other environmental externalities

The environmental externalities of energy generation technologies, including electricity generation technologies, are the subject of a wealth of academic literature and reports from international organisations. Nuclear generation sets a good example: its environmental impact is not significant compared to other power technologies.

The Joint Research Centre (JRC) of the EC report published in 2021, titled *Technical assessment of nuclear energy with respect to the "do no significant harm" criteria of Regulation (EU) 2020/852 ("Taxonomy Regulation")*, presents a summary of various scientific studies comparing the externalities of one kWh of nuclear with one kWh of other low-carbon technologies such as wind and solar PV (JRC, 2021). In its conclusions, nuclear appears as a technology whose DNSH (Do No Significant Harm) performance is at least as good as that of other low-carbon technologies. According to this report there would be no reason to exclude nuclear power from the taxonomy.

(1) Footprint of non-energy raw materials (not including uranium)

Over the last few years, the global economy has become highly intensive in raw materials, raising a variety of issues (scarcity, geopolitics, environment, etc.). International organisations have published indicators of aggregated categories of minerals and metals (UNECE, 2021), (IEA, May 2021), (JRC, 2021) that aim at comparing the material footprint of alternative power generation technologies. For example, the JRC 2021 report, using the figures from Treyer & Bauer (2016), provides an aggregated index of all metals in "kg of equivalent iron per kWh".[7] Compared with nuclear, the indicator is 4 to 5 times higher for solar PV, and 13 times higher for onshore wind.

(2) Pollutants and health and ecotoxicity indicators

The results presented by the JRC are mainly based on three academic references. The comparison of impacts is clearly in favour of nuclear, in particular on acidification, eutrophication (JRC p. 183) and potential ecotoxicity of fresh or sea water. Similarly, in terms of health, all impacts of nuclear (radiological and non-radiological) are considered to be comparable ("no more harm") to renewables.

The JRC concludes, "all potentially harmful impacts of the various nuclear energy lifecycle phases on human health and the environment can be duly prevented or avoided. Nuclear energy-based electricity production and associated activities in the whole nuclear fuel cycle (uranium mining, nuclear fuel fabrication, etc.) do not represent significant harm to any of the TEG objectives, provided that all specific industrial activities involved fulfil the related Technical Screening Criteria." (JRC p. 190)

(3) UN SDGs

In 2015, the UN adopted the *2030 Agenda for Sustainable Development*, including 17 SDGs. As shown by WEC (2019), "nuclear power has a number of benefits across a range of social, environmental and economic indicators when compared with other energy sources." The

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7 The aggregation metric seems to be based on the ADP (Abiotic Depletion Potential), an arithmetic sum for raw materials of the P^2/R^2 ratio, where P is the gross annual production of mining activities (recycling activities not used), and R is an "ultimate" reserve (percentage of the element considered to be in the Earth's crust). In this aggregated metric, gold has a greater weight than structural materials and metals. Usually, the index is normalised to "antimony equivalent". Here the equivalent is iron. But this does not matter for the relative comparisons between sectors.

development of nuclear energy and the nuclear industry contributes to 10 of the 17 goals, as illustrated below. IPCC (2022) confirms this positive assessment.

Nuclear Technology Contribution to Achieving UN Sustainable Development Goals

2	Zero Hunger	improves crop varieties and nutrition via radiation technologies – up to 20%-25% of food losses can be avoided
3	Good Health and Well-being	by development of radio-medicine and radio-pharmaceuticals
4	Quality Education	education and training of highly qualified engineers and workers, esp. in the emerging economies
6	CleanWater and Sanitation	offers nuclear-based desalination technologies
7	Affordable and Clean Energy	reliable, affordable and low-carbon energy supply 24 hours a day
8	Decent Work and Economic Growth	a 2 GWe NPP creates 400,000 labour-years of employment
9	Industry, Innovation and Infrastructure	an innovation-driven industry; supports other industries' development, esp. for industrialising economies
13	Climate Action	avoids contributing to climate change by generating low-carbon elecdtricity (29 tonnes CO_2-eq/GWh)
15	Life on Land	fights pests and diseases via radiation techologies; identifies soil erosion via radionuclides
17	Partnerships to Achieve the Goal	partnering via supranational organisations to ensure industry's safe and reliable operations

(Source: WEC, 2019)

Figure 3-3 Nuclear Technology Contribution to Achieving UN SDGs

3.1.3. Safety of nuclear waste management

(1) Less waste generation[8]

Uranium possesses high energy density. To produce 1 MWh of nuclear power, only 2.5 g of enriched uranium (or 20 g of natural uranium) is required. During fission through neutron capture, as only

8 The distinction between radioactive materials, radioactive fission products, and radioactive waste depends on rules and regulations specific to each country.

0.15 g is consumed there is a 0.13 g yield of fission products. Nearly 85% of fission products remain stable over the following years, with approximately 11% active within 30 years, and 0.03 g of nuclides categorised as long-lived waste. In France, 1-2 kg of radioactive waste and 10 g of long-lived waste are generated per person each year. This is significantly below the 100-200 kg/person/year of hazardous industrial waste generated[9].

(2) Internationally recognised long-term solution to radioactive waste

The management of radioactive waste involves addressing two key aspects: preventing the risks associated with radioactive waste and ensuring that radioactive waste does not penetrate the natural environment. In the interests of human health and environmental safety, countries with well-established nuclear power programmes have devised solutions tailored to various categories of waste. Although it constitutes a minor portion of the total waste, long-lived waste necessitates suitable long-term solutions. Several countries (including Finland, France, and Sweden) have adopted the internationally recognised approach of implementing deep geological disposal for long-lived waste.

3.2. Economic Benefits

As they require more transmission and distribution networks, backup power sources, and energy storage, the increasing part of variable renewable energy sources like wind and solar power in the energy mix

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[9] Bouttes, Jean-Paul, *Nuclear waste: a comprehensive approach*, s.l., Fondapol, 2022, p. 30.

is going to increase the cost of the power system. Therefore, the lower system costs associated with electricity mixes that include a significant proportion of nuclear energy will help to reduce the overall cost of energy transition. Moreover, generating significant economic benefits, the development of nuclear power industrial chain stimulates economic growth and industrial upgrading.

3.2.1. Nuclear power is a cost-effective generating technology

(1) Capital costs account for the major part of nuclear power's LCOE.

In the electricity industry, it is a common practice to divide the total discounted cost (including the capital cost, operation & maintainance cost, and decommissioning cost) of a power generation technology by its total discounted generation over its operating life. The indicator is referred to as the Levelised Cost of Electricity (LCOE). Its precise economic meaning is the constant (in real terms) selling price of quantity produced during the plant operation lifetime that allows for the total discounted operation revenue to be equal to the total discounted cost of the technology.[10]

In the representative example indicated in Table 3-1, capital costs represent the major part, 78%. It is therefore crucial to control the capital costs so as to minimise the LCOE.

Considering the learning effects on a series of new reactors leads various international organisations such as the IEA and OECD/NEA

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[10] For formal application to nuclear, let $t = 1, \cdots T_{operation}$ be the operating years of the nuclear plant, $t = T_0, \cdots, T_1$ be the dates of expenses F_t including both CAPEX before operation and expenses after operation for decommissioning and waste ($T_0 < 0$ and $T_1 > T_{operation}$), Q_t the power generated in year t, α the discounting rate. LCOE is defined by: $LCOE = \sum_{t=T_0}^{t=T_1} \frac{F_t}{(1+\alpha)^t} \Big/ \sum_{t=1}^{t=T_{operation}} \frac{Q_t}{(1+\alpha)^t}$.

Table 3-1 Cost Breakdown for Nuclear Power Levelised Cost of Electricity

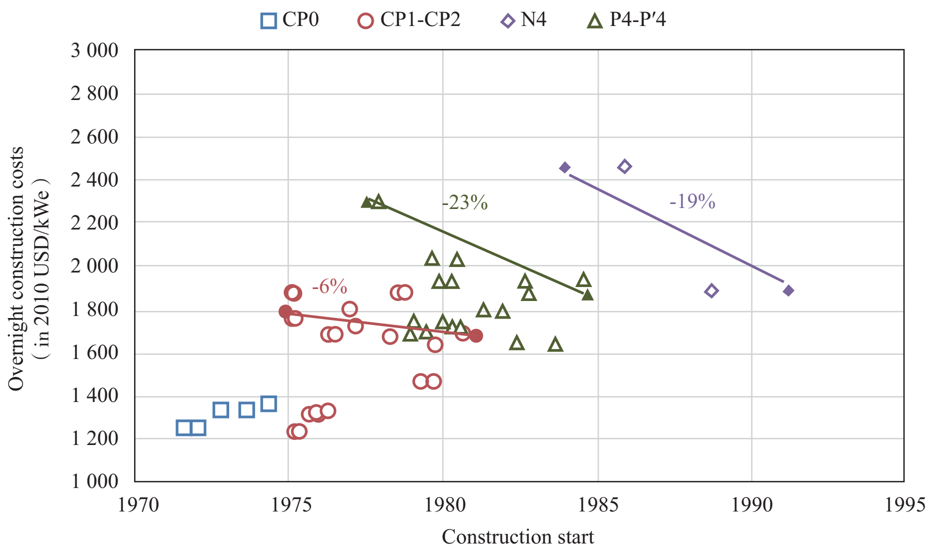
Cost Type	Cost Composition Specification	Hypothesis
Capital	Overnight construction costs (OCC): includes the materials, components, manpower and cost of capital required to design, construct and commission the plant.	11%
	Capitalised financial costs (CFC): includes interest during construction (IDC) and related fees.	20%
	Return of capital: the cost of capital, which is a combination of the cost of debt (i.e. loan) and required return on equity (from the shareholders). IDC can also be added to this cost category to isolate the overall financing costs.	47%
O&M	Operation and maintenance (O&M) costs: all costs related to staffing, consumables and recurring maintenance activities necessary for safe operations once the plant has been built and commissioned.	13%
	Fuel cycle costs: costs of the fuel used to produce electricity. In the case of nuclear power, includes costs related to mining, enrichment and manufacture of fuel assemblies to be loaded in the core (i.e. front-end activities), as well as to managing the used nuclear fuel and waste (i.e. back-end activities).	9%
Decommissioning	Costs associated with dismantling the plant once it has reached the end of its lifetime and returning the site to greenfield state.	

Overnight Capital Costs of 4,500 USD/kWe at a real discount rate of 9%.

(Source: OECD/NEA, Table 2, p. 30, Load factor of 85%, 60-year lifetime and 7-year construction time, 2020)

to assume overnight construction costs for new nuclear series of ca 4,500 USD/kWe (4,000 EUR/kWe) in Europe and the US. However, the full cost of nuclear power is highly sensitive to the cost of capital: with an overnight construction cost of 4,000 EUR/kWe, the full cost of new nuclear power is estimated at 44 EUR/MWh with a real discount rate of 3%, compared to 70 EUR/MWh with a rate of 7% and 90 EUR/MWh with a rate of 9%.

The graph below provides an illustration concerning the overnight construction costs of nuclear plants in France in the 1980s and 1990s that distinguish the first series of 900 MWe plants (CP0), the following series of 900 MWe plants (CP1-CP2), the series of 1,300 MWe plants (P4-P'4) and the series of 1,400 MWe plants (N4).



(Source: OECD/NEA based on data from *Cour des Comptes*, 2012)

Figure 3-4 French Nuclear Programme Construction Costs, 2012

For each of the series CP1-CP2, P4-P'4 and N4 mentioned above, the overnignt cost went down by 6%, 23% and 19% respectively throughout the series. The main reasons of this decrease are the management of the design and construction activities by a single in-house division, resulting in a standard design and significant cost reductions. Many of the design studies were generic, applicable to all new plants to be built. The productivity of the in-house "site supervision" teams was also increased. At the same time, an ambitious industrial policy was put in place, with multi-site contracts securing orders for external partners.

More generally the design of current French and Chinese nuclear reactors is based on the principle of series of similar reactors, which gradually reduces the overnight cost of each reactor throughout the series, with two main reasons:

- Series of reactors mobilise the industry. An essential condition for guaranteeing control and performance from the first construction phase is to mobilise industry. This requires a sufficient perspective on the construction of a series of reactors. This commitment is necessary to economically justify the investment in skills, organisations and methods by all the players involved in the programme.
- A standardised design for the entire production chain enables the industrial effect of pooling, replication and improved execution. Adaptations from one site to another must be limited to local specificities. This presupposes the greatest possible stability in the requirements imposed on the design, and in particular in the regulatory and technical reference framework.

To conclude, using LCOE and its components to assess past or future cost evolution of nuclear, as well as of any given power generation technology, is relevant conditionally to a well-defined and standardised usage.

(2) Extending unit life improves economics of nuclear power generation

One of the most economically efficient ways to produce dispatchable low-carbon electricity is by extending the life of existing NPPs.[11] Subject to government approval, the life extension of NPPs through increased investment could then be an attractive option for economics consideration and financing, ultimately maximising the contribution of

[11] IEA, *Nuclear Power in a Clean Energy System*, 2019.

nuclear power to a clean, low-carbon energy transition.

Factors influencing investment in life extension include reactor type, safety regulations, plant location, and project duration. The IEA estimates the typical investment costs for extending the operational life of a LWR NPP at 500-1,100 USD/kWe, primarily related to upgrades to the main process system, risk assessment, and a review of O&M procedures. Reactor life extensions are typically 10 to 20 years, with safety inspections every 10 years to ensure the continued safe operation of the reactor.

Based on an overnight capital cost of of 500-1,100 USD/kWe and a life extension of 10 to 20 years, the LCOE after plant life has been extended is 0.04-0.06 USD/kWh[12]. This range is similar to the one related to the average LCOE of new solar PV or wind projects under the same financing conditions. These figures from the IEA, which date from 2019, may have changed over time, but it remains clear that extending the life of NPPs is still one of the cheapest ways of obtaining carbon-free electricity. In its recent 2022 report[13], the IEA estimates that extending the life of NPPs is competitive with solar photovoltaic and wind power under most conditions, despite solar PV and wind power costs falling dramatically.

(3) The Chinese case: the advantages of nuclear capital cost compared with other clean energy sources

In absolute term, capital cost of nuclear power is much higher than other clean generating technologies. But since full-load utilisation hours

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[12] In 2019 USD.

[13] IEA, *Nuclear Power and Secure Energy Transitions*, 2022.

of each unit capactiy differ by power generating technology, when the annual full-load utilisation hours have been taken into account, the equivalent capital cost (defined as capital cost divided by annual full-load utilisation hours) of nuclear power will become more attractive, as the Chinese case shows in the table below.[14]

Table 3-2 Equivalent Capital Cost of Clean Energy

S/N	Power Source	Capital Cost Index (relative value, nuclear power= 100)	Full-load Hours (hours/year)	Capital Cost/Full-load Hours (relative value, nuclear power 100)
1	Nuclear power	100	7500	100
2	Hydro	67	3500	144
3	Onshore wind	54	2200	184
4	Offshore wind	112	2200	383
5	Solar PV	43	1500	216

3.2.2. The economic benefits of nuclear energy are substantial when considering the full cost of the system

Comparing the costs of different sources of electricity generation is very often based on the use of LCOE. However, the use of LCOE, which is appropriate for comparing dispatchable sources of electricity production (fossil fuels, nuclear, hydroelectric dams, biomass plants) capable of providing comparable services to the electricity system, is no longer appropriate when intermittent renewable sources of electricity, which do not provide the same services, are included in the comparison. We need to adopt a systemic approach that makes it possible to compare

[14] Data source: China Electricity Council, *2023 National Electricity Supply and Demand Situation Analysis and Prediction Report.*

different production technologies, on the basis of "equivalent services rendered".

(1) The need for backup resources

Unlike dispatchable sources, variabilities of installations of intermittent renewables are both highly correlated with each other, and decorrelated with periods of high consumption. For example, in mainland France, during the winter months when demand for electricity is highest, there is three to four times less sunshine than in summer, and in winter, at the height of the day, around 6 pm, it gets dark. Some winters see periods of a week or more with very little wind.

To make up for these shortfalls, we need "backup" resources such as dispatchable power plants or storage devices (hydroelectric pumping today, batteries or hydrogen tomorrow). Backup costs depend on the electricity system under consideration: For example, they are estimated by the OECD/NEA at around 8 EUR/MWh for a mix including 10% onshore wind power and 19 EUR/MWh for a mix including 10% of solar PV. Moreover, renewable energy production also varies greatly from one hour to the next depending on weather conditions. This variation needs to be balanced by putting flexible, dispatchable resources on standby and using them in real time.

(2) Network requirements have to be considered, as investments in transmission and distribution grids depend on the sources of generation

Renewable energy installations are built where there are both available space and a good wind or solar resource. These sites are often far from where electricity is consumed. Locally, renewable energy production is highly variable and generally has little correlation with demand.

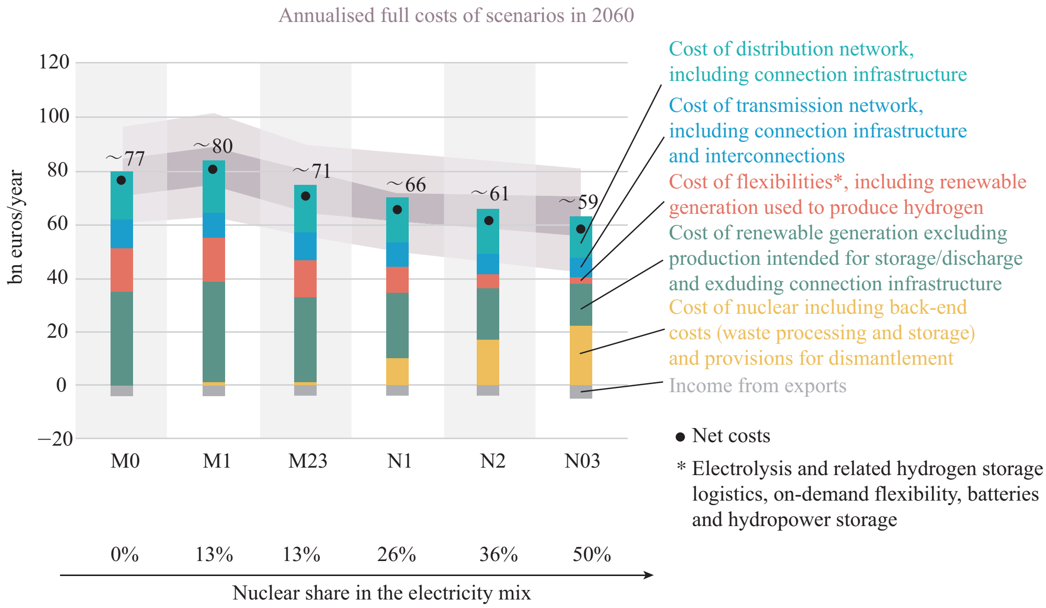
Moreover, because of the correlated variations of installations of intermittent renewables at different sites and of their decorrelation with periods of high consumption, the capacity of transmission and distribution grids must be higher to be able to absorb these variations, compared to the grid capacity of electricity systems with only thermal plants.

This dual geographical constraint of location and the "inconsistency" of local renewable energy production in real time mean that electricity transmission and distribution networks need to be further developed in systems with high share of renewables. Quantifying the network requirements generated by renewable energies is still poorly documented: They are highly sensitive to the level of renewable energy, their distribution between wind farms, photovoltaic panels and photovoltaic rooftops, and the geography in which they are located.

(3) A systemic approach is needed

Finally, to compare the cost of nuclear and renewable energies, we cannot simply compare their LCOEs and we need to adopt a systemic approach, incorporating the costs associated with backup, balancing and grid adaptation requirements, costs that increase non-linearly with the penetration rate of renewable energies, up to very high levels.

This brief example of the comparative economics of nuclear power and other sources of electricity illustrates the caution that must be exercised when discussing the full cost of the electricity system.



(Source: RTE)

Figure 3-5 Full Costs (Production + Transmission + Flexibility) in France per Scenario (Based on the Baseline Consumption Trajectory) in 2060, for Central Scenario and Variants

(4) The case of France

The necessity to compare the competitiveness of various technologies relatively to a common delivered service is well illustrated by an RTE 2021 report. Below are extracts from the RTE report *Energy Pathways to 2050* related to the respective role of nuclear and renewable sources of energy[15]:

"In compliance with its legal obligations and at the request of the French government, in 2019, RTE launched a wide-ranging study on the evolution of the power system called '*Energy Pathways to 2050*'."

RTE defined "a clear methodology centred around the distinction between two sets of scenarios representing societal trends observed in France today, depending on whether new investments in generation capacity focus exclusively on renewables ('M' scenarios) or a more

[15] RTE report, *Energy Pathways to 2050*, 2021.

technologically diverse mix combining renewables and new nuclear reactors ('N' scenarios)".

"The integration of large quantities of wind turbines or solar panels creates a very significant need for flexible resources (storage, demand side management and new backup plants) to offset their variability, as well as for grid strengthening. Once all these costs are factored in, the scenarios that include new nuclear reactors appear more competitive. The effect is even more pronounced when the nuclear fleet considered is significant enough to avoid the costs associated with a power-to-gas-to-power loop in France and massive grid strengthening."

(5) The case of China

The development of nuclear power in China effectively reduces the cost of low-carbon transition.

Nuclear power is less constrained by weather conditions than wind, solar PV, and hydro, making it a more reliable baseload energy source. The development of nuclear power during the power system transition will reduce the investment in power transmission and distribution, energy storage, standby power and so forth, compared with large-scale renewable energy development. When considering the entire power system, one may set comprehensive cost of power sources as the sum of LCOE and the system cost as a whole. The comprehensive costs associated with different power sources in China can be estimated on the basis of LCOE data from the OECD 2020 report[16] and a preliminary calculation of the system cost based on the research by State Grid Energy Research Institute (2023)[17]. At

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16 OECD/NEA, *Projected Costs of Generating Electricity*, 2020.

17 State Grid Energy Research Institute report, 2023.

a discounted rate of 7%, the LCOE of nuclear power in China is 30.3% higher than that of centralised solar PV and 13.1% higher than onshore wind power. However, since system cost for solar PV and wind power is about ten times as many as that for nuclear power (OECD, 2018), the comprehensive cost of nuclear power in China with the system cost taken into consideration is 12.3% lower than that of centralised solar PV and 23.2% lower than onshore wind, as shown in Figure 3-6. Therefore, from the perspective of the power system as a whole, the large-scale development of nuclear power would be conducive to reducing the economic costs of low-carbon transition in China.

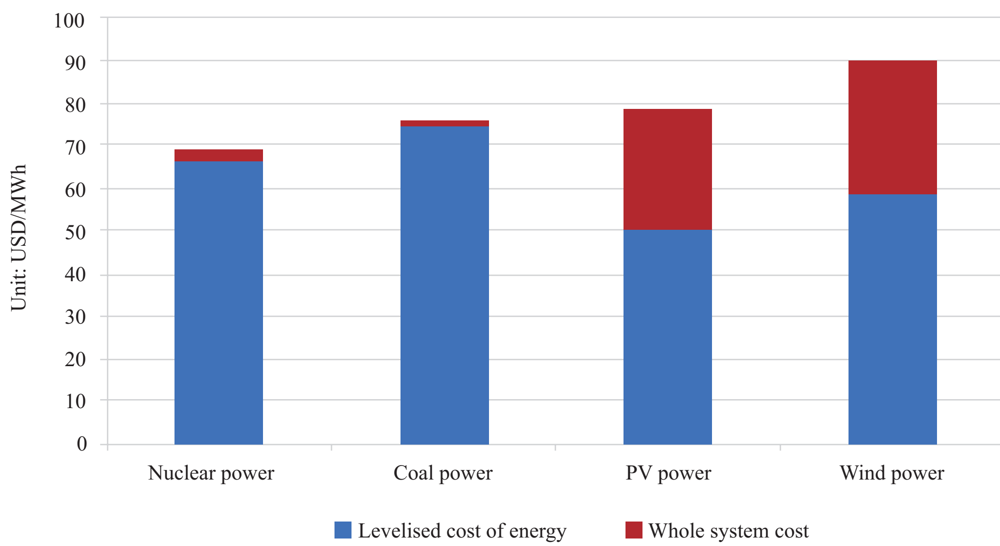

Figure3-6 Comprehensive Costs Associated with Different Power Sources in China

3.2.3. Nuclear energy driving strong economic growth

In standard economic growth analysis, energy is one of the basic factors of global productivity, along with labour, capital and raw materials.

Thus, it is essential that future decarbonised sources of energy contribute to this global productivity. Alongside renewables, nuclear has been and will be a good candidate for decarbonised economic growth.

In March 2021, the IMF published a working paper (Batini et al., 2021) using multiplier analysis to determine the impact that investment in clean energy would have on the economic recovery from the COVID-19 pandemic. According to the document, cumulated spending multipliers analysis indicates that spending on nuclear energy has a large output effect.

The table below reporting cumulated spending multipliers, indicates that spending on nuclear energy has a large output effect, about six times larger than the output effect associated with spending on fossil fuel energy.

Table 3-3 Cumulated Multipliers Associated to Energy

Horizon	Nuclear	Renewable	Non-Eco-Friendly
Impact	4.11*	1.19*	0.65*
1 Year	3.97*	1.20*	0.64*
2 Years	3.88	1.19*	0.62*
3 Years	3.83	1.17*	0.59*
4 Years	3.80	1.14*	0.55
5 Years	3.78	1.11	0.52

*Denotes multipliers with credible intervals, delimited by the 16th and the 84th percentiles, that exclude zero.
Source: Batini et al., 2021, Tables 2 and 4.

The report also mentions that compared to other forms of clean energy (solar and wind power, for example), investment in nuclear power can lead to greater use of high- and low-skilled resources for the construction of nuclear reactors than for lighter energy production infrastructures. It should be noted that while the construction and operation of nuclear reactors tend to take time (5.1 years on average for large, recently-built reactors), spending is not sequential as in the case of renewable energies and tends to be more concentrated at the beginning of the period, which could explain the greater impact in the short term (IMF, 2021).

The case of China: the nuclear industry chain drives regional economic development and employment

The nuclear power industry chain can play an essential role in promoting local and regional economic growth, stimulating equipment manufacturing and service industry development, creating employment, etc.

- Across the full lifecycle from construction, operation, and fuel supply to technical service, a single nuclear power unit in China could create an output value of a hundred billion yuan and tens of billions in tax revenue, with a strong impact on national economy.
- The demonstration project of the world's first Chinese HPR1000 reactor has driven more than 5,300 upstream and downstream enterprises, produced more than 400 core components locally, given a boost to the development of high-end equipment manufacturing in China, and significantly upgraded the manufacturing technology across dozens of industries, from materials, metallurgy, chemical industry, machinery, and electronics to the manufacturing of instrumentation.
- NPPs can positively impact local employment in significant ways. The construction of a GW-class nuclear power unit in China could

create 150,000 jobs, and every 100 million RMB investment of NPP can create more than 3,000 jobs[18].

3.3. Security of Supply

The high energy density and stable output of nuclear power make it an ideal baseload energy source for ensuring the secure and reliable supply of energy. The development of nuclear power is supported by abundant uranium resources and sufficient nuclear fuel processing capacity. Moreover, nuclear power consumes relatively few key mineral resources, further enhancing the security, stability, and reliability of energy supply.

3.3.1. Stable output and high energy density

(1) Stable output

Nuclear power generation operates independently of external factors and is not susceptible to cyclical, regional, or seasonal influences. According to an IAEA report, the lost nuclear power generation due to weather-related events between 1990 and 2020 was less than 0.1%[19]. Nuclear energy typically functions as a baseload, and in China, nuclear power utilisation hours have consistently exceeded 7,000 hours per year over the past five years, with an average unit capacity factor of 91.7%. This performance surpasses that of other power sources. Globally, the availability factor of nuclear power has remained above 70% in recent years.

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[18] Ye Qizhen et al., *Why develop Nuclear Power (Third Edition)*, China Atomic Energy Press, 2022.

[19] IAEA, *Climate Change and Nuclear Power*, 2022.

(2) High energy density

Natural uranium resources for electricity generation can be classified into conventional and non-conventional categories, with conventional resources being primarily exploited and utilised currently. The energy released by the fission of 1 kg of low enriched uranium is equivalent to that released by the combustion of 2,700 tonnes SCE. A GW-class NPP needs to replenish 170 tonnes of natural uranium per year, while a GW-class coal-fired power plant needs 2 million tonnes SCE per year, requiring two 40-car trains for transport all the year round.

3.3.2. A stable supply of global uranium resources

Uranium is a relatively abundant element and well distributed in the Earth's crust, but in very variable concentrations.

According to the latest edition of *Uranium 2022: Resources, Production and Demand* (commonly referred to as the "Red Book") published by the IAEA and the OECD/NEA, as of January 2021, the global identified recoverable uranium resources with a mining cost lower than 260 USD/kg amount to approximately 7.92 million tonnes. The global yet-to-be-identified resources (estimated resources + speculative resources) are about 7.37 million tonnes.

Furthermore, there are huge reserves of unconventional uranium resources in nature, amounting to 39 million tonnes (excluding uranium from seawater), which are of low grade.

Assuming that the currently known uranium reserves do not increase, and that a GW-class nuclear power unit requires 10,000 tonnes of natural uranium over its full lifespan (operating for 60 years), the identified 7.92 million tonnes of natural uranium resources can theoretically meet the full lifespan needs of about 790 GWe of nuclear power installations. Operational nuclear power units are less than 400 GWe currently, with an average lifespan of about 30 years. This means that existing nuclear power units will require approximately 2 million tonnes of natural uranium to operate until the end of their lifespan. Therefore, globally identified uranium resources can theoretically support the natural uranium needs for the full lifespan of over 500 new nuclear power units.

Based on the trend of recoverable resource quantities announced in the Red Book from 2009 to 2022, uranium resources have grown from 6.3 million tonnes to 7.9 million tonnes, with an average annual growth rate of about 2%. In the years with sufficient exploration funding, 2009-2013, the annual growth rate of uranium resources was about 5%. Based on this, it can be inferred that, in the future, as demand increases and prices rebound, exploration funding will gradually return to previous levels or even higher, and resource quantities are expected to grow steadily. Hence, there will be more natural uranium identified. Therefore, global uranium resources are reliable in meeting the long-term development needs of nuclear power.

Besides the aforementioned primary supply, there are secondary supplies of uranium resources, including significant government and commercial reserves, reprocessed uranium from spent fuel, re-enriched depleted uranium, and low enriched uranium produced from diluting highly enriched uranium. Based on the recorded production and consumption of uranium resources – and further enhancing the security of uranium resources – it is estimated that the current global secondary supply of uranium resources is about 500,000 tonnes.

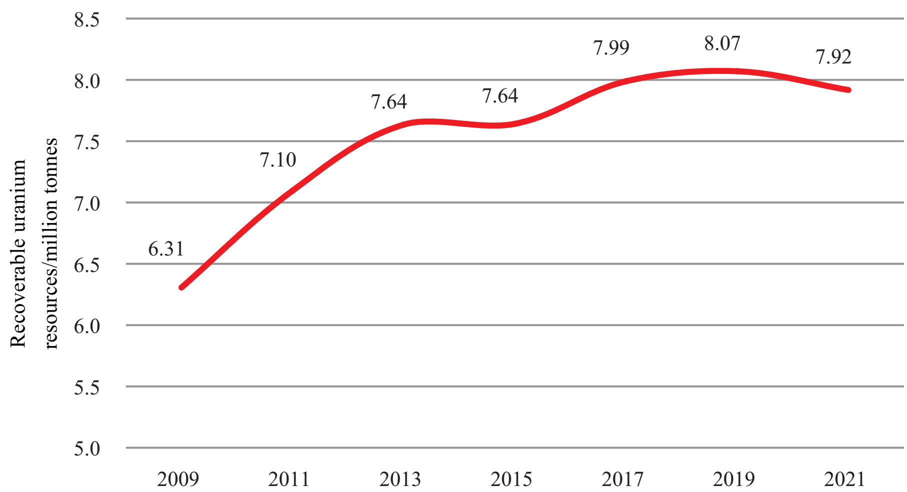

Figure 3-7 Trend for Recoverable Uranium Resources

3.3.3. Saving key mineral resources

Achieving carbon neutrality by 2050 will be accompanied by a strong and rapid rise in demand for so-called strategic materials. According to the IEA NZE scenario, aggregate demand for copper, nickel, graphite, lithium, manganese, cobalt and other minerals related to the decarbonisation of the energy sector is expected to increase by a factor of six by 2050.

This raises significant industrial (mining and refining capacity), environmental (effluents, water requirements, biodiversity), geopolitical (external trade dependence) and economic (price increases) risks. However, the risk of a physical shortage of resources is not expected to occur by 2050 or even beyond. The main risk lies in the ability to ensure a stable development of mines, processing and refining plants, as well as logistics chains, in the face of particularly dynamic demand over the next ten years, in order to comply with the *Paris Agreement* on a global scale. Risks are also significant from the point of view of location.

(1) Achieving carbon neutrality by 2050 requires a sharp increase in demand for materials

This increase has strong disparities: For clean energies, in 2050 the demand for lithium is multiplied by about 130, for nickel, graphite and cobalt by about 30, for manganese by about 20, and for copper by a little more than 3. The rate of growth is more than twice that of total material demand in the last fifty years. About 45% of these needs come from the deployment of electric vehicles, 35% from the development of networks and 20% from carbon-free electricity generation technologies. The impact of electricity generation equipment is significant for certain steel alloy components (nickel and molybdenum), and limited but sensitive for silicon. The impact of electricity networks is only significant for aluminium and copper.

Table 3-4 Demand for Metals in Clean Energy Sector, IEA NZE Scenario

Demand (Mt)	2020	2050
Copper	5.72	× 3.4
Nickel	0.20	× 30
Graphite	0.16	× 31
Lithium	0.02	× 133
Manganese	0.08	× 22
Cobalt	0.02	× 33
Others	0.90	× 4.7
Total	7.10	× 6

(2) The choice of electricity mix is a strategic lever to limit material risks

Some of the requirements in networks are linked to the development of technologies such as wind or solar power. Since nuclear power consumes significantly less material per kWh than other means of generation, a balanced mix between nuclear and renewables allows the demand for materials in the electricity sector to be reduced by a factor of two or more compared to non-nuclear[20] mixes. Since the nuclear industry is typically national, it is also an essential instrument for technological sovereignty.

Material intensity is a subject for all clean technologies, especially for batteries and renewable energy, but also for nuclear. Nuclear power is less intensive with regard to most structural metals since it has annual utilisation greater than 7,000 hours: 6 to 8 times less steel is used per MWh generated than wind or solar PV, 1.5 to 2 times less copper than wind and 9 times less than solar PV, and 15 times less aluminium than wind and 250 times less than solar PV. It is also less intensive in concrete and gravel: 10 times less than solar PV, and 2 to 3 times less than onshore and offshore wind. However, these values from studies on equipment manufacturing over the last decade should be interpreted with caution, with possible technical advances that could lead to a decrease in these material intensities, particularly for solar PV or offshore wind.

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[20] RTE, *Futurs Energetiques 2050 (Future Energy 2050)*, 2021.

Table 3-5 Material Intensities and Wholesale Prices for the Main Metals[21]

Main Metals		Wholesale Prices* (USD/kg)	Material Intensity in g/MWh**			
			Nuclear	Solar PV	Onshore Wind	Offshore Wind
Structural metals	Steel	0.7	320	2,100	2,600	1,900
	Copper	6	16	140	24	34
	Aluminium	2	3.2	790	51	48
	Sliver	700	0.021	0.76	0	0
	Lead	2	0.31	4.9	0	0
	Tin	20	0	4.9	0	0
	Zinc	2.3	0	43	16	14
Alloy metals	Chromium	9	11	23	19	14
	Manganese	2	4.3	20	28	21
	Molybdenum	20	0.53	2.3	16	11.4
	Nickel	12	6.4	14	88	65
Others	Concrete	0.2	2,800	11,000	7,300	20
	Silicon	1.5	0	128	0	0
	Rare eaths	50	0	0	1.3	2.2
	Uranium	90	7	0	0	0

*Order of magnitude of prices over the last 4 years.
**Source: Concordel, Thuillier, Wales, 2021.
Lifespan assumptions: nuclear 60 years, solar PV 30 years, wind 20 years.
Average load factor: nuclear 68%, solar PV 14%, onshore wind 22%, offshore wind 41%.

21 Source: Concordel, Thiollier, & Wales, 2021.

4 Key Topics of Sustainable Development of Nuclear Energy: Chinese and French Practices

For more than 70 years, efforts have been dedicated to the development of nuclear energy. This is due to its crucial role in mitigating climate change, ensuring energy security, and enhancing the economic viability of electric power systems. China and France – as leading nuclear energy producers – have gained rich experience and expertise in nuclear energy development.

4.1. Safety

Throughout history, the development of nuclear energy has faced three major accidents: the Three Mile Island accident in the United States, the Chornobyl accident in the Soviet Union, and the Fukushima accident in Japan. Despite the tragic nature of these events, they have motivated advancements in nuclear technology and management practices to reduce the likelihood of both natural and human-induced disasters, thereby enhancing nuclear safety. In particular, after the Fukushima accident in

Japan, Generation III reactors incorporating more advanced equipment and materials with superior performance emerged as the primary technology for new nuclear power projects and new system designs with an elevated safety level became standard.

Chinese Practice

(1) Establishing a sound legal and regulatory framework on nuclear safety

China has consistently prioritised safety and quality in its nuclear energy development. To achieve this, the country has established explicit criteria for nuclear safety in its laws and regulations, implementing stringent standards for supervision and management. Nuclear safety is integrated into every stage of nuclear energy development and utilisation, and a strong emphasis is placed on continuous improvement. Currently,

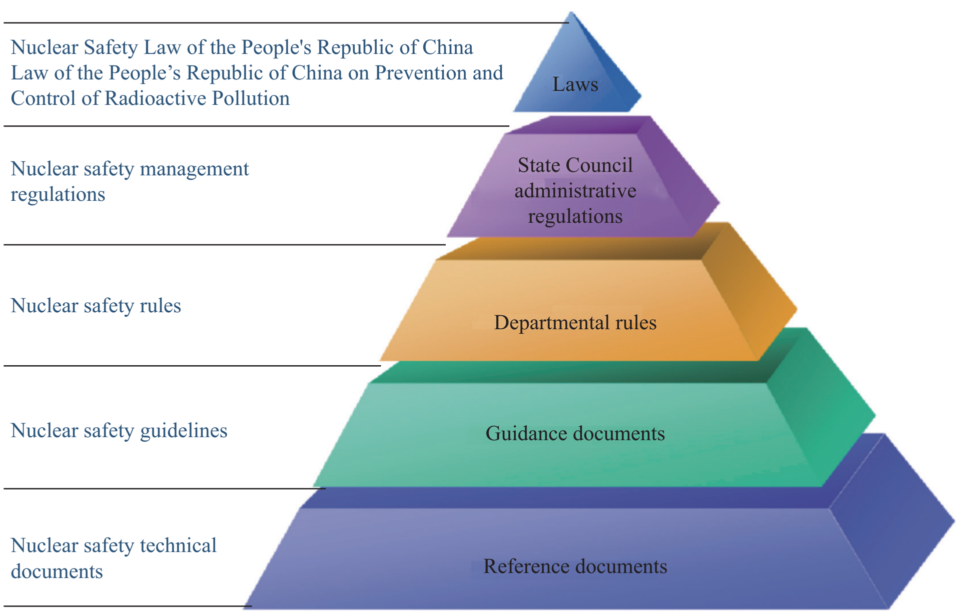


Figure 4-1 China’s Legal and Regulatory Framework on Nuclear Safety

China has built a robust legal and regulatory framework, with the *Nuclear Safety Law of the People's Republic of China* providing overarching guidance, administrative regulations and departmental rules aligning with the law, and provisions of laws, regulations, and technical standards complementing each other. The combination of central and local regulations aims to achieve the globally highest standards of nuclear safety in a manner that is both tailored to China's national context and incorporates insights from international practices in nuclear safety (see Figure 4-1).

(2) Establishing an effective regulatory system and a reliable nuclear emergency preparedness and response mechanism

China has established an independent, open, law-based, rational, and effective regulatory system to comprehensively oversee nuclear facilities throughout their lifecycle: from site selection and construction to operation and decommissioning. In addition, a rigorous safety licensing system has been implemented. In 1984, China established the NNSA to independently supervise nuclear safety. As nuclear energy develops on a large scale, China continues to strengthen technical support, develop a highly specialised workforce, and modernise the regulatory system and capacity, to ensure independent regulation of nuclear safety and enhance its authority and effectiveness.

In terms of emergency preparedness and response, China has established and maintained capabilities that ensure active, safe and orderly development of nuclear energy. The current emergency preparedness and response mechanism in China operates on a three-tiered structure (see Figure 4-2), with emergency preparedness and response organisations established at the national, provincial and enterprise levels. At the national level, China has intensified its efforts in conducting emergency preparedness and response exercises through the initiation of the Shendun joint-exercise series. These exercises effectively showcase the operational efficiency of China’s emergency preparedness and response mechanism, demonstrating its ability to provide a timely and sufficient emergency response. At the enterprise level, emergency preparedness and response exercises are carried out regularly.

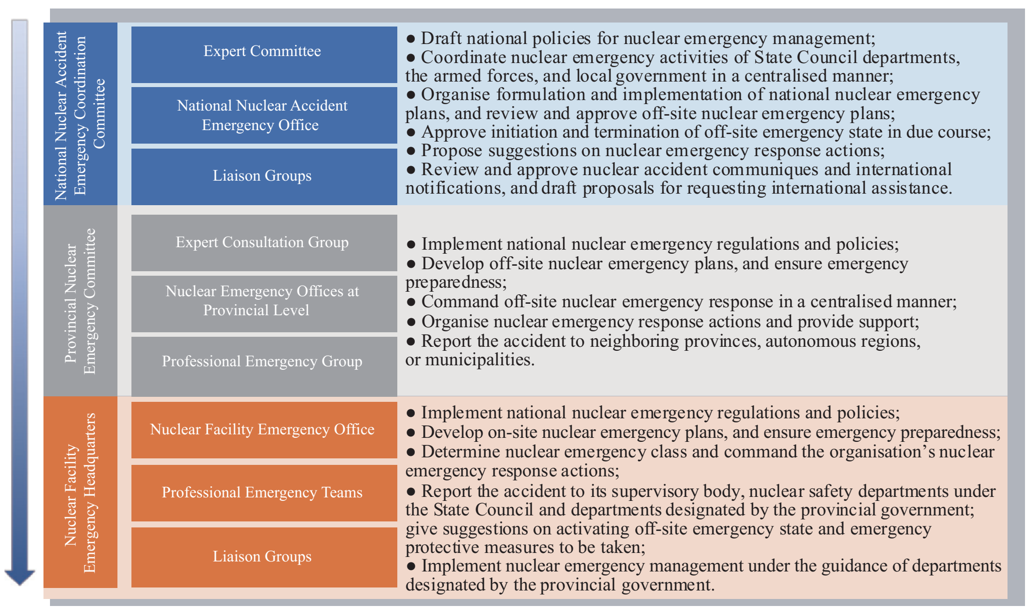


Figure 4-2 Three-Tiered Nuclear Emergency Preparedness and Response Mechanism

(3) Implementing nuclear safety improvements

Following the Fukushima nuclear accident in Japan, the Chinese government conducted a comprehensive nine-month safety inspection of the country’s operational NPPs, those under construction, research reactors, and other key nuclear facilities. The inspection results indicated a minimal possibility of nuclear accidents, given that the locations of China’s nuclear facilities were carefully selected with full consideration of extreme natural disasters, including earthquakes, floods, and tsunamis. Drawing insights from the lessons learned in Japan, the Chinese government has subsequently strengthened nuclear facility safety by implementing short-term, medium-term, and long-term improvement plans. Measures include enhancing the capacity of nuclear facilities to resist external events and preventing and mitigating serious accidents.

- In response to the threat of extreme disasters, various measures have been implemented to enhance the safety of nuclear facilities in China. This includes increasing seawall heights; adding mobile backup power supplies and passive reservoirs; formulating general technical specifications for safety improvement and implementing safety improvement action plans; and setting out safety requirements for the construction of new NPPs.
- Prior to the fuel loading of new units, a series of preparations are completed. These preparations include strengthening flood protection for nuclear safety-related plants and equipment, adding mobile backup pumps and other essential equipment, bolstering NPPs' seismic monitoring and anti-seismic response capabilities, optimising the Severe Accident Management Guidance (SAMG), performing risk assessments and Probabilistic Safety Assessments (PSA) of external events such as earthquakes and tsunamis.

(4) Ensuring constant peer reviews

On the one hand, China seeks external evaluation of its nuclear safety practices through regular requests for peer reviews and follow-up missions conducted by the IAEA via the Integrated Regulatory Review Service (IRRS). On the other hand, China actively contributes to the improvement of global nuclear safety by dispatching senior officials and experts to participate in IRRS peer reviews of regulatory bodies of other IAEA member states. These endeavours have offered an effective way for China to improve its nuclear and radiation safety regulatory framework.

- Over the past three years, China has undergone a comprehensive evaluation of its NPPs, with over 30 peer reviews conducted by the IAEA and WANO. At the same time, China actively contributes to the global nuclear safety landscape by sending its experts to participate in peer reviews conducted by the IAEA and WANO for NPPs in other countries.
- In addition to participating in international peer reviews, China has launched assessments targeting specific fields to deepen domestic operational assessments. These assessments evaluate various areas including procurement and supply chain management, security measures, implementation of maintenance procedures, supervision of installation manufacturing, management of overhauls, feedback, training, fire control, and crew performance observation.

(5) Constructing high-quality NPPs

By strictly observing the IAEA nuclear safety standards as well as its own nuclear safety laws and regulations, China upholds rigorous standards for construction quality and safety management during the development of NPPs. This steadfast adherence to standards has cultivated a notable and highly specialised competence in NPP construction, one of China’s competitive strengths in the field of nuclear energy development.

- Recognising nuclear safety as the lifeline of all activities, China places safety and quality as its foremost priorities. It has established a sound work safety system, nurtured a safety-oriented culture, and imposed rigorous requirements on safety and quality. This unwavering dedication to safety and quality permeates every facet of the nuclear workforce in China. Workers across the country are dedicated to providing products and services that not only meet the highest safety and quality standards but are also environmentally friendly.

- The Hualong One (HPR1000) demonstration project showcases China's unwavering dedication to safety and quality. Effective safety, quality, and schedule management measures were implemented all throughout its construction. Contributing to its higher level of intrinsic safety, the project also adopted integrated advanced information and intelligent technologies, risk-level-based management strategies, and a dual safety protection mechanism to enhance safety management.

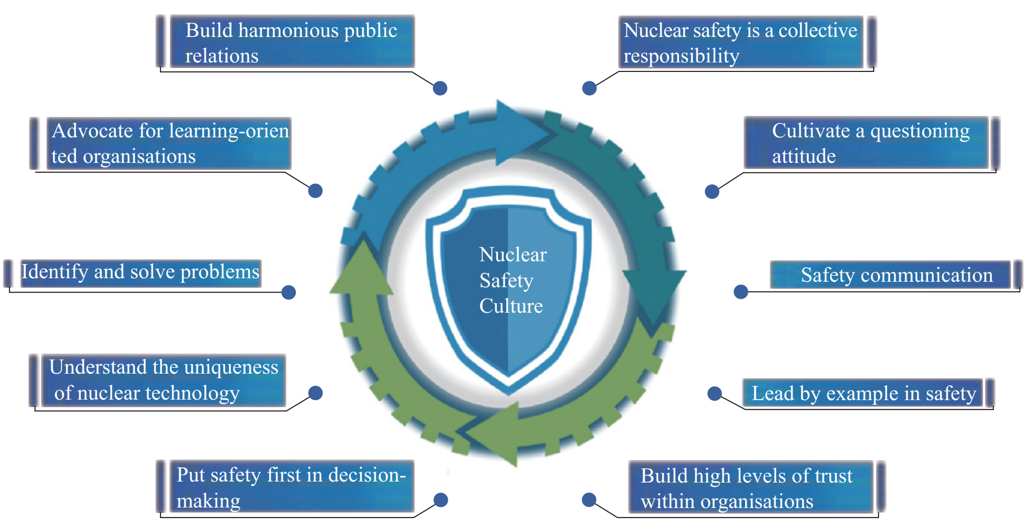
(6) Fostering a strong nuclear safety culture

China regards nuclear safety as the lifeline of the nuclear industry and has actively promoted a nuclear safety culture throughout the sector. Mechanisms for public communication on nuclear safety have been established to facilitate interaction between the central government which provides overall direction, local governments which provide guidance at the local level, industries which implement safety measures, and the public. Outlining the basic principles for fostering a robust nuclear safety culture, China issued the *Nuclear Safety Culture Policy Statement* in 2015.

- Including 36 attributes and 154 examples, China issued the

Nuclear Safety Culture Characteristics in 2017. This document serves as the primary reference for conducting nuclear safety culture assessments in China.

- The Ministry of Ecology and Environment/National Nuclear Safety Administration (MEE/NNSA) has established mechanisms that empower regulatory bodies to conduct independent nuclear safety culture assessments. The MEE/NNSA also urges nuclear facility operators to conduct nuclear safety culture self-assessments in accordance with the *Management Systems of Nuclear Power Plants Safety Regulations; Program for Nuclear Safety Culture Assessment in Nuclear Power Plants.*
- CNNC has put forward ten principles that underpin a strong nuclear safety culture (see Figure 4-3). Drawing inspiration from both Chinese cultural values and domestic and international best practices, these principles are founded on CNNC's accomplishments in building a nuclear safety culture.



(Source: CNNC)

Figure 4-3 Ten Principles for a Strong Nuclear Safety Culture

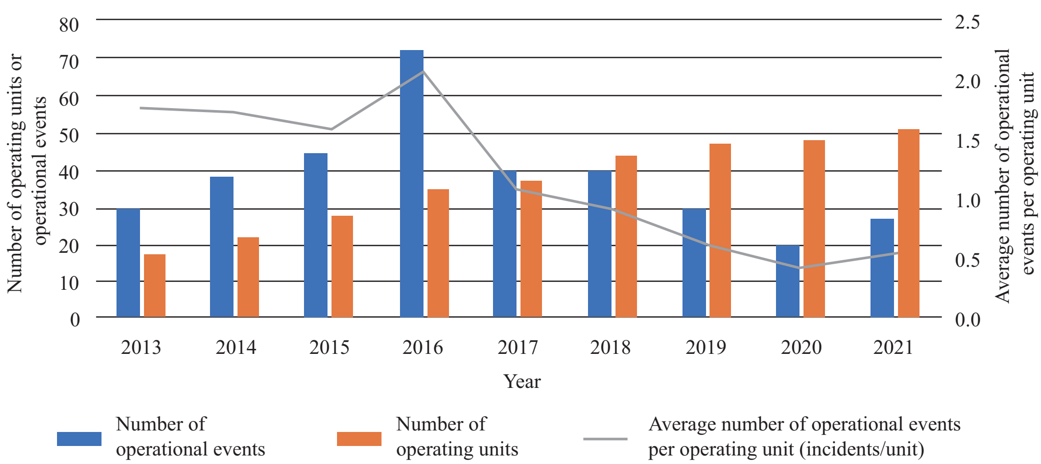
(7) Upholding the principle of safety and quality first

Throughout its four-decade journey in nuclear energy development, China has maintained an excellent nuclear safety record, marked by the safe and stable operation of all nuclear power units in the country. Notably, there have been no incidents or accidents in China that have reached or exceeded Level 2 on the INES. The frequency of Level 0 deviations and Level 1 anomalies have also decreased (see Table 4-1 and Figure 4-4).

Table 4-1 Numbers of Operating Units and Operational Events in China in Recent Years

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Number of operational events	30	38	45	72	40	40	30	20	27
Number of operating units	17	22	28	35	37	44	47	48	51
Average number of operational events per operating unit	1.8	1.7	1.6	2.1	1.1	0.9	0.6	0.4	0.5

(Source: China's 7th, 8th, and 9th National Reports under the *Convention on Nuclear Safety*)



(Source: China's 7th, 8th, and 9th National Reports under the *Convention on Nuclear Safety*)

Figure 4-4 Numbers of Operating Units and Operational Events in China in Recent Years

French Practice

(1) Nuclear and energy policies in France

The EDF Group's policies place nuclear safety as the overriding priority. The quality of design of the facilities and the rigour of their operation by engaged and competent staff make it a continuous shared priority.

France has safely deployed a civil nuclear programme with no major incidents that could bring the technology into question. The fleet has ensured the overall reliability of the nation's power transmission system and security of supply for almost 50 years, while making a significant contribution to balancing the European electrical grid under the terms of the *Euratom Treaty*.

(2) Nuclear safety policy

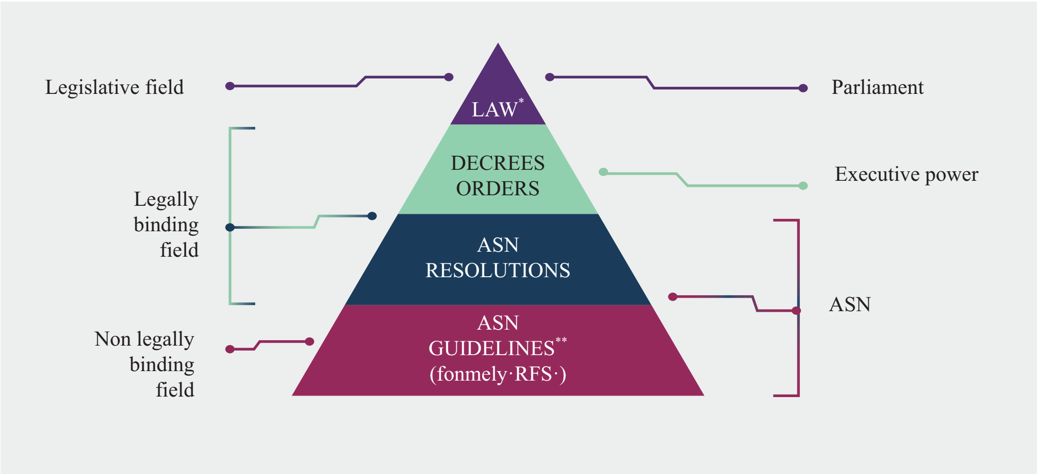
In France, the nuclear safety policy is built around the following principles:

- the prime responsibility of the licensee of a nuclear facility;
- the independence of the ASN (the authority responsible for oversight and regulation) and its transparency regarding the public;
- continuous improvement of nuclear safety.

(3) Legislative and regulatory framework

The *Environment Code* sets out a specific system for those installations using radioactive or fissile materials or particle beams "owing to the risks or adverse effects they can pose to public health and safety or protection of nature and the environment". (Article L591-1). These installations are called "Basic Nuclear Installations" or BNIs. Nuclear reactors are among these. Public health and safety, and protection of nature and the environment mentioned above, are called "protected interests".

Figure 4-5 shows an overview of the legislative framework in France.



* Ordinances, bearing similar power to laws, can also be issued by the government after review by Parliament.
** Circulars can also be published by ministerial departments.

Figure 4-5 Overview of the Legislative Framework in France

The conventions linked to nuclear safety ratified and published by France notably include the *Euratom Treaty*, signed by France in Rome on 25 March 1957, the *Convention on Third-Party Liability in the Field of Nuclear Energy* (1960 Paris Convention), the *Convention on Nuclear Safety*, the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, the *Convention on Early Notification of a Nuclear Accident*, the *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, the *Espoo Convention on Environmental Impact Assessment in a Transboundary Context*, and the *Convention on Access to Information, Public Participation in Decision-Making the Process and Access to Environmental Justice*.

The technical regulations, safety rules, and industrial codes are as follows:

- The updated general technical regulations for BNIs incorporate the "safety reference levels" and the safety goals and positions for new NPP designs drawn up by the Western European Nuclear Regulators Association (WENRA). The *INB Decree* (or *BNI Order*) defines the general rules for the design, construction, operation, closure and decommissioning of BNIs, as well as for the final shutdown, maintenance and monitoring of radioactive waste storage facilities. In particular, it incorporates into French law rules corresponding to international best practices.
- Technical regulations issued by ASN. The ASN can issue regulations to clarify the decrees and orders issued relating to nuclear safety and radiation protection. The technical regulations are consistent with those of the other European countries as they include the WENRA "reference levels". These regulations take account of the lessons learned from operation of the installations.
- Basic safety rules and guides. The ASN has drawn up fundamental safety rules (RFS, *Règles Fondamentales de Sûreté*) and guides on various technical subjects, with recommendations that specify the safety objectives and describe the practices that the ASN considers satisfactory for ensuring compliance with them. The guides take account of the safety requirements for reactor design taken from the publications of the IAEA and the reference levels, safety objectives or recommendations published by WENRA.
- French nuclear industry professional codes and standards. The nuclear industry produces detailed rules dealing with the state of the

art and industrial practices, which are compiled in industrial codes. These rules enable the requirements of general technical regulations to be transposed into concrete terms, while reflecting best industrial practices. They thus facilitate contractual relations between customers and suppliers. The industrial codes are published by AFCEN, the French association of design, construction and in-service monitoring codes, which brings together 60 French and international industrial companies, including EDF, Framatome and CEA.

(4) Safety culture under a continuous safety improvement framework

At the highest level of EDF, the priority given to safety is enshrined in a Safety Policy signed by its chairman. This policy sets the requirements and principles to ensure that all decisions taken at all levels of the company, priority is given to protection of interests, above all by preventing accidents and mitigating their consequences in respect of nuclear safety.

This policy, which has been inspired by international guidelines and safety requirements, aims to reaffirm the priority given to safety within the Group and to help each manager clearly embody this, including the involvement of industrial partners.

The responsibility for implementing this policy lies with the corresponding management line in each professional entity that deals with nuclear issues. It reaffirms the priority given to safety, to allow the sustainable use of nuclear energy, with strong commitments in terms of behaviour and safety culture, the search for continuous improvement, openness to international best practices, preparedness for emergency situations, transparency, and dialogue. This policy is disseminated to each member of staff and to each contractor and subcontractor.

International Peer Reviews

EDF regularly hosts and participates in international reviews, particularly under the auspices of the IAEA, the EC and WANO. They include:

- *IAEA's OSART missions*. The entire French nuclear fleet has already undergone at least one OSART mission. The recommendations are taken into account in EDF's action plans.
- *European Topical Peer Review (TPR)*. Council Directive *2014/87/Euratom* of 8 July 2014 amending Directive *2009/71/Euratom* established a community framework for the safety of nuclear installations and instituted a six-yearly peer review of a technical aspect relating to the safety of nuclear facilities. The first peer review focused on ageing management. The next European TPR to be held in 2024 will focus on fire protection.
- *WANO reviews*. The mission of WANO is to maximise the safety and reliability of NPPs worldwide by working together to assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practices. The safety performance of the NPPs in the French fleet is assessed by WANO peer reviews. Each NPP undergoes a review every four years.

Continuous improvement is promoted and organised, drawing on all the skills within the Group and those of international organisations with nuclear safety experience. Operating experience feedback is collected, analysed, and presented to the appropriate decision-making level and integrated.

The Group's nuclear licensees regularly receive international assessments, in particular the OSART and IAEA missions dealing with the topic "leadership and management for safety". Additionally, WANO, on average, conducts four peer reviews per year on the in-service fleet. The recommendations from these assessments are incorporated in the sites' improvement plans.

EDF reinforces safety culture, notably in each NPP, by developing safety leadership and a corresponding "Safety Culture" roadmap. In order to reinforce safety leadership, a Nuclear Safety Culture Perception Questionnaire (SPQ), now aligned with the WANO nuclear safety culture traits, is conducted every two years, alternating with a self-assessment regarding safety management practices. These results and feedback can be considered together with any "whistle-blower" alerts from staff and used as a whole to enable debate in the management and worker collectives.

Multi-year safety culture roadmaps consist of different types of improvement actions in response to the NPP/divisional diagnostics, covering training, the use of safety management levers and practices (risk assessment, enhanced human performance practices, inspection/monitoring, etc.), as well as the timetables set for sharing and debate within the teams.

EDF devotes considerable efforts to guaranteeing the competence levels of staff, by adopting a forward planning of employment and skills (GPEC) approach, based on harmonised principles, notably for all the NPPs, built up gradually from actual feedback from the field. EDF has also put in place a system of pre-qualification of external contractors who perform a large proportion of maintenance operations on the French nuclear fleet.

(5) International harmonisation and standardisation

For decades EDF has been directly involved in interaction with international organisations whose activities contribute to international harmonisation and standardisation. They notably include the IAEA, the OECD/NEA, the WENRA, the EC, the European Atomic Energy Community, and the European Utility Requirements (EUR).

A major goal of the international harmonisation and standardisation activities is to enable the replication of standardised designs worldwide. The route to success implies:

- A clear direction from governments and associated commitments, with long-term views.
- Strong cooperation between regulators.
- The need to develop regulatory capabilities to accept different ways of implementing harmonised safety requirements. These capabilities should result from changes in assessment approaches, for example:
    - Enable the recognition of equivalences between different codes & standards, and between different relevant good practices (including key features of safety analysis methodologies).
    - Propose methods to facilitate the reconciliation of requirements and the granting of equivalence.
    - Appropriately embed risk-informed approaches, for example,

including the means to evaluate the safety benefits of design simplification.

- Designers with high-level competencies in nuclear safety and sound knowledge of regulatory and operators' expectations.
- The nuclear industry sector to efficiently develop towards the goal of a high level of standardisation, including a strong and diversified supply chain.

(6) Nuclear risk prevention and management

Although the probability of a nuclear accident is extremely low thanks to the many measures taken at the design stage and throughout the lifespan of the nuclear plants, EDF and the public authorities have jointly set up a major organisation to protect people and the environment in any eventuality. They have drawn up two closely coordinated emergency plans for deployment in the event of a nuclear emergency. To ensure maximum effectiveness, these plans clearly set out the roles and responsibilities.

The Internal Emergency Plan (PUI, Plan d'Urgence Interne) covers the actions to be taken onsite: The station director is responsible for its implementation, under the oversight of the ASN. Under the plan, on-call personnel are mobilised to bring the facility back to a safe state and to minimise the impact on people and assets. The plan provides for treatment of casualties, if needed.

The Offsite Emergency Plan (PPI, Plan Particulier d'Intervention) covers all the measures deployed externally to protect the public and monitor the environment if there is a confirmed risk of radioactive discharges. It is activated by the Prefect of the department in which the plant is located. Depending on the nature of the event and how it develops, the Prefect, on the advice of the ASN, may decide to take early action and roll out three types of protection measures: an instruction to take shelter, to take iodine tablets, and/or to evacuate the area. These decisions affect a defined area around the power plant and depend on the severity of the event. In all circumstances, the authorities keep the public continuously informed of the situation.

The activation of these safety plans also entails the mobilisation of the national crisis organisation.

(7) Improvement of nuclear safety twelve years after Fukushima

The analysis conducted by EDF following the Fukushima nuclear accident demonstrated robustness of the existing arrangements for emergency response management and worker protection. However, the Fukushima nuclear accident underlined the need to thoroughly assess the risks associated with natural hazards, particularly climatic events, flooding and earthquakes, and to provide protection with significant margins to take account of the uncertainties, which affect the knowledge of this type of phenomenon.

EDF has therefore launched an extensive action and development plan to improve risk prevention in emergency response management, thus factoring in the lessons to be learned from the accident. This action plan focuses on organisational arrangements internal to EDF or related to the public authorities and is based on robustness of existing equipment, a new emergency response management centre, the setting up of a nuclear rapid reaction force (Force d’Action Rapide Nucléaire) and research actions.

The nuclear rapid reaction force (FARN, Force d'Action Rapide Nucléaire) and the deployable back-up equipment (DBUE)

The FARN and the DBUE ensure the resilience of the organisations by providing sites with mobile units, which can restore nuclear safety functions autonomously, in all circumstances.

The nuclear rapid reaction force is designed to rescue any French NPP, with all its reactors, in less than 24 hours, in all circumstances including earthquake, external or internal flooding, and storm. In these situations, the FARN acts to resupply the plant with water, compressed air and electricity, so as to maintain minimum safety functions and avoid any release into the environment. The FARN has around 300 team members spread over four regional bases. Each base has its own equipment including trucks, cranes, barges, generators, compressors, and pumps, and can use helicopters.

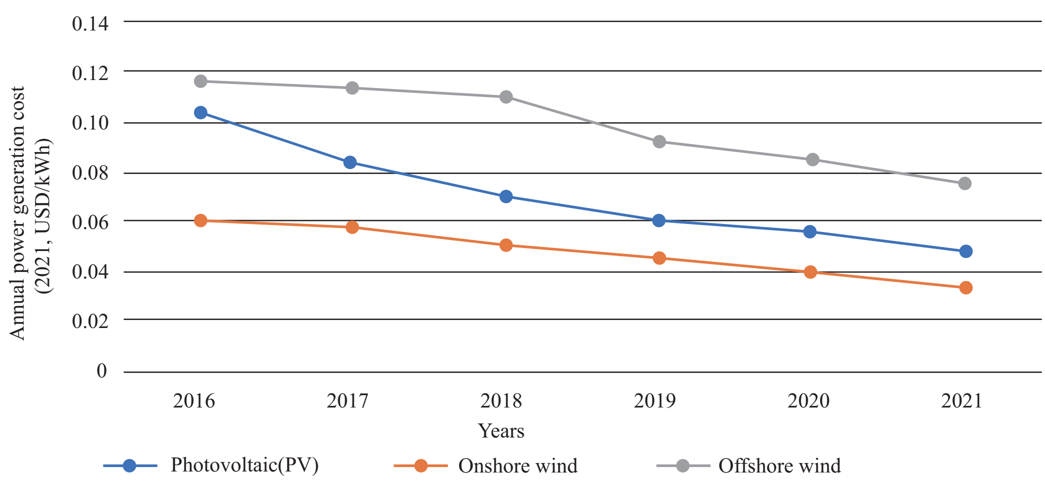
Provisions designed for very severe hazards strengthen the defence in depth when faced with the risk of a total loss of heat sink and power supplies (off-site and internal). At all French sites, the ultimate diesel generators and an additional emergency water source are operational, providing at least three days of complete autonomy in water and electricity.

4.2. Economics

To enhance its competitiveness while also ensuring the reliable and efficient delivery of clean electricity, China has focused on implementing effective cost-control measures in nuclear power construction.

4.2.1. Cost Control

According to the *Renewable Power Generation Costs in 2021* released by IRENA, the cost of renewable energy has continued to decline. In 2021, the global weighted average LCOE for onshore wind, offshore wind, and solar PV projects decreased by 15%, 13%, and 13% year-on-year, respectively (see Figure 4-6). Although the current cost of NPPs remains acceptable, the decreasing cost of renewable energy poses considerable challenges for nuclear energy development in terms of scale and cost.



(Source: IRENA)

Figure 4-6 Changes in Annual Power Generation Costs from Different Sources

Chinese Practice

(1) Adhering to design optimisation to control investment cost

Design optimisation plays a crucial role in enhancing the economic viability of NPPs. Over the past few years, China has been actively engaged in refining the design of its reactors (including HPR1000) to achieve improved economic performance. Table 4-2 shows the measures China has taken to optimise the design of HPR1000 reactors.

Table 4-2 Design Improvements for HPR1000

Design improvements	①	Increaing unit capacity by 3.5% higher than the demonstration project which has led to a significant reduction in unit investment cost
	②	Extending the refueling cycle to 18 months, which increases the design burnup of fuel assemblies
	③	Increasing resistance to aircraft impact
	④	Improving the seismic safety design based on plant site conditions
	⑤	Improving the safety design for severe accidents
	⑥	Optimising nuclear island layout
	⑦	Modular design

(2) Creating new models of management to enhance the efficiency of project management

Building on historical experiences in nuclear projects, China has developed a new and refined project management model to ensure high-quality project construction (see Table 4-3).

Table 4-3 Improvements in Project Management for HPR1000

Improvements in project management	①	Leveraging advanced information technology in project management to facilitate data and knowledge sharing; making concerted efforts to tackle challenges in 3D model design and construction techniques, aimed at design-construction integration; and optimising project schedules and costs
	②	Increasing centralised procurement efforts, particularly for bulk construction materials; and optimising material inventory based on consumption
	③	Establishing a TOP10 risk management mechanism, which prioritises the prevention of major risks that may occur during construction
	④	"1+N" centralised procurement of equipment with a long manufacturing period to ensure the construction progress is under control
	⑤	Establishing an efficient knowledge management system; conducting timely post-project reviews; and summarising project implementation experiences

(3) Promoting large-scale standard construction and strengthening refined management

A standard system was established during the construction of HPR1000. This system optimises the general layout, ensures sequential execution of construction activities, and centralises procurement processes (see Table 4-4). These endeavours have effectively reduced the construction cost.

Table 4-4 Large-Scale, Standard Construction and Refined Management for HPR1000

Large-scale, standard construction, and refined management	①	Constructing HPR1000 rectors on a large scale; and implementing a “learning by doing” approach and experience review
	②	Conducting research on HPR1000 to establish a comprehensive technical standard system and standard products
	③	Optimising staffing; and optimising positions and job responsibilities on fuel production lines to reduce overall staff costs
	④	Promoting industry-university-research institute cooperative; optimising production processes; configuring equipment rationally; intensifying operational training; and sharing best practices to improve the yield rate of fuel assemblies
	⑤	Accelerating localisation of core materials; promoting production expansion by upstream enterprises; and continuously optimising fuel assembly costs

(4) Improving operational and management to reduce O&M costs

To bolster the economic competiveness of nuclear power, China is dedicated to operating nuclear power units in strict adherence to high safety standards. This will ensure the stable operation of the NPPs with a larger number of utilisation hours while also effectively reducing O&M costs (see Table 4-5).

Table 4-5 Operational Management Improvements and Cost Reduction Measures for HPR1000

Operational management improvements and cost reduction measures	①	Promoting the construction of "digital NPPs" by integrating intelligent technologies across operation, maintenance, technical support, supply chain, safety management, and training
	②	Optimising overhaul activities to reduce both the duration and cost of overhauls without compromising safety and quality
	③	Standardising operational management processes by establishing technical documentation systems to improve operational management
	④	Establishing a spare parts management system consisting of strategic spare parts, spare parts for preventive maintenance based on equipment classification, and minimum reserves to control material surpluses

4.2.2. Policy guidance for the nuclear power market

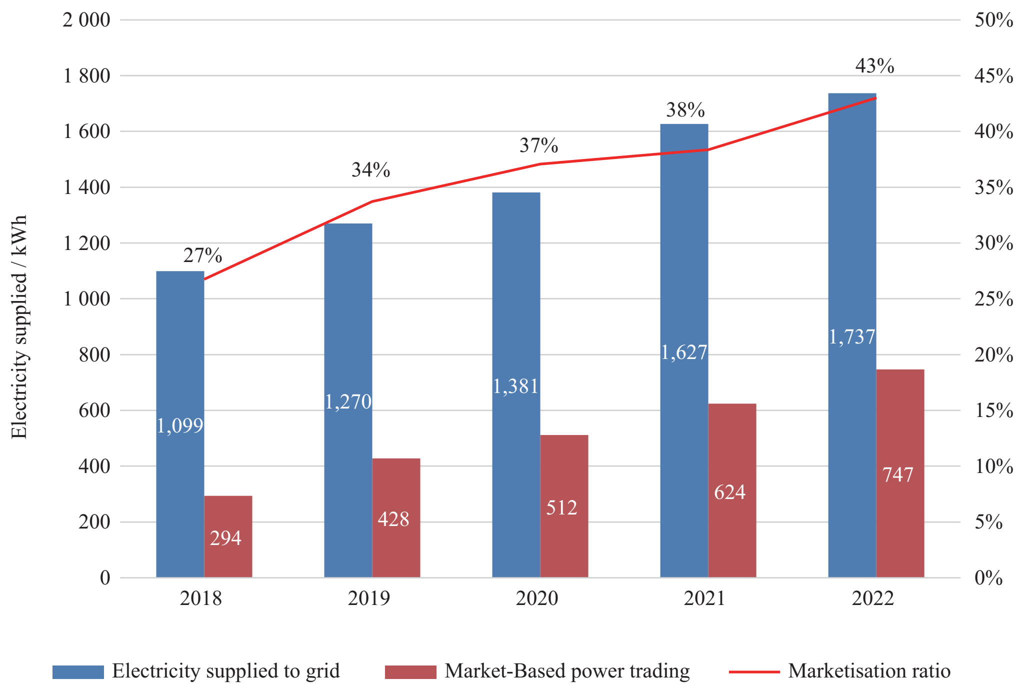
Chinese Practice

(1) Market-oriented reform of the power system

China has been actively promoting market-oriented reform in the power sector since 2002. The issuance of the *Opinions on Further Deepening the Reform of the Electric Power System* in 2015 marked the initiation of a new phase of electric system reform. In 2022, China furthered these efforts by releasing the *Guiding Opinions on Accelerating the Construction of a National Unified Power Market*. Covering the spot and long-term market, a full range of reform measures have been implemented. China has witnessed a rapid influx of participating entities. Shaping a competitive landscape with diverse types of market entities, China has currently established an electricity market where regulatory and deregulatory mechanisms coexist.

(2) Continued growth in market-based nuclear power trading

In recent years, the electricity market has undergone significant transformations characterised by a gradual increase in market-based



(Source: CNNC)

Figure 4-7 Portion of Nuclear Power in Market-Based Power Trading

power trading and competition between nuclear energy and other sources. The share of nuclear power in market-based power trading has steadily risen from 27% in 2018 to 43% in 2022 (see Figure 4-7). As China continues to integrate more industrial and commercial consumers into the power market, the demand for power trading is expected to rise significantly. Consequently, the supply side needs to expand to meet this burgeoning demand. It is anticipated that China will experience an increase in nuclear power trading in the future.

French Practice

(1) A strong need for investments

To remain on track with the *Paris Agreement*, most countries need to convert entirely their energy system to stop emissions of greenhouse gases. This evolution relies on a massive electrification of uses, whether direct or indirect, investments in mature low-carbon technologies and the development of new technologies that are currently at the demonstration or prototype phase.

The IEA assessed in its 2022 report the global investment needs in the power sector, showing that the current annual pace must at least double in the next decade. That means additional 800 billion USD per year globally within 10 years, including 150 billion USD for grids. Meanwhile, investments on the customers' side should grow even faster: more than doubling for energy efficiency and more than quadruple for end-use investments, such as electric vehicles, as our economies electrify.

This alone would represent a big challenge for the international community. However, an additional difficulty lies in the inherent characteristics of mature low-carbon generation technologies (renewables, nuclear, hydro): They are much more capital-intensive than fossil fuel-based technologies and they have little to none variable costs.

These two combined characteristics can endanger the financial structure of the projects and, if not rightfully handed, prevent the transition.

(2) New tools are necessary to trigger investments

Prices in the competitive short-term markets are equal to the variable cost of the marginal plant. In scarcity hours, prices can reach extreme values, revealing the Value of Lost Load, when for example rolling blackouts occur.

A recent study[1] shows at scale what could be the impact of massive decarbonisation on market prices:

The price duration curve for 2020 is extremely flat, which means there is a very limited price volatility derived from the structure of the mix. The price volatility currently observed in Europe is massively imported from the volatility of fossil fuel prices. In 2050, the share of intermittent renewable energies will increase up to 50%-70% depending on the future energy mix. As a consequence, the electricity price will strongly depend on the climate conditions and will be increasingly volatile.

On the one hand, this price volatility has an impact on the extension of existing units and the development of new units. On the other hand, customers want to pay relatively stable prices over the long term. This volatility increases financial risks. Therefore, investors need other mechanisms to secure their revenue schemes to develop new units or extend the lifetime of existing units that are needed to ensure the security of supply. This is already the case in the EU, where only a quarter of new installed capacity in the last decade did not require additional support.

(3) Long-term visibility is required

This example of EU’s electric market shows that even if short-term wholesale market ensures optimal dispatch and an optimal use of transmission networks within Europe, new tools such as long-term

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1 OECD/NEA report: *Market design for financing capital intensive low carbon technologies*, www.oecd-nea.org/jcms/pl_53049/market-design-for-financing-capital-intensive-low-carbon-technologies, 2023.

Power Purchase Agreements (PPAs) or Contracts for Difference (CfDs) are necessary to provide price signals to incentivise long-term investments. This emphasises the need of long-term visibility.[2]

In the US, Joskow examined the current shifts in the energy context and drew a clear conclusion in favour of a move towards hybrid markets with long-term contracts.[3]

	Context of the 1990s and early 2000s	Context
Policy	Focus on competiton and market integration	Focus on decarbonisation requires step up in investments
Market	Focus on day ahead wholesale market integration	Focus on intraday and real time markets to manage VRE growth
Technology	Dominance of technologies with variable costs ("dash for gas")	Dominance of fixed costs (CAPEX) / decentralised technologies
Consumers	Passive (no decentralised generation: storage, DSR)	Active demand participation, rise of prosumers
Networks	Focus on optimal use of existing infrastructure	Need to reinvest to upgrade grid to decentralised gen. & VRE growth

Figure 4-8 Long-Term Contracts and Commitments Well Fitted for a Major Shift in Context[4]

Such long-term contracts would share risks between new stakeholders and minor the economic cost of risk. The IEA shows[5] that long-term contracts could reduce by half the cost of capital for PV projects compared to a remuneration at market prices.

This result holds for all other technologies, a report[6] shows that the infrastructure-type remuneration scheme (Regulated Asset Base model,

[2] UK BEIS, 2022.

[3] Joskow, 2019.

[4] Keppler, I.-H., Quemin, S., & Saguan, M. (2022).

[5] IEA, November 2019.

[6] Newbery et al., 2019.

largely used to finance electricity or water networks) could also reduce the cost of capital of new nuclear projects by a factor of two, hence half reducing the levelised cost of the produced kWh.

It ensures an energy transition that is massively cheaper and therefore better for the consumer, leaving countries to choose their electricity mix (production, flexibilities, uses, hybridisation) to ensure decarbonisation objectives are met at the lowest cost and in a timely way, while enhancing security of supply.

4.3. Public Acceptance

Public acceptance plays a key role in the development of nuclear energy. This is a complex matter encompassing not only considerations of nuclear and radiation safety but also addressing the interests and conflicts of various stakeholders. It could also be influenced by political and cultural factors. Gaining positive outcomes and valuable experiences, China and France have conducted extensive explorations in terms of public acceptance of nuclear energy.

Chinese Practice

China is committed to improving the public acceptance of nuclear energy and has invested substantial efforts towards achieving this goal. Specifically, it encourages public participation during the planning phase of NPPs. Before a decision is made, extensive efforts are made to gather public opinion through public announcements, questionnaires, hearings, seminars, and feasibility study meetings.

(1) A well-established legal and regulatory framework guarantees improved public acceptance of nuclear energy.

The *Nuclear Safety Law of the People's Republic of China*, serving as the nation's comprehensive legislation on nuclear safety, imposes stipulations on nuclear information disclosure and public participation. Furthermore, China has established robust laws and regulations regarding nuclear knowledge dissemination, public participation, public opinion response, and public communication.

Laws and regulations on nuclear knowledge dissemination. These include the *Law of the People's Republic of China on Popularization of Science and Technology*, the *Law of the People's Republic of China on Prevention and Control of Radioactive Pollution*, the *Notice of the General Office of the State Council on Issuing the Overall Implementation Plan for Science Popularization of Emergency Management*, and the *Opinions on Further Strengthening the Popularization of Environmental Protection Science and Technology*. In particular, the *Law of the People's Republic of China on Prevention and Control of Radioactive Pollution* mandates that "governments at or above the county level must organise targeted publicity and education to keep the public informed of the latest developments and relevant knowledge about radioactive pollution prevention and control". The *Law of the People's Republic of China on Popularization of Science and Technology* establishes the code of conduct for organisations and individuals engaging in science popularisation.

Laws and regulations on public participation. These include the *Law of the People's Republic of China on Environmental Impact Appraisal*; the *Measures for Public Participation in Environmental Protection*; and the *Interim Measures for Public Participation in Environmental Impact Assessment*. For instance, the *Law of the People's Republic of China on Environmental*

Impact Appraisal mandates that "the planning authority, when drafting plans, actively seek public opinions on projects that may have adverse environmental impacts and directly affect the public's environmental rights and interests". Additionally, the law stipulates: "Unless otherwise specified by national regulations for confidentiality purposes, public opinions must be solicited for projects that may have significant environmental impacts to the extent that an environmental impact assessment report must be prepared."

Laws and regulations on public opinion response and public communication. These include the 2017-amended *Regulations on Environmental Protection Management of Construction Projects* (a supplement to the *Law of the People's Republic of China on Environmental Impact Appraisal*), the *Regulations on Environmental Impact Assessment of Construction and Development Plans*, the *Guidelines for Public Communication in Nuclear Technology Utilisation Projects (Trial)*, the *Plan for Nuclear and Radiation Safety Regulation Information Disclosure (Trial)*, and the *Notice on Strengthening Nuclear and Radiation Safety Information Disclosure of Nuclear Power Plants*. Article 9 of the first item in the list above mandates that "administrative authorities for environmental protection must make the registration and approval of environmental impact assessment reports available online for information disclosure purposes", and Article 17 mandates that "project owners must publicly disclose their project acceptance reports in accordance with the relevant laws, unless otherwise specified by national regulations for confidentiality purposes". Article 4 of the *Regulations on Environmental Impact Assessment of Construction and Development Plans* specifies that "the government must establish information sharing systems for environmental impact assessments of various construction and development plans and governments at or above the county level and their relevant departments must implement information sharing for the data necessary for environmental impact assessments", and Article 13 outlines specific measures for public communication regarding plans that may have adverse environmental impacts and directly affect the public's environmental rights and interests.

(2) Seeking new ways to disseminate nuclear knowledge

China attaches great importance to nuclear knowledge dissemination and actively explores innovative approaches to enhance communication and engagement with the public. Various forms of science popularisation materials, including brochures, books, posters, animations, courseware, and webpages, have been developed to achieve this. Furthermore, a wide array of interactive activities has been launched to provide the public with immersive and participatory experiences. These activities include but are not limited to lectures, visits to nuclear science and technology museums, science popularisation activities in schools and communities, cultural and sports activities, science galas, and public open days.

(3) Enhancing information transparency and public communication

To demonstrate its commitment to information transparency, China has promulgated the *Regulations on Nuclear Safety Information Disclosure*. The Regulations specify that NPP operators must establish nuclear safety information disclosure systems. This includes defining the department responsible for disclosure, specifying the extent of disclosure, and establishing the procedures and channels for information disclosure.

The MEE/NNSA is responsible for disclosing government

information about nuclear safety. In addition to information disclosure, the MEE/NNSA also oversees civil nuclear facility operators' disclosure activities.

Enhancing transparency through diverse channels. To disseminate information related to nuclear projects and provide updates on the construction and operation of nuclear power units, China employs a diverse range of channels including central and local government websites, disclosure platforms for NPPs' operation data, and nuclear and radiation information, and environmental monitoring data release platforms.

(4) Managing and responding to public opinions

Leading to a substantial improvement in public acceptance of nuclear energy, China has established sound mechanisms for managing and responding to public opinions including both a multitude of systems (for public opinion reporting; for spokespersons, liaison officers, and internet commentators; for daily reporting and routine communication; for liaising with ministries, commissions, and local governments) and a toolkit incorporating public opinion response plans with various communication channels.

French Practice

(1) Dialogue and consultation are the priority

Dialogue and consultation are at the heart of EDF's social responsibility. EDF Group is in continuous contact with the stakeholders in the areas where its facilities are located. This dialogue is enriched by the EDF's commitments in the context of its corporate responsibility, with ambitious objectives on six key themes from the UN's SDGs: climate, human development, precariousness, energy efficiency, dialogue, and biodiversity.

For each new project EDF is committed to organising a transparent and constructive dialogue and consultation process with stakeholders. This commitment includes training employees and project managers in the importance of dialogue and consultation.

In 2021, EDF set up a Stakeholder Council made up of 13 leading representatives of civil society. This council's mission is to inform the stakeholders of EDF's decisions in terms of sustainable development and corporate social responsibility. Its members include environment and climate experts, academics, solidarity advocates, student representatives, consumers, and economists.

The creation authorisation for a BNI is subject to a public debate procedure when it involves a new nuclear power production site. The public debate focuses on the appropriateness, the objectives and the characteristics of the project. Moreover, the BNI creation authorisation and then the BNI decommissioning decree are granted following a public inquiry.

EDF's policy aims to ensure that dialogue and transparency result from clear and accurate information about events and their potential impacts. This policy of dialogue and transparency is sought and maintained with the staff and their representatives, the subcontractors, the oversight bodies, the local communities, especially the Local Information Commissions (CLIs) created for any site with nuclear installations, tasked with a general duty of informing the public on nuclear safety, radiation protection and impact on people and the environment, and all other nuclear safety stakeholders.

For example, these transparency and communication actions take a variety of forms: annual report, CLI meetings and thematic visits, meetings with elected officials, press releases, monthly newsletters, public information centre, website (www.edf.com), toll-free telephone number, and answers to public queries about the safety, radiation protection and environmental protection measures taken.

In particular, the report required by Article L.125-15 of the *Environment Code* for each NPP describes the steps taken concerning nuclear safety and radiation protection against incidents and accidents, the nature and results of radioactive and non-radioactive environmental discharge measurements, and the nature and quantity of radioactive waste stored on the facility site. This report is made public and transmitted to the CLI set up for each NPP.

(2) EDF has many experiences of public consultation

The consultation process on new nuclear constructions aims to involve the public at every stage of the projects, as the participatory process is an essential part of an industrial project. For each construction project, the participatory process is an ongoing one:

- It starts with the preliminary dialogues in the design and preparation phase.
- It goes through the regulatory consultation prior to the project owner's application for administrative authorisations, and then through the public inquiry as part of the administrative examination of such applications.
- It continues through regular dialogue during the construction phase, the operating phase and until the end of the dismantling of each installation.
- The sites where new nuclear reactors are to be built already have

their own dialogue body: the CLIs, whose mission is to monitor nuclear installations and inform and consult with the population.

CLIs (Commissions Locales d'Information)

CLIs were set up in the 1980s around most nuclear installations. A 2006 law on transparency and security in the nuclear field, known as the TSN (*Transparence et Sécurité en matière Nucléaire*) law, reinforced their existence by giving them legislative status. It provided for the creation of a CLI at each BNI.

A CLI can be common to several nearby facilities. The law defines the mission of the CLIs as a general mission of monitoring, information and consultation in terms of nuclear safety, radiation protection and the impact of nuclear activities on people and the environment with regard to the site installations.

The CLI provides information that is as objective and intelligible as possible, so as to best communicate it to the local population. It brings together members of civil society and institutional members, who are not necessarily specialists in the nuclear field except for qualified scientists. Thus composed, the CLI plays an interface role between the NPPs and the public. The CLI is also a forum for constructive debate between the operator and the members of the commission.

Regulatory consultation, for which each construction project is eligible, is governed by the rules specific to major land use projects. Once the contracting authority has submitted a request, it is up to the National Public Debate Committee (CNDP), in its role as the authority in the matter, to decide on the form of this regulatory consultation.

The CNDP (Commission Nationale du Débat Public)

The CNDP is the independent administrative authority that guarantees the right of every person in France to information and participation on projects and policies that have an impact on the environment. This right is enshrined in Article 7 of the *Environmental Charter*.

This public right to debate also makes it possible to improve the decisions of project or policy makers by informing them of the public's values, expectations, and questions. The CNDP must be consulted on the basis of the criteria and characteristics of projects defined in the *Environmental Code*.

Since the creation of the public debate procedure in 1995, most BNI projects have involved a public debate supervised by the CNDP. This was notably the case for the construction of the first EPR in France at the Flamanville site in 2005-2006, at Penly in 2010 for the construction of a second EPR in France, and at Penly in 2022-2023.

The High Committee for Transparency and Information on Nuclear Security (HCTISN, Haut comité pour la transparence et l'information sur la sécurité nucléaire)

Created by the 2006 law on transparency and security in the nuclear field, the High Committee is an independent and pluralist body where the players sit with the mission of guaranteeing and promoting transparency and information regarding nuclear security. The HCTISN is the cornerstone of transparency to the public in nuclear safety matters.

A pluralist body, the HCTISN is made up of all the players in the nuclear world, in all its diversity – operators of nuclear installations, the ASN, the Institute for Radiation Protection and Nuclear Safety (IRSN), State services, CLIs, associations, trade unions, parliamentarians and qualified individuals. In the HCTISN, all these actors share information, question each other, debate in a contradictory manner, and identify what is missing in terms of transparency and what needs to be improved.

The missions of the HCTISN are:

- Making information on nuclear safety available to the public;
- Proposing measures to guarantee or improve transparency;
- Issuing opinions and recommendations to public authorities and operators;
- Designing consultations and debates with the public to ensure that nuclear safety issues are discussed beyond expert circles;
- Commissioning expert reports necessary for the accomplishment of its missions and organising debates.

EDF takes part in the work of the HCTISN. Any question regarding information about nuclear safety and its regulation oversight can be referred to the HCTISN by the competent authorities, by the chairpersons of the CLIs or by the licensees. In addition, EDF informs the public of any significant events occurring in its facilities, by publishing them on the website of the NPP, or in its external newsletters.

(3) 2022-2023: A new public debate on the nuclear programme proposed by EDF

- In response to the joint referral from EDF and RTE on the "Project for the first pair of EPR2 reactors on the Penly site (Normandy), as part of the planned programme of new nuclear reactors in France", dated 14 February 2021, the CNDP decided to set a new public debate.

- The debate was held from 27 October 2022 to 27 February 2023, with a wide range of discussion forums, including public meetings and online contributions. They related to a local dimension (regarding the Penly project) and to a national dimension (regarding the national industrial programme proposed).

For EDF, these consultation sessions are essential to meet with the public and discuss the project for the construction of each pair of reactors:

- On the one hand, consultation and dialogue are a fundamental objective of EDF's corporate responsibility; they constitute a major and high-priority commitment.
- On the other hand, as nuclear energy is the main source of electricity production in France and is regularly debated, a major challenge of the participatory process is to give full scope to exchanges. It must also give the greatest possible number of citizens access to participation in the debate: EDF considers that the participation of younger citizens is particularly important, insofar as they are the most concerned by a nuclear construction programme from which their generation will be the main beneficiaries.

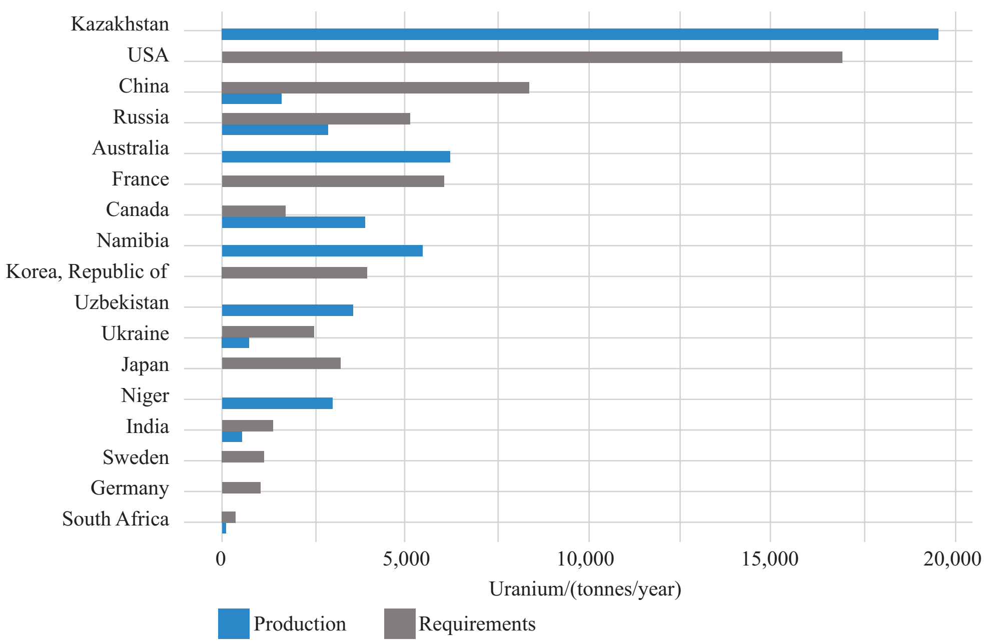
Alongside this public debate, the French government has organised a consultation on energy policy and the electricity mix of the future, which will also provide input for future decisions.

4.4. Supply Chain Security

China and France are among the few countries in the world with a complete nuclear energy industry chain, encompassing the entire nuclear fuel cycle, from uranium mining and milling to fuel processing, nuclear engineering design, construction, and equipment manufacturing.

4.4.1. Uranium supplies

As of the end of 2022, the major uranium-producing nations included Australia, Canada, Kazakhstan, and Namibia, and the leading consumers included China, France, Russia, and the United States (see Figure 4-9).



(Source: *Uranium 2022: Resources, Production and Demand*)

Figure 4-9 Uranium Production and Reactor-related Requirements for Major Producing and Consuming Countries

Chinese Practice

China attaches great importance to ensuring the security of its uranium supply and has undertaken substantial efforts to advance the sustainable and large-scale development of nuclear energy, with remarkable progress achieved.

(1) Establishing a sound policy system for uranium development

The Chinese government attaches great importance to the stable supply of uranium, with a specific focus on supply security, economics, and supplier diversification. To ensure the reliability of uranium supply and maintain moderate reserves for nuclear energy development, China has implemented various measures. These include consistent investments in domestic uranium development, supporting investments and developments in overseas uranium resources, and capacity building for uranium products (see Figure 4-10).

(2) Establishing a four-pronged uranium supply system

To meet the demands of nuclear power development, China has placed significant emphasis on constructing a robust system with the capacity to ensure a stable uranium supply. After more than six decades of dedicated effort, China has successfully developed an efficient organisation (integrating scientific research, design, construction, and production) that strengthens its technological competitiveness in this field; and has established a four-pronged uranium supply system through domestic and overseas uranium mining, international uranium trading, and the maintaining of moderate reserves (see Figure 4-11). With this improved supply security system, China is well-positioned to adequately

2000
Catalogue of Industries, Products and Technology Encouraged by the State
- "VII. Nuclear Energy" included geological exploration for uranium deposits and advanced uranium mining and milling.

2001
Suggestions on the Implementation of Policies and Measures for Large-Scale Development of Western China
- Reducing (or waiving) royalties on uranium development exploration and mining rights.

2006
Medium- and Long-Term Development Plan for Nuclear Power (2005-2020)
- Establishing a three-pronged uranium supply system consisting of domestic production, overseas development and international uranium trading.

2008
Opinions on Strengthening Geological Exploration of Uranium Deposits
- Promoting comprehensive, coordinated, and sustainable development of geological exploration for uranium deposits, and improving uranium supply security to meet the needs of national defense and nuclear power development.

2009
National Mineral Resources Planning (2008-2015)
- Strengthening uranium deposit exploration and comprehensive exploration and evaluation of paragenetic and associated uranium deposits, with a focus on sandstone-type deposits in northern China, and hard rock-type deposits in southern China.

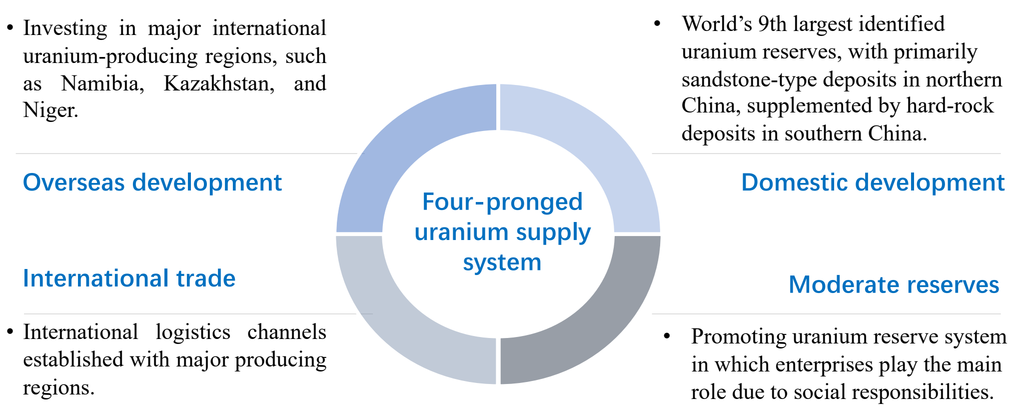
2016
Measures for the Administration of Special Funds for the Conservation and Comprehensive Utilisation of Mineral Resources
- Enhancing management to improve the use efficiency of funds dedicated to the conservation and comprehensive utilisation of mineral resources. Focusing on the comprehensive development and utilisation of paragenetic coal-uranium, boron-uranium, and molybdenum-uranium deposits, sandstone-type uranium deposits, hard rock-type uranium deposits, and paragenetic and associated rhenium resources.

2021
Outline of the 14th Five-Year Plan (2021-25) for National Economic and Social Development and Long-Range Objectives Through the Year 2035
- Improving conservation and comprehensive utilisation of mineral resources, promoting green exploration and construction of green mines, intensifying domestic mineral exploration, and enhancing energy and strategic mineral resource security.

2022
Report to the 20th National Congress of the Communist Party of China
- Developing nuclear power in an active, safe and orderly manner, strengthening energy production, supply storage, and marketing systems, and guaranteeing energy security.

(Source: CNNC)

Figure 4-10 Chinese Policies for Uranium Development meet both its present and future uranium requirements for the continued development of nuclear energy.



(Source: CNNC)

Figure 4-11 China's Four-Pronged Uranium Supply System

(3) Advancing uranium exploration, mining, and milling technologies

By continuously advancing uranium exploration, mining, and milling technologies, China has built up a comprehensive capacity for exploration and R&D. In addition to conventional mining techniques, China has also developed a number of advanced techniques such as heap leaching, blasting-based in-situ leaching, and in-situ leaching. Of these, the CO_2+O_2 in-situ leaching technique stands out as a green and efficient method for uranium mining that has successfully achieved industrial-scale application.

Important breakthroughs have been made in the research and development of uranium exploration technology. China has created a new theory of uranium exploration and made breakthroughs in uranium exploration.

New advances have been made in the efficient mining of complex uranium ores, comprehensive utilisation of polymetallic paragenesis ore deposits, and refined in-situ leaching techniques. These developments include "fast construction and fast mining" technologies for single kilotonne-level uranium mines, digital well construction technology, and the industrial application of the world's first high-flux uranium extraction equipment.

Uranium mines in China have undergone a digital transformation. China has already established its first basic database for uranium mine digitisation and a cloud platform dedicated to uranium mining and milling. Furthermore, China has independently developed and implemented an industry-wide digital uranium exploration system that ensures end-to-end digitisation across the entire uranium exploration process.

French Practice

In the short term, contrary to oil and gas prices, potential wholesale price spikes of imported natural uranium have insignificant impact on consumers' electricity bills. To illustrate that:

- Over the last 20 years, the average spot wholesale price for natural uranium was less than 50 USD/lb of U_3O_8, or around 130 USD/kg of natural uranium, which represents approximately 3 USD per MWh produced by nuclear power, since it takes around 25 g of natural uranium to produce 1 MWh of electricity. This represents roughly 2 USD per MWh consumed by the average customer in an electricity mix with about two-thirds coming from nuclear energy, as is the case in France. For the average electricity consumer over the long term, this cost represents between 1% and 2.5% of the average electricity bill in Europe (bills range from 300 USD per MWh for residential use to 80 USD per MWh for industrial use).

- Current wholesale prices for natural uranium are of the order of 90 USD/lb of U_3O_8, which represents around 230 USD/kg of natural uranium, or around 5.8 USD per MWh. If this relatively high level were to persist for a whole year, it would have an impact on less than 10% of the average supply of uranium, based mainly on long-term contracts, and therefore on less than 0.25% of the average electricity bill in Europe.

Even if this high uranium price level were to persist for a few years with an impact on the prices of long-term contracts, the impact would be around 1 to 2% of the average electricity bill.

In the medium term (a few years), existing storage of natural uranium in importing countries (including depleted uranium with lower U_{235} content) can guarantee supply for many years. Projections of the global supply/demand ratio carried out by EDF show that the mines currently in operation will be sufficient to cover global uranium requirements for another ten years, beyond which new capacity, already at the project or study stage, will have to be brought into operation. It should also be noted that secondary resources are also available (destocking, recycling of plutonium and/or uranium extracted from spent fuel, underfeeding and re-enrichment of tails), which account for 15% to 25% of global demand.

In the long term, France has, through Orano, a resource portfolio that represents more than 30 years of natural uranium consumption.[7]

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[7] French Society for Nuclear Energy (SFEN).

In the very long term, the Red Book, developed jointly by the IAEA and the OECD/NEA, identifies 8 million tonnes of uranium available worldwide, with current technical capabilities (and therefore still more taking into account future technical developments), or about 120 years of demand for the current global nuclear fleet (65 000 tU, based on the WNA Fuel Report 2023-2040).

4.4.2. Nuclear fuel processing

Nuclear fuel processing encompasses uranium conversion, enrichment, and fuel fabrication. At present, a reliable nuclear fuel supply system has been established worldwide, with ongoing advances in nuclear fuel technologies to enhance safety and economic efficiency. Both China and France have well-established scientific and industrial systems for nuclear fuel, providing an important guarantee for the processing and supply of nuclear fuel to satisfy domestic and international demand.

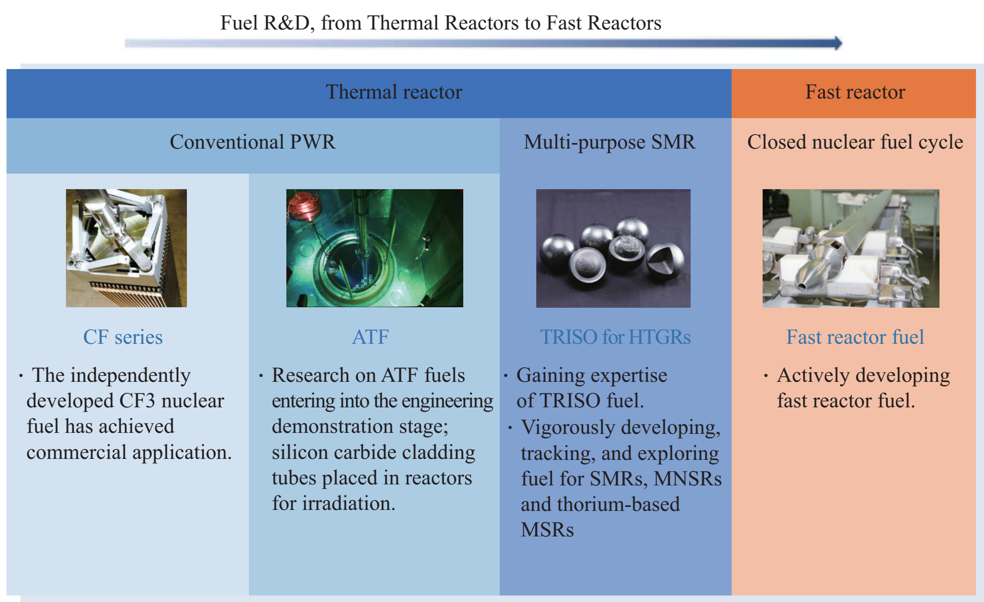
Chinese Practice

China is committed to technological innovation aimed at enhancing the economics and safety of fuel elements. Vigorous efforts have also been made to establish a nuclear fuel supply system that incorporates both domestic and international circulation to ensure its security of supply.

(1) Improving the safety and economics of nuclear fuel

Thermal reactor fuel. Promoting advanced technology and economics, China has focused on advancing the R&D and industrialisation of CF fuel, and independently developed a series for PWRs. As part of improving safety, China has also made strides in the development of ATF. Furthermore, China has not only acquired expertise in tristructural isotropic (TRISO) particle fuel for HTGRs, but is also studying fuel for SMRs, miniature neutron source reactors (MNSRs), and thorium-based molten salt reactors (MSRs).

Fast reactor fuel. China places significant emphasis on the closed nuclear fuel cycle and is actively driving efforts (in research, development, and production) focused on mixed oxide (MOX) fuel and metal fuel specifically designed for fast reactors. See Figure 4-12 for China’s pathway for nuclear fuel element technology development.



(Source: CNNC)

Figure 4-12 Pathway for Nuclear Fuel Element Technology Development

(2) Participation in the global nuclear fuel supply

China has consistently worked towards ensuring a secure and sustainable global nuclear fuel supply. To bolster the resilience and flexibility of the nuclear fuel supply, China actively participates in international procurement and export of nuclear fuel products and services. With a primary focus on domestic supply, and complemented by diverse sources, this approach has contributed to shaping an open nuclear fuel supply landscape. In the field of fuel fabrication, China has established long-standing and extensive cooperation with other countries such as France, the Republic of Korea, Russia and the United States. It engages in open exchanges with global participants in nuclear fuel, making contributions to fostering a fair and cooperative nuclear fuel market.

French Practice

The main focus of EDF's nuclear fuel procurement policy is security of supply, which is achieved through the following guidelines, applied at every stage of the fuel cycle:

- **Diversify as much as possible the supplier portfolio**, so as to be robust to all types of risk that may affect the actual availability of supply: technical (output performance lower than expected, major breakdown, etc.), financial (poor cashflow, insolvency, etc.), geopolitical (transport disruption, sanctions, etc.), climate-related (wildfires, hurricanes, etc.) and any other relevant risks.

For instance, EDF's policy specifies the limit level of exposure to a single facility, a single supplier, or a single country that must not be exceeded. Moreover, supplier diversification brings also commercial benefits through the competition it creates among suppliers.

- **Negotiate long-term contracts with primary producers** that own and operate their own facilities, which gives a more direct access to suppliers issues, allows a better assessment of the risks they are exposed to and helps build a deep, industrial and mutually beneficial partnership with suppliers.

For instance, EDF's policy specifies the level of future requirements that must be covered through long-term contracts in the next 3 years, 5 years, decade, etc. Moreover, building strong industrial relationships with suppliers gives access to more stable purchase prices and reduces exposure to market price volatility.

- **Build appropriate reserve stocks**, to be able to cope with a major supply disruption. A dedicated tool considers the probability of the different types of risk that may affect the production availability of each supplier of the portfolio to compute the amount of uranium (in all its sorts) needed in the reserve stock.

4.4.3. Nuclear engineering construction

Chinese Practice

(1) A strong nuclear engineering construction capacity

Since the construction of the Qinshan-1 NPP in 1985, China has been engaged in nuclear engineering construction for more than 38 consecutive years. Currently, CNNC has the capacity to simultaneously construct up to 40 units and has mastered the technologies for building prominent global reactor models (including M310, CNP, CP, CPR, HPR1000, AP, CAP, EPR, VVER, HTGR, and SFR). Furthermore, as part of maintaining its leading position in NPPs construction, it has proposed the idea of achieving a "shorter construction period, lower cost and better quality".

(2) A complete and reliable nuclear power equipment supply system

With manufacturing bases located across the country (in northeast China, Shanghai, and Sichuan), China has established a comprehensive supply chain for key nuclear power equipment. This has given rise to a growing number of supporting equipment and component manufacturers. The products and systems developed by these manufacturers have found successful applications in numerous projects (such as the HPR1000, CAP1400, ACP100, and the HTGR demonstration project). Notably, the world's first HPR1000 demonstration project possesses over 70,000 equipment sets supplied by 5,300 manufacturers. Many core components and systems (including reactor vessels, steam generators, reactor internals, control rod drive mechanisms, advanced core measurement systems, passive system equipment, fuel transfer devices, personnel gates, pit filters, equipment gates, mechanical and electrical penetrations, containment filtration and discharge systems, and spent fuel storage grids) are independently manufactured in China. As of now, China has developed a robust nuclear power equipment industry system capable of supporting the simultaneous construction of 10 to 12 units per year.

(3) Refined management

CNNC has developed the *Guidance for the Construction Management of Nuclear Power Projects Using HPR1000 Reactors During the 14th Five-Year Plan*

Period to serve as the top-level management framework for overseeing the extensive construction of HPR1000 reactors. With specific emphasis on "stringent control in six key areas and the aim of no failures across seven domains", this guidance underscores the implementation of refined management practices throughout the construction process. The overarching objective is to achieve full preparation and success on the first attempt, thereby enhancing both management efficiency and construction quality while ensuring NPPs featuring HPR1000 design are completed on schedule and within budget.

French Practice

The French nuclear industry brings together all the players involved in the production of electricity from nuclear technologies, located in France: international French industrial groups, public research organisations and a wide network of large, medium and small companies.[8]

(1) Sector overview and key figures

The French nuclear sector is organised around major companies. Most of the activity is carried out by around 500 companies, including around fifty large companies and large groups, and around 400 medium-sized companies, and a large number of medium, small and micro enterprises.

The nuclear sector is characterised by a long cycle, due both to the size of industrial and human investment required and to the lifespan of the facilities. It evolves in a context of permanent search of the highest

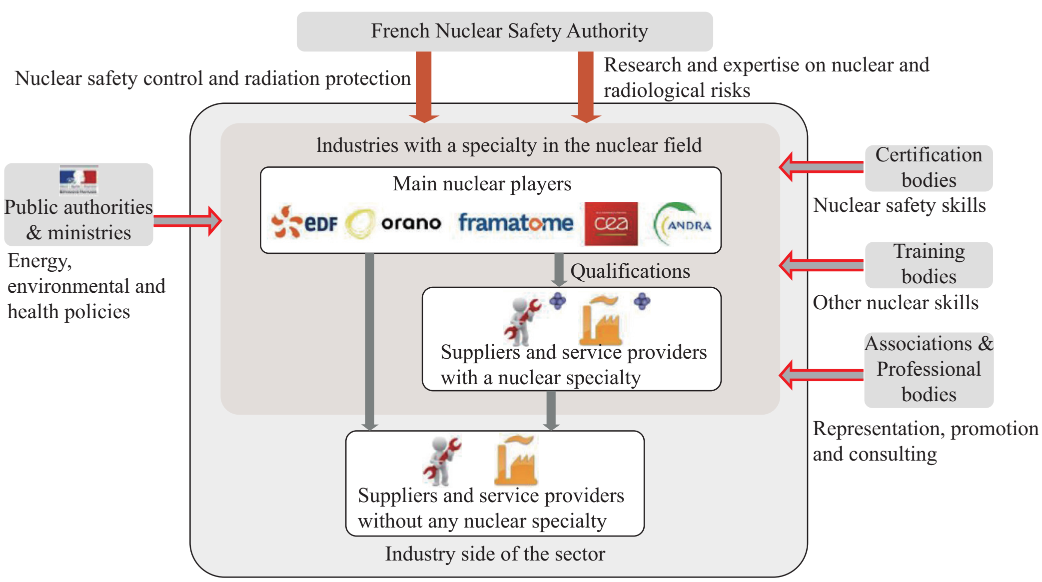
8 Each figure quoted in this sub-section is from known data in 2019.

level in the fields of safety, security and industrial performance. The requirement for a high level of competence from every actor leads to an elevated level of qualification and training of employees.

(2) The nuclear industry is made up of major nuclear players, a large number of suppliers, specialised bodies and agencies, and professional associations and organisations

The main nuclear players operate one or more nuclear installations, different in size and nature depending on their main activities.

Professional associations and organisations aim to represent their member companies and help them in various fields (markets, security, technology, etc.), promote them, provide them with a monitoring service or promote the renewal of skills in their sector. The main one is the French nuclear industry group GIFEN, which brings together companies



(Source: CSFN 2019)

Figure 4-13 Main Components of the French Nuclear Industry operating nuclear installations, large companies, medium, small and micro companies, professional organisations and associations covering all types of industrial activity (studies, manufacturing, construction, maintenance, etc.) as well as all areas of nuclear electricity production (fuel cycle, research, power generation, equipment manufacturing, dismantling, etc.).

4.4.4. Human resource support

The nuclear industry relies heavily on a specialised and highly trained workforce for its development. China and France have taken various measures to strengthen human resource development to ensure the sustainability of the industry.

Chinese Practice

As of the end of 2022, China has – across its nuclear-related enterprises (including CNNC, CGN, State Power Investment Corporation (SPIC), and China Huaneng Group (CHNG)) – successfully developed a highly skilled nuclear workforce of over 200,000 employees. Of this workforce, nearly 185,000 staff members – including 69,000 specialised technicians – are employed by CNNC. This specialised workforce serves as a cornerstone for China's advances in scientific and technological innovation and industrial progress in nuclear power generation, the nuclear fuel cycle, and the application of nuclear technologies. With a multi-pronged approach (including improving human resource management systems, establishing diverse pathways across different positions, and implementing tiered human resource training plans), nuclear-related enterprises in China are actively pursuing ongoing reforms in personnel recruitment and training systems. These programmes are aimed at further enhancing human resource development in the nuclear industry.

China places, not only for its own benefit but also for the broader international community, significant emphasis on cultivating nuclear professionals with a global vision. Since becoming a member state of the IAEA, China has arranged more than 3,000 overseas visits for its nuclear professionals, consistently providing them with opportunities for further education, training, and scientific exchanges. At the same time, China has hosted approximately 4,000 foreign technicians coming for further study and training. In 2017, China Atomic Energy Authority (CAEA) collaborated with the Ministry of Education to establish the Atomic Energy Scholarship of China, which annually welcomes 40 students from developing countries to China to pursue master's or doctoral degrees in nuclear science and technology. To date, this programme has already supported 188 international students in their educational pursuits.

Furthermore, China actively encourages professionals and scholars from nuclear-related enterprises to serve in international nuclear energy organisations, such as the IAEA and the WNA. This commitment has facilitated the training of personnel with a deep understanding of international regulations and the ability to effectively engage in global affairs. China also actively supports its personnel at participating in international conferences, collaborating on international research projects, and providing consulting services for other countries. In recent years, there has been steady growth in the number of Chinese personnel working at WANO. As of June 2022, the personnel dispatched to WANO just by CNNC subsidiary China National Nuclear Power Co., Ltd. (CNNP) amounted to over 50 people. Additionally, CNNP actively engages in personnel training activities organised or sponsored by WANO (such as the WNU Summer Institute, the "Young Generation" Workshop, and the Institute of Nuclear Power Operations (INPO) leadership training programmes).

Since the International Construction Training Center (ICTC) was inaugurated in China on 22 October 2011, China has consistently shown its commitment to providing training to nuclear power construction professionals around the world. The ICTC is the world's first facility dedicated exclusively to nuclear construction training. To date, it has conducted training sessions for over 300 nuclear professionals from more than 30 countries (including Brazil, the Republic of Korea, Indonesia, Pakistan, South Africa, Sudan, and Thailand); and its contributions have garnered widespread recognition and commendation from the international community.

French Practice

(1) A dynamic sector

The sector accounts for more than 220,000 people, highly qualified and highly trained, totally or partly dedicated to nuclear power activities:

The main companies, including EDF, Orano, Framatome, CEA and Andra, make up just over a quarter of employees. Large companies and medium-sized companies (over 250 people) employ around 56% of these employees. Small and medium-sized enterprises (SMEs) (under 250 people) and micro enterprises account for just over 16% of the workforce.

- Companies in the sector are characterised by a higher level of employee qualification than the French industry average.

- More than three quarters of the workforce have a managerial or supervisory status, and the proportion of managers is twice that of the French industry in general.
- Nuclear operators receive an average of nearly 9 days of training per year, which is more than 3 times the French industry average.
- Companies in the sector have a dynamic age pyramid, with nearly 60% of employees under the age of 45, nearly 20% under the age of 30.
- The average turnover in the electronuclear activities of companies in the sector is 4.9%, three times lower than the average turnover of French companies in general. This reflects the high stability of employees in the sector, which is explained by the high level of qualification and training, encouraging companies to keep a trained workforce.

(2) A structured human resource approach

In order to prepare and deliver the skills required for construction projects, engineering entities must implement an HR approach based on six key points:

- Setting up and implementing a skills anticipation process that considers the multiplicity of projects to which they respond. As projects are multiple and long-term, professionalisation is sometimes long, and professions are regularly transformed, it is advisable to actively anticipate.
- Sourcing and bringing in the right skills, quantitatively and qualitatively, with preference given to people who are already experienced. Formalised partnerships with target schools enable

them to offer students internships and work experience.

- Organising training programmes, especially the integration and skills enhancement periods, in particular by ensuring they are based on expertise and the transfer of knowledge and know-how. Experts must devote at least 20% of their time to knowledge transfer.
- Retaining and capitalising on their skills for future projects. Capitalising on experience over the long term is also achieved through mobility and stronger management of career paths.
- Mastering the "faire-faire" (subcontracting management). The rates of subcontracting are sometimes high in nuclear engineering. In order to better control this situation, it is important to strengthen the in-house skills of the design offices. A rate of 30%-35% of subcontracting seems to be a maximum that should not be exceeded.
- Assisting the industrial sector. The design teams accompany the nuclear industry on which they rely. They help it to acquire the skills necessary for the smooth running of its activities.

4.5. Adaptability of Nuclear Energy

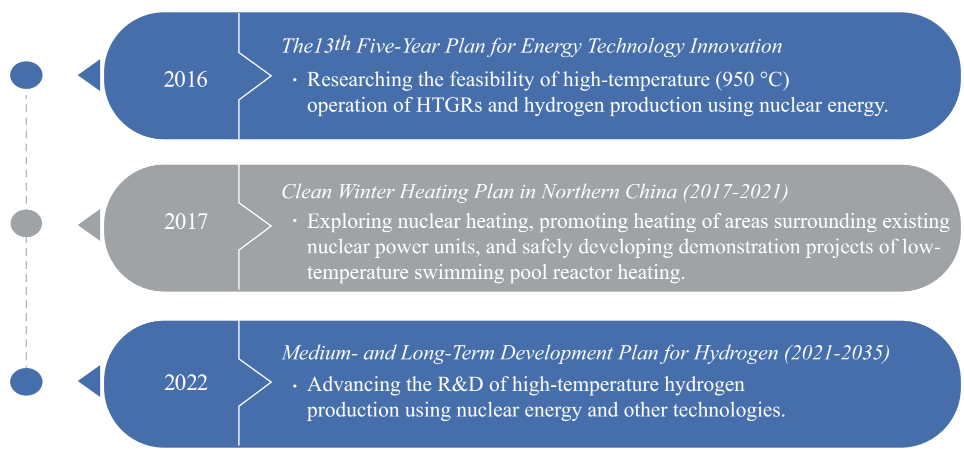
Although nuclear energy is primarily used as a baseload power supply, ongoing exploration into new application scenarios presents additional opportunities and modes for nuclear energy to align with market demands. In an ever-changing environment, nuclear energy must enhance its adaptability to factors such as market demand, climate change, and grid access.

4.5.1. Multipurpose use of nuclear energy

While nuclear energy's current primary usage is power generation, it shows great potential in a number of other fields such as maritime development, heating and refrigeration, industrial steam supply, seawater desalination, and hydrogen production.

Chinese Practice

The multipurpose application of nuclear energy plays an important role in mitigating climate change and addressing challenges in hard-to-abate sectors such as industry, transportation, and construction in emission reduction. China has rolled out a series of policies to facilitate the adoption of nuclear energy in various sectors, including industry and construction (see Figure 4-14).



(Source: CNNC)

Figure 4-14 China's Blueprint for Multipurpose Nuclear Energy Use

(1) Launching nuclear heating projects

Developing various models of low-temperature heating reactors, including CNNC's DHR-400 (Yanlong), China has initiated three nuclear heating projects located in Shandong, Zhejiang, and Liaoning provinces (see Figure 4-15).

(Source: SPIC, CNNC, CGN)

Figure 4-15 Nuclear Power Heating Projects in China

(2) Providing high-quality industrial steam

China is the world’s largest energy consumer, with industrial applications accounting for approximately 70% of total energy consumption, and low- and medium-temperature heat accounting for 45% of process heat. In 2022, the first nuclear energy industrial heating project in China commenced operations at Haiyan in Zhejiang Province. The Tianwan Nuclear Steam Project is currently under construction, as shown in Figure 4-16.

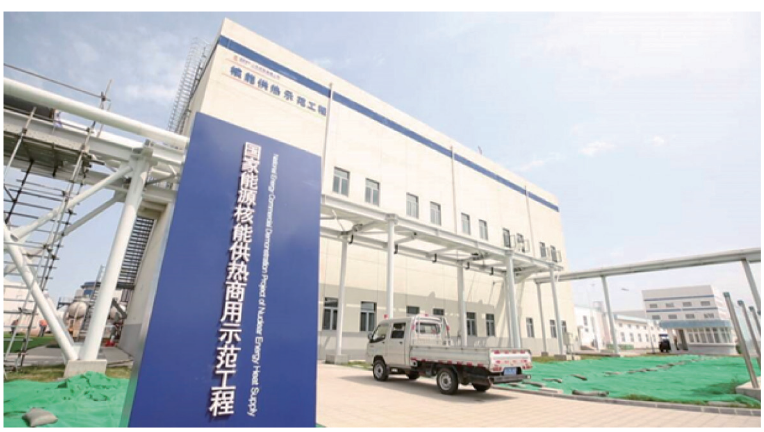
(3) Advancing nuclear desalination

Data from research institutes indicates that the cost of nuclear desalination ranges between 0.5~2.5 USD/m^3 and CO_2 emissions between 0.009~0.045 kg/m^3. With increasingly stringent carbon regulations, nuclear desalination has a promising future. In 2021 – by directly converting seawater into high-quality desalinised water at 95°C –

(Source: CNNC)

Figure 4-16 Tianwan Nuclear Power Steam Supply Project

the Haiyang NPP set an example with the successful launch of the Combined Water and Heat Supply Project (see Figure 4-17). In addition to producing electricity and industrial steam, CNNC's Tianwan Nuclear Steam Project is also working on desalination.



(Source: SPIC)

Figure 4-17 Combined Water and Heat Supply Project

(4) Providing high-temperature steam for the petrochemical industry

HTGRs offer numerous advantages, including inherent safety, high core outlet temperature, small modularisation, non-stop refueling, efficient power generation, and considerable potential for cost reduction in construction, operation, and maintenance. At the same time, they can be used in a number of scenarios such as the production of high-temperature steam and nuclear hydrogen, contributing to the decarbonisation of energy-consuming sectors. Signifying a significant stride for China in decarbonisation by integrating HTGRs with the petrochemical industry, the HTGR demonstration project was connected to the grid in 2021. CNNC is actively promoting the application of HTGRs in petroleum refining and chemical parks near the reactors in Xuwei (Jiangsu Province) and Maoming (Guangdong Province).

French Practice

NPPs have historically been designed and optimised for electricity generation, placing them among the most universal energy carriers in the world. However, they could play a wider role in the supply of other products and services over the next few decades.

In France, nuclear energy is used almost exclusively to produce electricity. Currently, warm water from the tertiary circuit that flows out of some nuclear power stations can be used to heat facilities such as greenhouses, horticultural farms, municipal swimming pools and even a crocodile farm. However, this is not cogeneration as such, but a system specifically dedicated to heat production. The idea of using nuclear energy for applications that are not purely electrical is not new. For example, since the 1950s, nuclear energy has been used as a heat source for desalination of seawater (in India, Japan, Kazakhstan, Pakistan, and the United States), urban heating (in Russia and Switzerland), and steam supply to manufacturers (in Canada, Germany, Norway, and Switzerland).

One example of EDF investigation topics: hydrogen production

In addition to these existing applications, which are likely to develop further in a world that is more dependent on carbon-free heat, new applications could also develop such as the use of heat in hydrogen production methods using high-temperature electrolysers or processes to capture CO_2 in the air (Direct Air Capture).

The basic principle for producing quality heat (between 150 °C and 250 °C) is based on the diversion of part of the steam produced by the Steam Generators, most often at one of the turbine housings, to limit the impact in terms of safety.

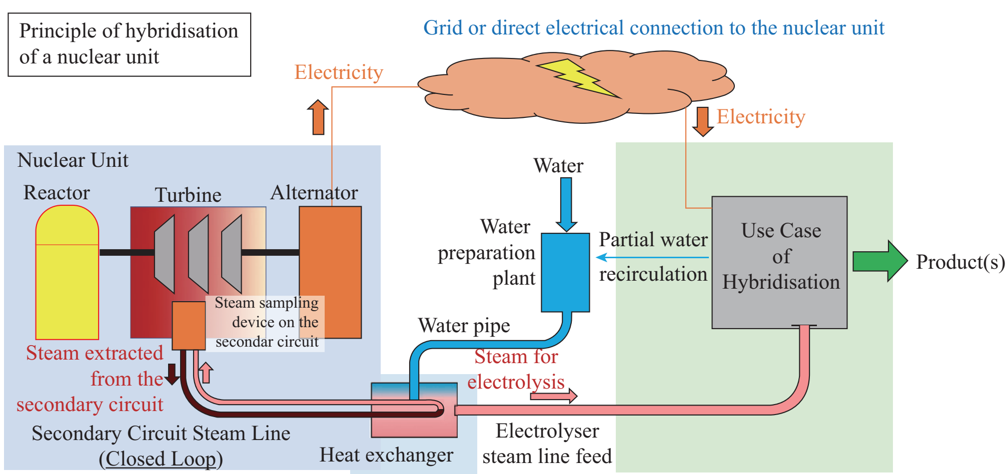


Figure 4-18 Multipurpose Use of Nuclear Energy in France

The implementation of these heat extractions is better suited to a nuclear fleet under construction than in a nuclear fleet already in use on which heavy and complicated work would not be appropriate.

Low-carbon hydrogen is currently the subject of a great deal of activity, and many industrial pilot projects are underway. It should not be forgotten, however, that currently hydrogen production is still 95% carbon-based. The French National Hydrogen Strategy aims to install a low-carbon hydrogen production capacity of 6.5 GWe using electrolysis by 2030.

Genuine industrialisation of low-carbon production by electrolysis must therefore be organised. Nuclear energy, together with renewable energy, can contribute to the low-carbon hydrogen production goals in three different value chain models, over three successive time scales:

- In the short term, electrolysis makes it possible to take advantage of the low-carbon electricity produced on the grid to maximise the load factor of the electrolysers and produce hydrogen where it is needed, thus avoiding high transport and storage costs.
- In the medium term, on the next generations of nuclear reactors, including EPR2 and SMRs, a high-temperature electrolyser could be coupled to a reactor (with steam extraction from the turbine) and increase efficiency.
- In the longer term, fourth-generation nuclear reactors at very high temperatures (above 500°C) could allow new types of nuclear coupling, with thermochemical cycles, such as water thermolysis or water "cracking".

4.5.2. Nuclear power plants responding effectively to extreme weather

Climate change, caused by the rising average global temperatures, has led to more frequent and severe extreme weather events, including elevated temperatures, droughts, and significantly rising sea levels. Amidst the continued progression of climate change, the reliability of earlier observation and prediction models has diminished. Nuclear power units are assuming an increasingly important role in coping with climate change, particularly in natural disaster relief.

Chinese Practice

Intensifying efforts to ensure the smooth operation of energy infrastructure and enhance its capacity to withstand extreme weather events (like storm surges, high temperatures, and freezes), China has enhanced the climate resilience of its infrastructure and major projects. Given that China's NPPs are situated along the coast, climate risks primarily stem from the gradual rise of sea levels and extreme weather disasters rather than droughts. To fortify the climate resilience of its NPPs, China has implemented measures such as refining plant design, enhancing cold source safety, and establishing an early warning system for natural disasters.

(1) Optimising nuclear power project designs for climate change adaptation

The seismotectonic conditions in China's coastal areas are not susceptible to earthquakes or tsunamis. Additionally, the extensive continental shelf and the outer sea are shielded by island arcs that provide protection to NPPs against earthquakes and tsunamis. China remains committed to refining its nuclear power project designs to adapt to climate change. In 2012, after the Fukushima nuclear accident in Japan, the NNSA issued the *General Technical Requirements on the Improvement of NPPs after the Fukushima Nuclear Accident (Trial)*, which charted the course for the ongoing and continuous improvement of NPPs.

HPR1000 is designed to be flood-resistant and capable of adapting to gradual sea-level rise. During the design of the baseline flood level in the Fuqing NPP Unit 5 and Unit 6 plant site (the first HPR1000 demonstration project), the design factored a “once-in-a-thousand-year” rainfall scenario. Serving as the reference for the waterproof sealing of relevant structures and facilities, the maximum depth of accumulated water was set at 100 mm, leading to an increase from 150 mm to 300 mm in the height difference between the indoor and outdoor areas of each of these two Fuqing NPP units’ sub-items. This adjustment should effectively prevent any water accumulation in the plant area from entering the nuclear island.

In the HPR1000’s electrical plant, fuel plant, operation service plant, and nuclear auxiliary plant, waterproof sealing has been employed in all passages with a height below 0.00 m. This is done to prevent potential internal flooding caused by external flooding. After technical research, flood prevention measures have been introduced in underground penetrations.

The HPR1000’s optimised design allows for buffer time for restoration and external support in the event of extreme disasters. In the case of a beyond-design-basis accident (BDBA) due to extreme disasters, the NPP’s relevant systems, equipment and structures are designed to mitigate the consequences of the accident by stalling damage in the form of providing buffer time for restoration and external support. Unit design incorporates various measures, including inherently safe reactor cores, multiple means of removing heat from the core, large containment vessels, passive hydrogen recombiners, and a containment filtration and ventilation system, to mitigate BDBAs.

(2) Conducting cold source safety management

In August 2014, China's National Energy Administration issued the *Notice on Strengthening the Safety Management of Circulating Water Intake Facilities in Nuclear Power Plants*. To mitigate the impact of marine organisms, this directive mandates the inclusion of fixed interceptor nets and other facilities in the design of circulating water intake structures. To implement these measures, CNNC has incorporated comprehensive defence strategies and specific measures for cold source protection. As part of this protection system, the trash-intercepting net is integrated into the marine layout of NPPs. The design aligns with the principles that are based on objects of protection, capable of self-cleaning with tidal currents, and for easy maintenance and replacement.

- Based on research on the protection object, the trash-intercepting net should completely cover its protection scope. In addition to addressing marine organisms that could potentially induce disasters, it should also encompass other debris (including floating oil, driftwood, ships, and garbage) that may compromise the safety of water use.
- For items such as marine organisms and debris, it is possible that – if they enter the water intake channel – they might not be carried away by tidal currents and they could potentially impede filtration

and cleaning equipment. Therefore, they should be intercepted at the start of the water intake. The role of self-cleaning of accumulated debris in the trash-intercepting net should be highlighted as this lowers the labour cost and risk of manual cleanup operations.

• Minimising blockage and enhancing its stress resistance, the trash-intercepting net should be designed for easy cleaning with mesh that has been designed for easy repair and replacement in the event of local breakage. Furthermore, it should not block navigation.

Cold source disasters result from multiple factors, and there is no one quick fix. As not all hazards can be identified by technical means, attention should also be paid to correlating factors. Risk assessment requires long-term efforts, and building a comprehensive environmental monitoring system is key. A thorough assessment and update of the NPP’s environmental conditions, including information on climate, storm surges, abundance and habits of marine life, physical and chemical indicators of seawater, possible pollutants, debris, and siltation, should be conducted no less than every five years. To ensure the safety of cold sources, it is imperative to strengthen monitoring and risk prevention.

(3) Establishing an early warning mechanism for natural disasters

The meteorological and oceanographic authorities responsible for the NPPs can provide 24-, 48-, and 72-hour forecasts and analyses of meteorological and oceanographic data. Upon receiving a warning, the designated individual will – based on the risk level – promptly issue an alert regarding potential external disasters. With a series of targeted contingency plans rolled out by the NPP (including the *Contingency Plan for*

Damaging Earthquakes, the *National Marine Disaster Contingency Plan,* and the *Contingency Plan for Meteorological Disasters),* the HPR1000 has improved its extreme disaster prevention scheme. These plans were developed using information on earthquakes, meteorology, and marine conditions at the plant site, along with professional data on geographical, meteorological, and marine environments provided by national organisations.

French Practice

(1) Natural hazards have been considered from the outset of the nuclear programme

EDF's NPPs were designed from the outset to withstand all types of external event, including natural events. Thanks to experience feedback and advances in knowledge, their place in the safety approach has been strengthened over time and through periodic safety reviews.

The consequences of global warming are also being addressed in France as part of the ten-yearly nuclear safety review. This is an opportunity to consider new models based on temperature increases, events such as river flows and tornadoes, and international knowledge to improve the safety of power plants by adapting their design.

The availability of the cold source is a key element in this issue: Recent years have been marked by increasingly frequent heat waves and prolonged periods of low water. Riverside facilities must adapt so that they can continue to operate while complying with regulatory limits on thermal discharges and the maximum deviation from the water temperature to be maintained downstream, even in the event of extreme temperatures.

In a situation known as "extreme heat", the regulations applicable to power plants set temperature limits. These values have been established on the basis of scientific studies, in order to avoid any consequences for aquatic fauna and flora.

For riverside power stations, two parameters can influence compliance with these limits: **the flow rate of the river and the temperature of the water upstream** of the power stations. These can lead power stations to modulate their output to limit their thermal discharges into the river and thus comply with regulations. These modulations can go as far as shutting down production units. The sites most affected by these modulations are said to be heat-sensitive. These include the Bugey, Saint-Alban, Cruas, Tricastin, Nogent, Cattenom, Chooz and Golfech NPPs.

Just like the "extreme heat" situation during the summer period, the "extreme cold" situation is also one of the external events that must be managed to guarantee the safety and availability of generation resources, and to preserve EDF's industrial assets. Preparing EDF's facilities for winter also helps to ensure their long-term operability and avoid the damage that cold weather could cause to equipment (freezing of water in pipes, crystallisation of boron, etc.).

(2) Preparing for the future: the ADAPT project

Climate change is unprecedented over such a short time scale. As Figure 4-19 shows, its evolution is clear, rapid and seems irreversible from the 1980s onwards.

Building on long-standing work, EDF has started the ADAPT project, which aims to make power generation from thermal and nuclear sites secure by anticipating the consequences of climate change and adapting as necessary the fleet.

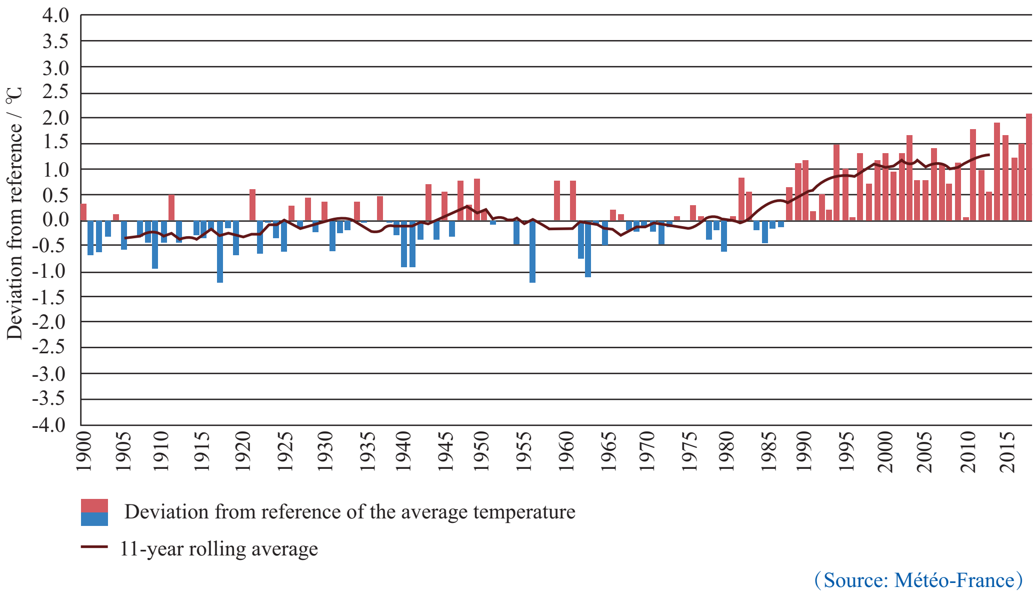


Figure 4-19 Annual Average Temperature in Metropolitan France
Deviation from Reference 1961-1990

New reactors are already factoring in the consequences of climate change in their design for their expected lifetime. However, there is a strong interaction with the adaptation project to integrate the systemic nature of climate change affecting all stakeholders and to propose a holistic response for a nuclear site.

The aim of the ADAPT project is to carry out an in-depth analysis of the level of adaptation of the thermal and nuclear fleet to climate change, in order to draw up an inventory of potential weaknesses, and to propose an action plan to resolve them with sufficient anticipation to enable the generation fleet to adapt to the consequences of climate change in a systemic way. A climate change adaptation plan is built around a set of model/scenario pairs that reflect potential future climate scenarios. It will be broken down by asset type.

The main strategic risk is to secure the generating capacity

and operability of the fleet in the face of climate change. EDF is currently identifying the modifications to be made to the facilities which are considered as immediately interesting to be implemented without waiting for the ten-yearly review. These modifications would aim to improve operating and working conditions and the maintenance of the equipment needed for production during periods of high heat.

(3) Some major countries, including China and France, have already successfully begun to adapt their nuclear fleet to climate change

According to the IAEA, the adverse weather conditions that regularly disrupt nuclear power generation have increased almost fivefold in three decades, with a marked acceleration since 2009.

Over the period 1990-2019, less than 50 TWh of production losses were directly attributed to meteorological events worldwide, or less than 0.1% of the nuclear electricity produced over the same period.[9] In 73% of the events reported, the production outages concerned power plants located on rivers or lakes, given that the continuity of production depends directly on their strictly regulated access to water sources, which guarantees minimal impact on ecosystems.

NPPs in countries such as China and France, which have experienced numerous forced outages following severe weather events, have seen their ten-year economic losses fall steadily since the 1990s. However, nuclear sites in other countries have experienced both more frequent outages and higher average production losses since that time.

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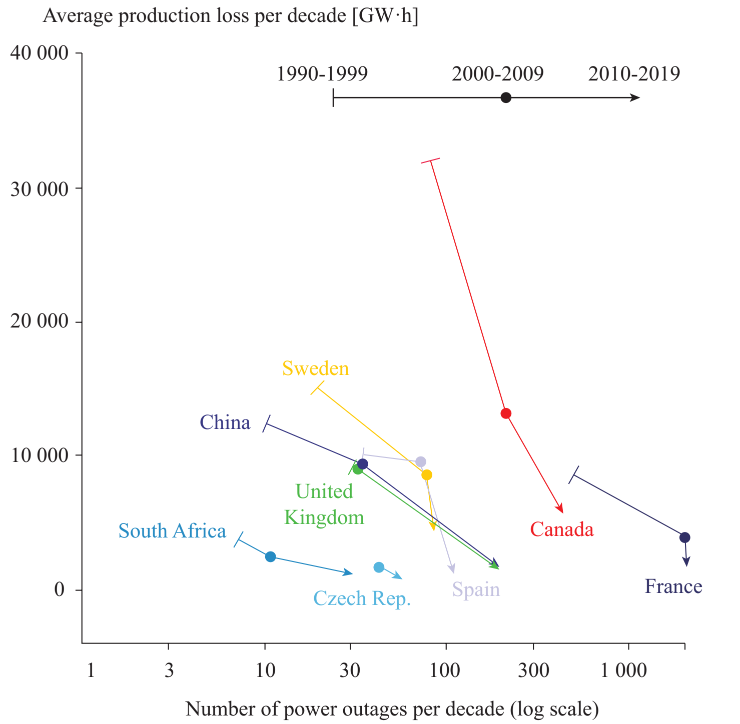
9 IAEA, *Climate Change and Nuclear Power 2022*.



(Source: IAEA, 2022)

Figure 4-20 Average Production Loss as a Function of Power Outages per Decade

On average, the impact of weather incidents has been significantly reduced in many countries thanks to revised regulatory regimes and improved operational experience. Extreme weather events have led to specific adaptation measures.

The design of the power plants was adapted through various technical solutions including reduction in the use and consumption of cooling water; modification of the water intake; investigation of on-site water production; increase and more efficient use of heat exchanger capacity; and redesign of condensers to offset river intake of warmer water.

4.5.3. Nuclear energy’s compatibility with the grid

The growing proportion of intermittent renewable energy, such as wind and solar power poses a challenge to the electric system. To address this challenge, it is crucial not only to improve grid adaptability but also to integrate low-carbon backup power sources to maintain a balance between supply and demand. Nuclear energy is highly compatible with the grid, given that nuclear power units offer a stable load and can function as a baseload power source. Besides, nuclear power is predictable, making it well-positioned for the overall scheduling of the grid.

Chinese Practice

The Chinese government has adopted a guaranteed consumption approach for nuclear power. In 2017, the National Development and Reform Commission (NDRC) and China’s National Energy Administration issued the *Interim Measures to Ensure the Safe Consumption of Nuclear Power*. These measures outline the basic principles for guaranteed consumption, including safety assurance, preferential grid access, ensured power generation, and balanced interests.

Recent years have witnessed a tight balance between power supply and demand. The current electric power system requires full-capacity power generation from nuclear power. During the Spring Festival, and in accordance with the overall dispatch plan, some NPPs continued operations, albeit with reduced output. CNNC has been actively exploring methods to enhance grid compatibility and has introduced joint peak-shaving initiatives to bolster the role of nuclear power in the peak-shaving system.

The construction of the Yunxiao Pumped Storage Power Plant in Fujian Province began in 2022. Upon completion, it will synergize with the Zhangzhou NPP in integrated nuclear storage operation (Figure 4-21). Enabling the consumption of excess power during off-peak hours, the storage facilities will thereby optimise the operational efficiency of the NPP and will generate additional revenue by selling stored power during peak hours.

(Source: CNNC)

Figure 4-21 Integrated Nuclear Storage Demonstration Project

French Practice

The great flexibility provided by French nuclear power shows the way for the complementarity of nuclear and variable renewables in a decarbonised economy.

(1) Coordinated development of nuclear and renewables is a pillar of decarbonised power generation

Promoting energy savings, electrifying end-uses, and decarbonising the energy sector are keys to fighting climate change. Because of the resulting surge in demand for zero-carbon electricity, the complementarity of renewables and flexible nuclear is a pillar of the energy transition.

Accommodating a growing share of intermittent renewable energies (wind, solar PV) will be a challenge for the power system. Rising to that challenge will require not only strengthening the grid but also adding zero-carbon backup to maintain electricity quality and the supply-demand balance. Thus, over the long term, nuclear, a flexible and zero-carbon energy, will be an operational and proven source among the other flexible sources being developed (batteries, vehicle-to-grid, Demand Side Management, and other dispatchable low-carbon sources). Tapping this potential will require skills and expertise both in design engineering and operations, to guarantee that reactor operations meet all safety standards.

(2) An example of complementarity between renewables and flexible nuclear in France

Figure 4-22 shows different metrics on Sunday 15 January 2023 in France. Main characteristics of that day are as follows:

- Electricity consumption in France: ranging from 44 GWe (at 5 am) to 60 GWe (at 7 pm).
- Generation from wind and solar, as high as 20 GWe (at 1 pm).
- Net exports from 5 to 8 GWe, between 12 am and 12 pm.
- Nuclear power ranging from 32 to 41 GWe.

The flexibility of operations is reflected as follows:

- Between midnight and 6 am, downward consumption, small imports and pumped hydro, quite stable wind: nuclear generation decreased slightly from 35 to 32 GWe.
- At 6 am, low consumption, growing wind generation, low exports:

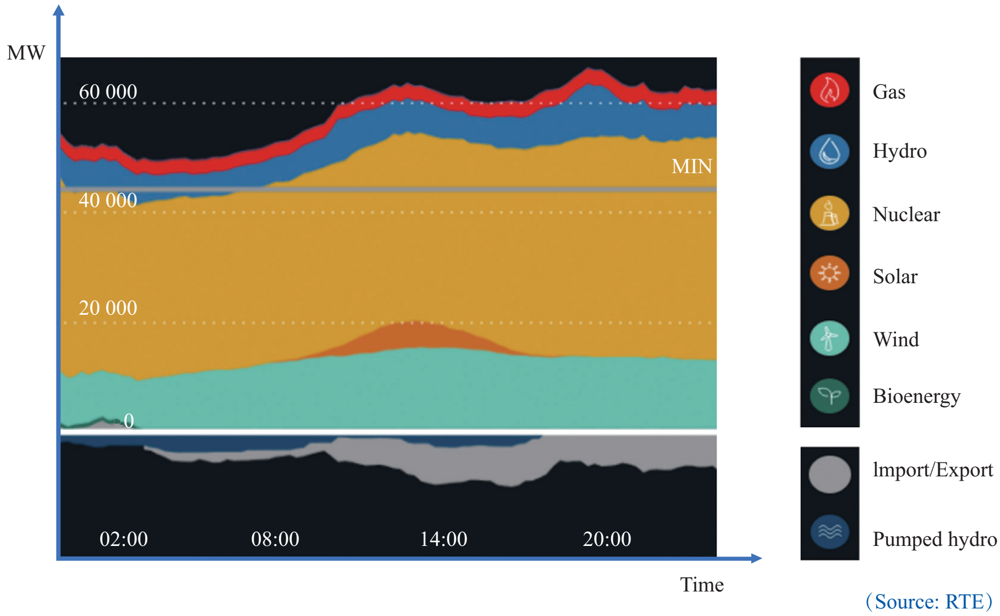


Figure 4-22 Different Metrics on 15 January 2023 in France

this was the lowest point of the day for nuclear generation with 32 GWe of nuclear operating.

- At noon, first consumption peak, high wind and solar generation, growing exports: nuclear slightly increased up to 34 GWe.
- At 7 pm, second consumption peak, no more solar generation, high exports: nuclear power reached ca 40 GWe.

(3) Dispatchability of nuclear power

French nuclear reactors were designed for flexibility from the beginning, as nuclear accounts for 70% of the power mix. They are designed to be able to reduce output from 100% to 20% of rated capacity twice a day in under 30 minutes. They have thus a ramp up/ down ability of 30-40 MWe per minute, depending on the type of reactor, which ranks French nuclear reactors among the most flexible means of electricity generation. To keep pace with fluctuating demand, a major load variation programme is agreed upon in advance with the grid operator. In addition, the grid operator can ask for an unplanned load variation within 20 minutes.

Electric capacity delivered by Reactor 2 at the Dampierre NPP over one day on 31 March 2023. Output was cut sharply twice, in the middle of the night and in the afternoon, with variations from 850 MWe to 300 MWe within half an hour. The beginning of a third sharp decrease took place just before midnight.

Figure 4-23 Example of Power Variations over One Day
Dampierre 2 Reactor - 900 MWe

This flexibility is amplified by the fleet effect. Of France’s 56 nuclear reactors at the beginning of 2023, with a combined net capacity of 61 GWe, all of which are operated by EDF, up to about 20 GWe can be ramped up and down within 30 minutes. The nuclear fleet also contributes to power system stability as nuclear reactors can contribute to primary reserve. At fleet level, EDF is also optimising its refuelling and maintenance programme in line with power demand.

(4) Innovations have enhanced the grid adaptability of nuclear power

Innovation has allowed EDF to operate its nuclear plants in a flexible manner and to develop technical skills. Key areas of innovation are design modifications, extended safety studies, and control room operation, which all require well-trained personnel.

Enhanced design: The design of French NPPs has evolved to include features not found in standard PWRs. These modifications have primarily involved using different types of rods and changing their position in the core depending on power levels. The use of special "grey rods", composed of materials that absorb fewer neutrons than standard ones, makes it possible to modulate chain reactions more precisely.

Extended safety studies: Safety studies have been extended to consider a wide power range. Dedicated specifications, validated by the French ASN, are applied to flexible operation.

Well-trained operators: Control room operators receive specific training in this mode of operation on full-scope simulators that are exact physical replicas of control room equipment. Assistance tools have also been developed over the past 15 years.

4.6. Resource Recycling and Environmental Friendliness

Uranium serves as the cornerstone of nuclear energy. To ensure the sustainable development of nuclear energy, it is essential to promote the recycling of uranium. The key to enhancing uranium utilisation efficiency lies in the reprocessing and recycling of spent fuel. It is essential to properly dispose of the radioactive waste generated throughout the operational process, ensure safe decommissioning of nuclear installations and facilitate the environment-friendly development of nuclear energy.

4.6.1. Reprocessing and resource recycling

"Spent fuel" refers to irradiated nuclear fuel which has been discharged from reactors. Recycling fissionable nuclides by processing them into new nuclear fuel for the reactor allows for the reuse of spent fuel. This practice reduces the consumption of natural uranium and diminishes the toxicity and quantity of high-level radioactive wastes. This is an important measure to ensure the sustainable development of nuclear energy. Compared with direct disposal of spent fuel, reprocessing and recycling alleviate the storage burden (both on-site and off-site), with a reduction of more than 75% in the amount of high-level waste requiring deep geological disposal, and significantly decrease the volume of waste necessitating final disposal. Through reusing the uranium and plutonium in thermal reactors via a single cycle, the utilisation rate of uranium increases by around 25%.

In the case of multiple cycles in fast reactor, in theory, it is possible for more than 10 cycles to raise the uranium utilisation rate by a factor of 40 or higher. The schematic diagram of a closed nuclear fuel cycle is shown in Figure 4-24.

Chinese Practice

(1) Adhering to a closed nuclear fuel cycle policy

In the 1980s, China formulated a "three-step" strategy (including thermal, fast, and fusion reactors) for nuclear energy development,

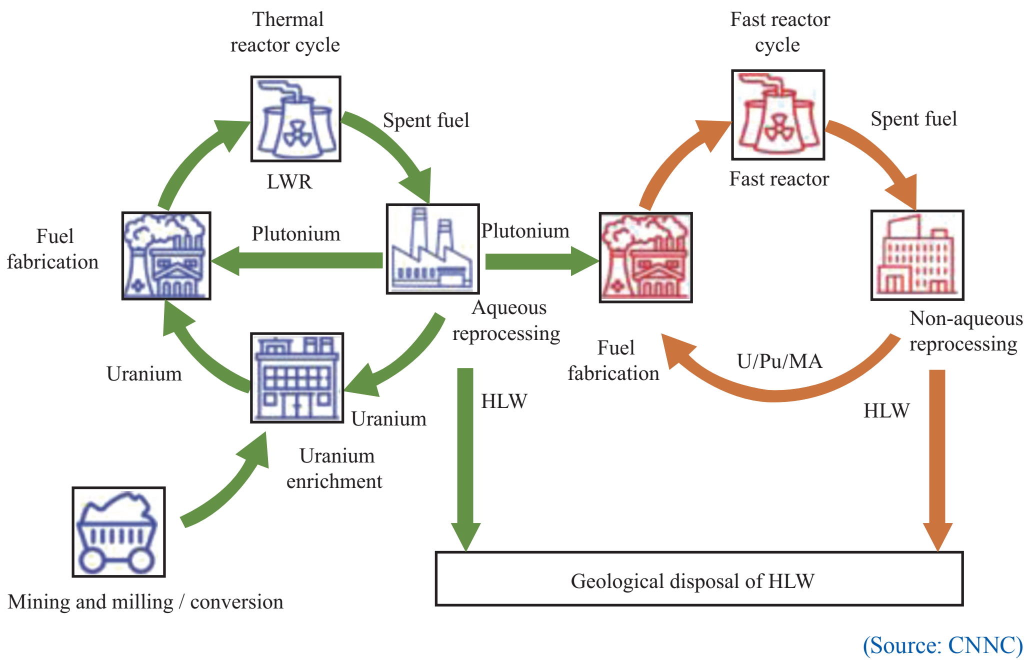
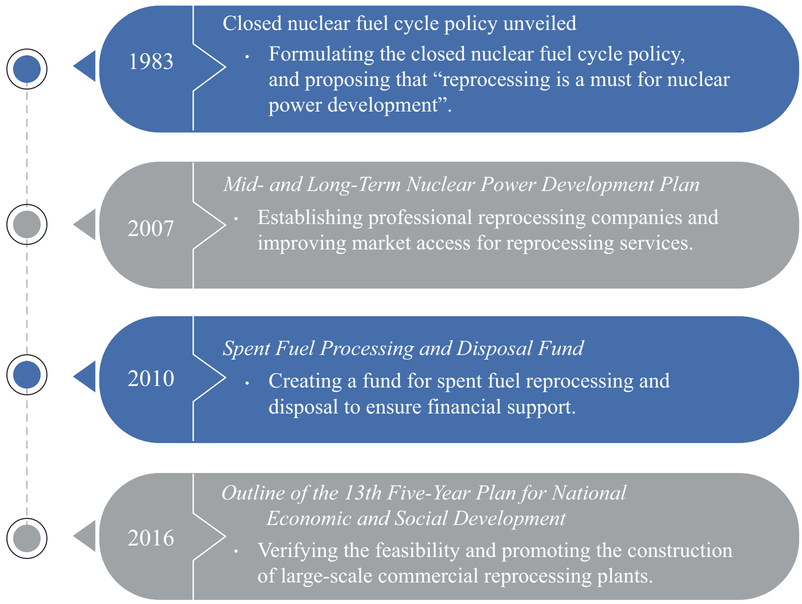


Figure 4-24 The Schematic Diagram of a Closed Nuclear Fuel Cycle

along with a closed nuclear fuel cycle policy. Since then, this strategy has guided the pathway of research in the closed nuclear fuel cycle (see Figure 4-25).

(2) Developing spent fuel reprocessing and recycling technology

Ensuring its feasibility and establishing the groundwork for the commercialisation of spent fuel reprocessing for NPPs, China has intensified its efforts in developing spent fuel reprocessing technology for power reactors. CNNC is committed to setting an example in spent fuel reprocessing and supporting the commercialisation of spent fuel reprocessing.



(Source: CNNC)

Figure 4-25 Relevant Policies and Regulations of Closed Nuclear Fuel Cycle

French Practice

Spent fuel reprocessing and recycling are carried out at the Orano La Hague and Melox plants in France.

The plutonium extracted from the spent fuel is mixed, as an oxide, with the depleted uranium oxide produced by enrichment plants to make MOX fuel. The manufacture of MOX fuel at the Melox plant (Marcoule) follows roughly the same method as the manufacture of UO_2 fuel, but handling plutonium requires special protection measures. Due to the alpha radiation from plutonium, operations must be carried out in glove boxes. MOX fuel assemblies, with the same structure as UOX (Uranium Oxides) assemblies, are incorporated in the reactor core among UOX assemblies. To date, twenty-two 900 MWe design reactors in the French fleet use MOX fuel.

Regarding reprocessed uranium (RepU), the conversion, enrichment and fuel manufacturing stages (the fuel is known as ERU fuel, for Enriched Reprocessed Uranium) are similar to those for natural uranium, but may require dedicated production chains/facilities. ERU fuel was used on four 900 MWe design reactors in the French fleet between 1994 and 2013. After an interruption of around ten years for reasons of competitiveness compared to natural uranium and the environmental performance of associated facilities, the use of ERU is resuming in 2024 in the French fleet with the aim of extending its use to about fifteen 900 MWe and 1300 MWe reactors over the next few years.

Fuel reprocessing introduces additional industrial processes into the fuel cycle but has technical advantages compared to an open cycle without recycling:

- Front-end of the cycle, annual savings in natural uranium resources:
  - of the order of 10% due to plutonium recycling.
  - 10 to 15% more due to the recycling of reprocessed uranium.
- Back-end of the cycle:
  - a reduction in the annual amount of spent fuel to be temporarily stored, currently by a factor of 10, corresponding to more than 1,000 tonnes/year.
  - a reduction in the volume of waste by a factor of 5, by separating the recoverable materials from the waste, the separation of high-level waste (HLW – fission products and minor actinides) from intermediate-level waste (ILW – fuel assembly cladding and end caps) and the reduction in the volume of intermediate-level waste through compaction.
  - a reduction by a factor of 10 of the long-term toxicity of the ultimate waste to be sent to final storage, thanks to the

recovering and recycling of the plutonium.

- the safe and stable packaging of high-level waste in a glass matrix (vitrification). The packaging of long-lived HLW and ILW waste also facilitates its handling and temporary storage until final storage.
- reducing the volume of thermal waste (LL-HLW and fuel) and its residual thermal power, which is the determining factor for the design of the storage. This reduction in surface area also results in a reduction in costs.

Mono-recycling of materials (recycling once) is also a first technological step towards multi-recycling (recycling multiple times) in PWRs or fast reactors which would allow significant additional gains in terms of material and waste management. The fast reactors enable the fuel cycle to be closed. They open up the prospect of energy independence for thousands of years, given the stocks of depleted uranium available in France.

4.6.2. Decommissioning of nuclear installations and environmental remediation

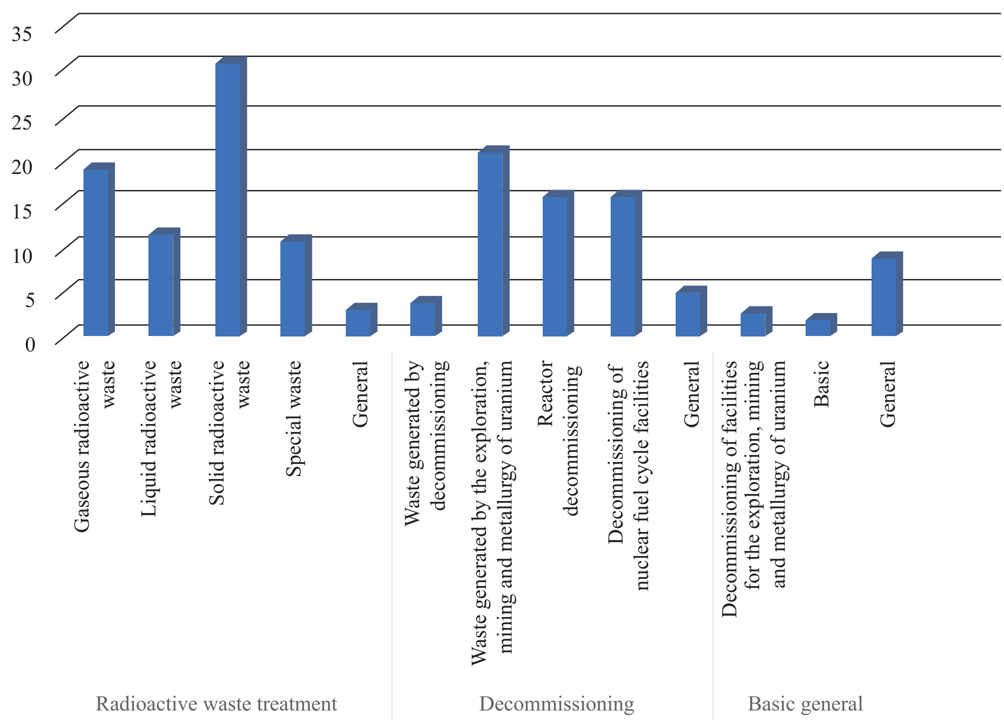
The decommissioning of nuclear installations includes preparation, decontamination, dismantlement, and environmental remediation. As the decommissioning process may span several years or even decades, it is crucial that the radiation levels at the NPP comply with laws and regulations to ensure the safety of both the environment and personnel.

Chinese Practice

As a latecomer in nuclear energy, China has not yet decommissioned any nuclear power units. However, as a significant player in nuclear power and to ensure environmental protection, China has introduced regulations and standards for the decommissioning and treatment of outdated nuclear installations. At the same time, preparatory work has been conducted to pave the way for the future decommissioning of NPPs.

(1) Establishing a sound system of laws and industrial standards for the decommissioning and treatment of nuclear installations

Under the principle of harmonious coexistence between humanity and nature, China prioritises the proper decommissioning and treatment of nuclear installations, and is fostering the safe and sustainable development of nuclear energy through the establishment of a robust legal and industrial standards system. Serving as a legal basis for decommissioning, a series of laws and regulations (including the *Law of the People's Republic of China on Prevention and Control of Radioactive Pollution* and the *Nuclear Safety Law of the People's Republic of China*) have been promulgated. Furthermore, nearly 100 technical standards for decommissioning and treatment have been released (see Figure 4-26). These standards cover a wide range of fields, including source term investigation and radiation safety, environmental protection for the decommissioning of uranium mining and milling facilities, treatment and disposal of radioactive waste, discharge of wastewater and exhaust gas, and environmental remediation and clearance. By setting the industrial standards for decommissioning and treatment of



(Source: CNNC)

Figure 4-26 Decommissioning Standards of Nuclear Installations

nuclear installations, China has clarified the technical requirements for decommissioning.

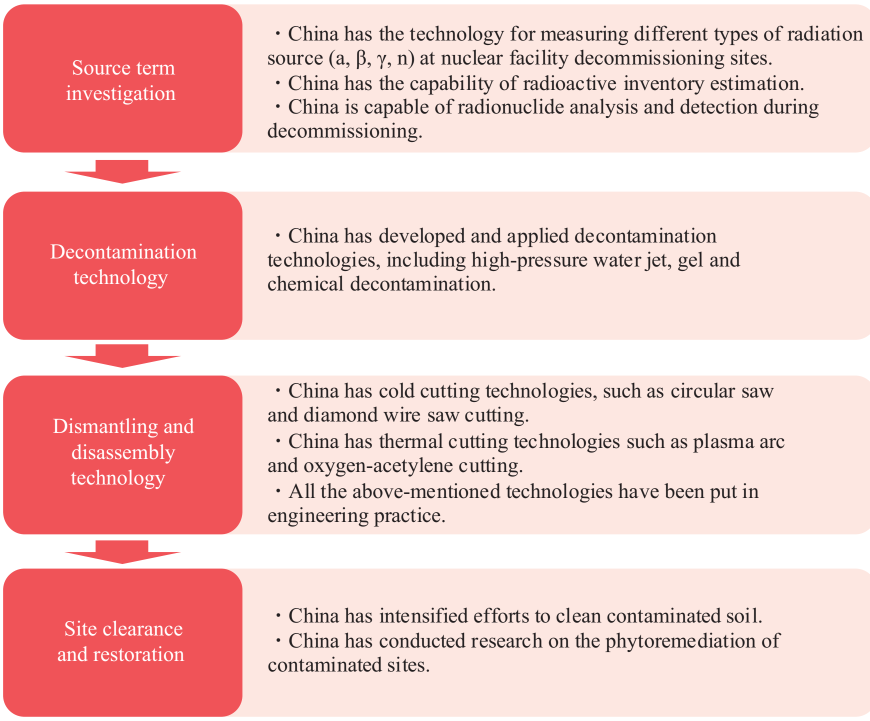
(2) Developing technical capabilities for the decommissioning and treatment of obsolete nuclear installations

In the 1980s, China began the R&D and project implementation of the decommissioning of obsolete nuclear installations. Since then, the country has developed a relatively mature technical system and key equipment, and devised solutions in a number of areas (such as overall design, source term investigation, clearance and decontamination, dismantling and disassembly, radioactive waste treatment and disposal, and general technologies). These advances have supported the decommissioning and treatment of obsolete nuclear installations. Furthermore, as China has mastered the key technologies (including dismantling, cutting, lifting, and remote control of megawatt-level research reactors) in this regard, a number of large-scale mechanical cutting platforms, underwater cutting equipment, and simulation technologies have been utilised in real projects. Various decontamination techniques including chemical, gel, foam, and strippable membrane decontamination, have been applied in scenarios such as radioactive pipelines and storage tanks. In the process of dismantling and disassembling radioactive items, China has employed industrial use-scalable cold cutting and thermal cutting technologies using circular saws, diamond wire saws, plasma cutting, flame cutting, and oxygen cutting. Further details are provided in Figure 4-27.

(3) Gaining experience in the decommissioning of nuclear installations

China has assembled a dedicated team of professionals specialising in nuclear installations' decommissioning and treatment. Accumulating substantial experience through the practical application of their technical advances across various projects, this team – which is committed to the R&D of decommissioning and radioactive waste treatment – has successfully decommissioned some research reactors and radiochemical production lines, enabling (with follow-up plans) unrestricted or restricted openings in the facility sites. The strides currently being made in decommissioning and treatment technologies for outdated nuclear installations have set the stage for the future decommissioning of NPPs.

To align with China's goals for 2040 as well as the national



(Source: CNNC)

Figure 4-27 Technical Capabilities for Decommissioning and Treatment

medium- and long-term goals, preparations are currently underway for the decommissioning of operational nuclear power units. Multiple documents including decommissioning plans, environmental impact assessment reports, and safety analysis reports for various nuclear power units across the country have been drafted; and China has showcased its decommissioning strategy and specific plans with the Qinshan-1 serving as an illustrative example. Estimating the retention of radioactivity, on-site source team investigation of nuclear power units has been conducted; decommissioning plans have been formulated and continue to be updated; and framework research is in progress on the standards for NPP decommissioning.

French Practice

As an operator, EDF takes full regulatory, financial, and technical responsibility for the decommissioning of its plants and the other nuclear installations it operates. EDF therefore ensures that it controls the entire lifecycle of nuclear power generation resources.

(1) Regulations applicable to the decommissioning of nuclear facilities

The decommissioning of a BNI is ordered by a decree, issued after an opinion by the ASN and completion of a public inquiry. This decree determines the characteristics of the decommissioning, the timeframe for its completion, and where applicable, the operations incumbent upon the operator after decommissioning.

The reference scenario adopted by EDF since 2001 is consistent with French regulations. The operator proceeds with its dismantling as soon as possible after final shutdown, under economically acceptable conditions and in line with the principles set out in accordance with the legal provisions in force. In accordance with the IAEA recommendation, France has adopted a strategy of immediate dismantling. It can be spread over several decades, even in the case of immediate dismantling.

(2) Status of decommissioning of nuclear facilities in France

To date, 11 reactors using four different technologies have been permanently shut down:

- three PWRs: one at Chooz A and two at Fessenheim;
- one HWR at Brennilis;

• the Superphénix fast neutron reactor;

• six UNGG reactors at Bugey, Saint-Laurent and Chinon.

The decommissioning of EDF's historic nine first-generation reactors in final shutdown will produce approximately one million tonnes of primary waste materials, of which 80% is standard waste material and none is high-level waste. Among the remaining 20% of radioactive waste, only 2% is long-lived and none is high-level waste.

Chooz A

The Chooz A reactor of the Ardennes NPP was the first PWR built in France. It was commissioned in 1967 and operated until 1991. The reactor location, in a rocky cave in a hillside, means that access conditions, entry and exit of materials and effluent management are more difficult than those of the rest of the existing PWR fleet. The work begun in 2017 to decommission the Chooz A reactor vessel. Today, the dismantling of the reactor vessel is scheduled to be completed by the end of 2026.

Fessenheim

Reactors 1 and 2, commissioned in 1977, were permanently shut down in 2020. At the end of 2020, the "PREDEM Fessenheim" project was put into place to coordinate all the end-of-operation procedures, draining of circuits, evacuation of bore, permanent locking-out and removal of certain equipment and support functions, removal of fuel, decontamination of primary circuits, etc.

All spent fuel was removed from the site and sent to La Hague in the space of just over two years. As a result, 99.9% of the radioactivity has been removed from the site.

Brennilis

The Brennilis NPP, commissioned in 1967, on the Monts d'Arrée site, is an industrial prototype heavy water moderator nuclear power reactor cooled with CO_2, which was definitively shut down in 1985. Partial decommissioning operations were carried out from 1997 to mid-2007. Since 2000, EDF has become fully responsible for the decommissioning of this facility. The safety concrete for the effluent processing station has been demolished, and the spoil removed.

Creys-Malville

The Superphénix fast neutron reactor, commissioned in 1986, a 1,200 MWe sodium-cooled industrial prototype, is situated at Creys-Malville. It was definitively shut down in 1997. The majority of the sodium was treated in the form of concrete blocks. The remainder was subsequently treated and there is no longer any sodium in the facility. In 2020 and 2021, the first two caps were cut and the cutting of the last cap ended in 2022. It was removed and replaced by the "rotating confinement structure" (structure de confinement tournante, SCOT) from which the in-water cutting of the internal components of the reactor vessel will be carried out; this work is scheduled to continue through until 2026.

The gas-cooled reactors

Bugey 1, Chinon A1, A2 and A3, Saint-Laurent-des-Eaux A1 and A2, commissioned in 1972, 1963-1965-1966, and 1969-1971, constitute the gas-cooled reactors (GCR). These first-generation reactors functioned with natural uranium as the fuel and graphite as the moderator. They were cooled by gas. There are two types of GCR: "integrated" reactors (Bugey 1, Saint-Laurent A1 and A2), whose heat exchangers are situated beneath the reactor core inside the pressure vessel, and "non-integrated" reactors (Chinon A1, A2 and A3) whose heat exchangers are situated on either side of the reactor pressure vessel. The current industrial strategy (in-air dismantling) entails decommissioning work on the reactor caissons coming to different end times that depend on the type of reactors.

Decommissioning of Orano facilities

As nuclear operator of front-end and back-end facilities in France, Orano fully ensures the end-of-life preparation, the associated licensing, the management of the project, the financing, waste treatment and packaging, and the operation of the decommissioning of its shutdown facilities. Two main facilities are under decommissioning:

- La Hague UP2-400 reprocessing plant. After 38 years of operation by Orano, this plant with a reprocessing capacity of 400 tonnes of spent fuel per year, was shut down in 2004. Organised in 18 projects, including 9 projects ongoing, more than 2,600 rooms need to be cleaned up and dismantled, for a global duration of around 30 years.
- Georges Besse 1 uranium enrichment plant. During more than 30 years, the Eurodif gaseous diffusion uranium enrichment plant (GB1) ensured enrichment needs of 25% of NPPs for around

100 reactors in France and worldwide. Thanks to the cleanup successfully implemented to recover Uranium from the process, the objective of the oncoming operation will be to manage 160,000 tonnes of metal with very low uranium contamination.

4.6.3. Nuclear waste treatment and disposal

Radioactive waste can be classified into gaseous, liquid, and solid waste, each requiring appropriate management, treatment, and disposal measures. HLW, in particular, is designated for long-term management through deep geological disposal. According to the IAEA, "the safety of geological disposal is widely accepted amongst the technical community and a number of countries have now decided to move forward with this option."[10] Extensive studies on deep geological disposal have been conducted globally, including in countries such as China and France.

Chinese Practice

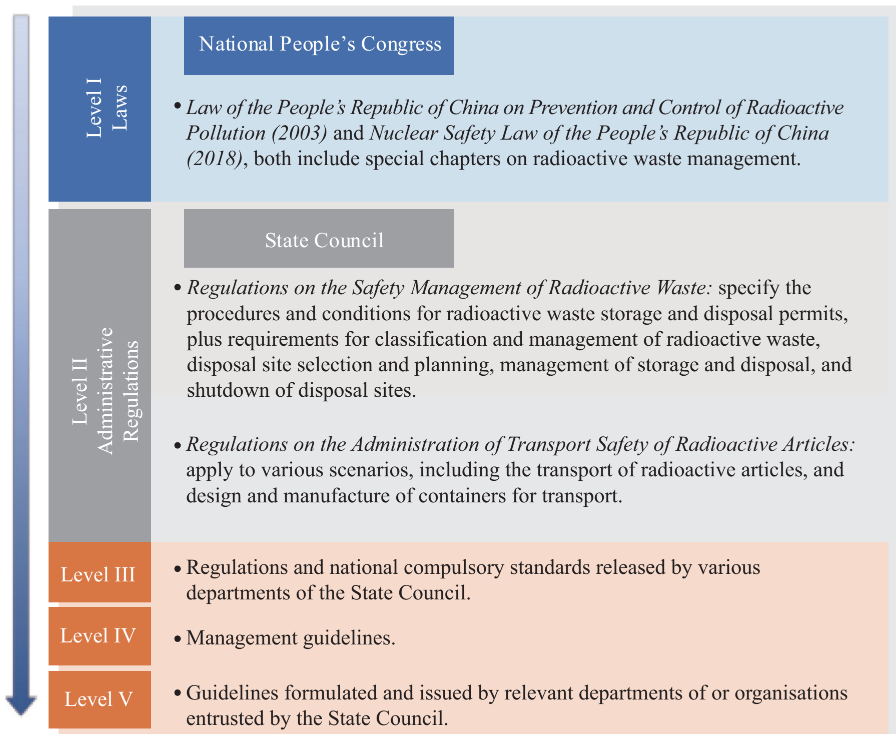
(1) Establishing a radioactive waste management system

China has established a comprehensive framework comprising policies, regulations, and standards to govern the treatment of radioactive waste. A series of measures have been adopted to ensure the safety of radioactive waste management, prioritising the protection of workers, the general public, and the environment from potential radiation hazards.

Regulations and standards for radioactive waste management continue to be improved. China has strengthened regulations

[10] IAEA, *The Long-Term Storage of Radioactive Waste: Safety and Sustainability – A Position Paper of International Experts*, 2003.

covering the siting, design, construction, operation, and post-closure monitoring of diverse radioactive waste management facilities, to better protect individuals and the environment. The system of regulations and standards for radioactive waste management in China is illustrated in Figure 4-28.



(Source: CNNC)

Figure 4-28 China's System of Regulations and Standards for Radioactive Waste Management

The division of responsibilities among government departments in radioactive waste management is well-defined in China. Competent authorities have designated responsibilities, as shown in Figure 4-29.

The CAEA formulates policies, regulations, plans, and standards

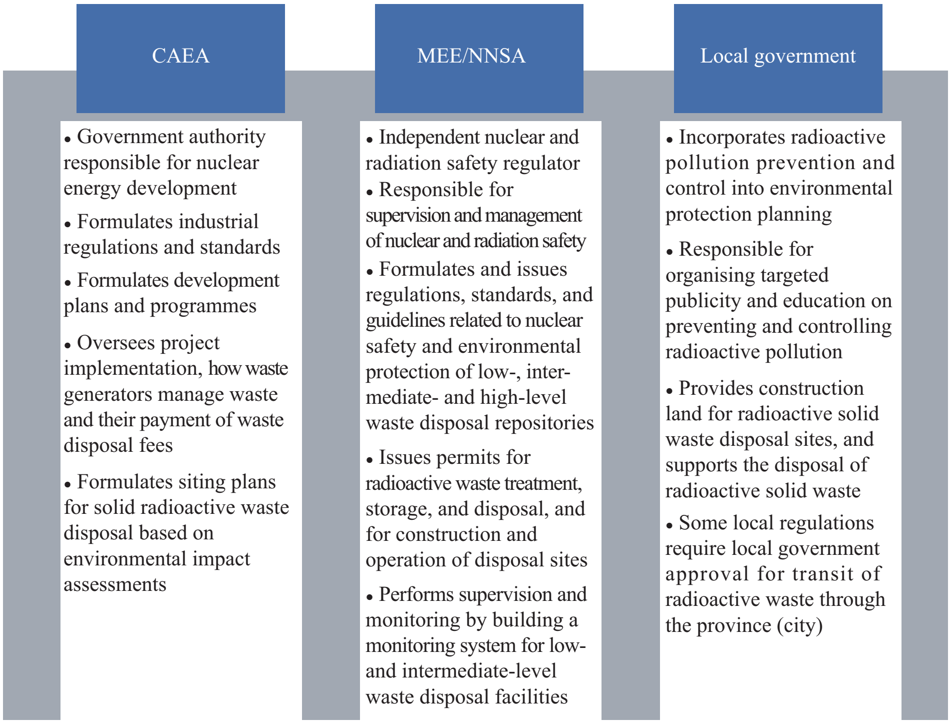
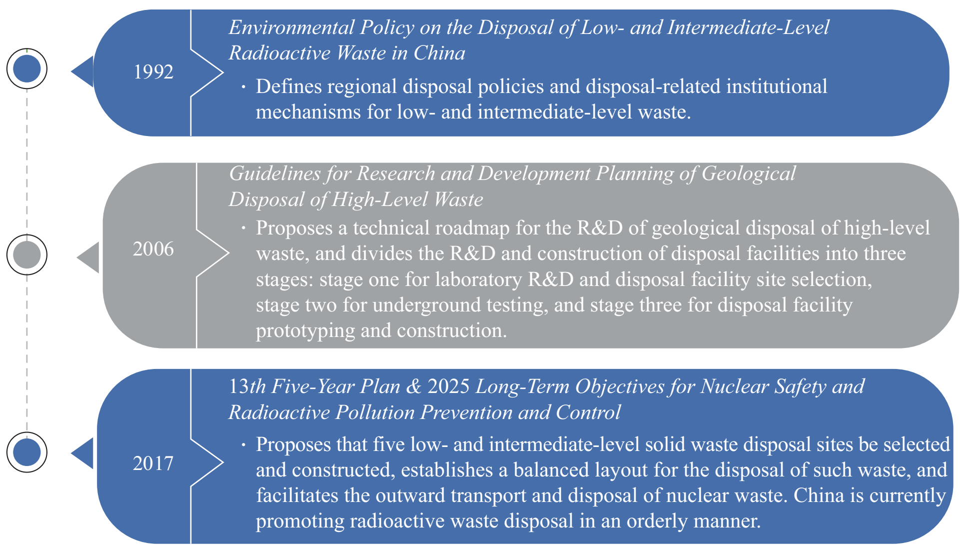


Figure 4-29 China's Division of Responsibility in Radioactive Waste Management

for spent fuel and radioactive waste management; it also spearheads efforts in addressing nuclear-related emergencies and bolstering capacity building. The MEE/NNSA oversees the prevention and control of radioactive pollution nationwide and is responsible for the supervision and management of radioactive waste in the country. Other relevant departments regulate the management of spent fuel and radioactive waste according to their designated responsibilities and in accordance with the law.

China's policies and plans for radioactive waste management are characterised by a people-centred focus, harmonious development, a combination of prevention and treatment, strengthened management, and a priority on safety. In the

1990s, China rolled out a series of policies and plans including the *Environmental Policy on the Disposal of Low- and Intermediate-Level Radioactive Waste in China*, the *Guidelines for Research and Development Planning of Geological Disposal of High-Level Waste*, and *13th Five Year Plan & 2025 Long-Term Objectives for Nuclear Safety and Radioactive Pollution Prevention and Control*, to chart the course for the safety and management of the country’s radioactive waste.



(Source: CNNC)

Figure 4-30 China’s Policy and Planning of Radioactive Waste Management

(2) Building waste treatment and disposal capacity for the safe development of nuclear power

In China, radioactive waste primarily originates from NPPs, research reactors, the nuclear fuel cycle, the use of nuclear technology, and the exploitation of uranium (thorium). To maximise technical, economic, environmental, and social benefits, meticulous control and optimisation are applied throughout the entire process, from waste generation to disposal, and covering all types of radioactive waste, including gaseous, liquid, and solid waste (see Figure 4-31).

Control of waste generation	Pretreatment	Treatment	Conditioning	Disposal
• Optimised system • Balanced design • Reliable equipment and strict management	• **Gaseous waste** treatment methods include filtration, adsorption, and storage for decay • **Liquid waste** treatment methods include filtration, evaporation, ion exchange, silica gel adsorption, and membrane treatment • **Solid waste** treatment methods include cement solidification (stabilisation), supercompression, high-integrity containers and hot compression		• Conversion of radioactive waste into stable, standardised packages that meet disposal requirements	• Storage for decay • Landfill disposal • Near-surface disposal • Intermediate depth disposal • Deep geological disposal

(Source: CNNC)

Figure 4-31 Basic Steps of Radioactive Waste Management

First, disposal of low-level waste. For low-level waste, China has adopted a "centralised + region-based" approach. The Longhe Disposal Site was built for centralised disposal. The construction of regional disposal sites have commenced, as shown in Figure 4-32, in those coastal provinces with NPPs (such as Fujian, Guangxi, Liaoning, Shandong, and Zhejiang).

Second, disposal of intermediate-level waste. China is actively conducting research (encompassing source term investigations on relevant wastes, technology development for intermediate depth disposal, and preparatory efforts for constructing disposal repositories) on the disposal of intermediate-level waste. In October 2019, the CAEA approved the initial research projects for intermediate depth disposal of radioactive waste.

Third, deep geological disposal of high-level waste. China has initiated the construction of an underground laboratory in Beishan, Gansu Province that will be dedicated to geological disposal. Substantial advances have been achieved in building the main component of this underground laboratory. Additionally, the IAEA Collaborative Center for Geological Disposal of High-Level Waste has been established.

Longhe Near-Surface Disposal Site

Underground laboratory

01 **Near-surface disposal**

- Longhe Near-Surface Disposal Site has a capacity of 1 million m^3; phase one came into operation in 2022.
- Preliminary selection of decentralised disposal sites was conducted in coastal provinces with NPPs, including Fujian, Zhejiang, Guangxi, Liaoning, and Shandong.

02 **Intermediate depth disposal**

- China has basically gained the intermediate depth geological disposal technology; in October 2019, CAEA approved the preliminary research project (top-level design) for intermediate depth disposal of radioactive waste.

03 **Deep geological disposal**

- CAEA, Ministry of Science and Technology (MOST), and former State Environmental Protection Administration jointly issued the *Guidelines for Research and Development Planning of Geological Disposal of HLW.*
- In 2011, Beishan, Gansu Province was identified as the preferred pre-selection area for HLW disposal in China. The project on underground laboratory for geological disposal of HLW was approved in 2019. Major works on the underground laboratory shaft begun in 2021, marking the start of engineering practice.

(Source: CNNC)

Figure 4-32 Radioactive Waste Disposal Sites in China

(3) Minimising radioactive waste from NPPs

China is actively working – through various measures (including the exploration and application of innovative technologies such as membrane technology for liquid radioactive waste processing, drying technology for chemical liquid waste, drying and hot pressing technology for waste resin, wet oxidation and efficient solidification technology for waste resin, incineration technology for combustible waste, high integrity containers, and mobile liquid waste treatment devices) – to reduce radioactive waste generated by NPPs. Currently, under normal operating conditions (after conditioning), the annual volume of radioactive solid waste generated by China's operating GW-class PWRs is less than 50 m^3.

French Practice

(1) The role of Andra

Andra is responsible for finding and implementing safe management solutions for all French radioactive waste in order to protect present and future generations from the risk presented by this waste. The role of Andra has been defined by two successive laws: the law of 30 December 1991 which created the Agency as an industrial and commercial public institution and entrusted it with, in particular, research into the deep storage of long-lived high-level radioactive waste and the law of 28 June 2006 relating to the sustainable management of radioactive material and waste.

In France, the waste is produced each year mainly through the generation of nuclear energy (about 60% of the stored waste in 2020) but also by research, national defence, industry and the health sector. The most radioactive and long-lived waste, some of which will remain hazardous for more than 100,000 years, cannot be stored on the surface, or at a shallow depth, as it cannot be guaranteed that appropriate protection will be maintained over such time scales.

(2) Purpose of the CIGEO underground storage facility

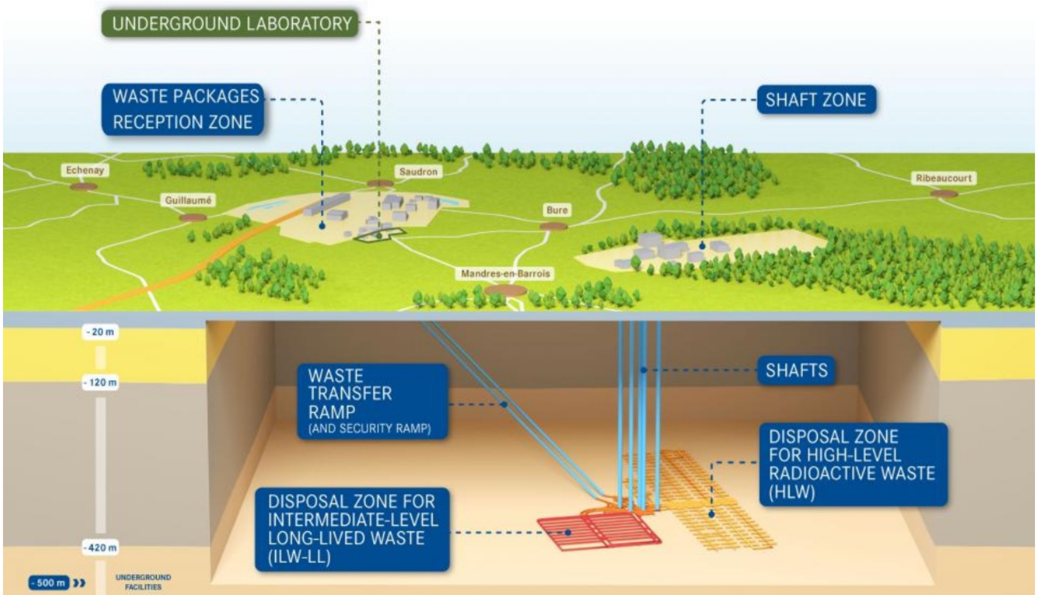
France was one of the first countries to recognise the requirement to establish a responsible and proactive policy for the management of radioactive waste. With the 1991 law, the French Parliament placed

French policy in a context of finding sustainable and safe solutions for this waste, with the aim of not leaving future generations with the burden of waste produced by the activities from which we benefit daily.

This is why, in 2006, Parliament selected the implementation of deep storage as the only solution capable of ensuring the long-term safety of radioactive waste while limiting the burden on future generations. The law of 28 June 2006 gave Andra the task of designing and setting up the CIGEO storage facility that will receive the waste. France was supported in this choice by a Council of the EU directive in 2011. Many countries have also started research on deep storage. In Sweden and Finland, construction permit applications are under examination.

In 2022, the *Declaration of Public Utility* was published, confirming the importance of the project for the nation. At the end of 2022, the application for construction permit for the storage centre was submitted by Andra to the competent authorities and a period of examination of approximately three years by the French ASN began, which will be followed by a public inquiry before the construction permit is enacted in law.

CIGEO is designed to store waste whose level of radioactivity and lifespan do not allow its long-term safe storage on the surface, or in the shallow storage centre also studied by Andra. High-level waste (HLW) and long-lived intermediate-level waste (LL-ILW) come mainly from the nuclear power sector and associated research activities, as well as, to a lesser extent, national defence activities.



(Source: Andra)

Figure 4-33 CIGEO Disposal Facility Project

(3) Assumptions used for the sizing of CIGEO

The scenario used today as the reference case for the sizing of CIGEO is a continuation of nuclear power generation with an assumption of 50 years of operating life for existing facilities. This assumption does not prejudge the decision of the public authorities to authorise or not authorise an extension of the operating life of the reactors. Waste that will be produced by the nuclear facilities under construction or being commissioned is also taken into account (Flamanville EPR, Jules Horowitz experimental reactor, ITER research facility). CIGEO could be adapted to waste produced by a potential future reactor fleet.

The volumes of HLW and LL-ILW that could be stored in CIGEO are thus estimated at approximately 10,000 m^3 for HLW (i.e.

approximately 60,000 packages), and approximately 73,000 m^3 for LL-ILW waste (approximately 180,000 packages). These volumes relate to conditioned waste.

5 Scientific and Technological Innovation in Nuclear Energy

Both China and France have established comprehensive systems for nuclear scientific and technological innovation. With mature technology in large PWRs, both countries are stepping up their efforts in advanced nuclear technologies and are making significant contributions to global innovation in nuclear energy.

A "three-step" scenario of the sustainable development of nuclear energy and related innovation can be achieved by transitioning from thermal reactors to fast reactors and then fusion. Laying the groundwork for large-scale construction, China and France have made substantial progress in scaling up the development of thermal nuclear reactors. Additionally, both countries are promoting the R&D and deployment of SMRs and Generation IV reactor technologies to enhance safety, cost-effectiveness, and proliferation resistance. Furthermore, both China and France are actively involved in the research and development of controlled fusion technology, participating in the ITER project of the International Big Science Program.

5.1. A Three-Step Strategy in Nuclear Energy

Drawing global attention, the field of nuclear science and technology has always been full of vitality. In recent years, a great number of innovative nuclear reactors, advanced nuclear fuel cycles and multipurpose solutions for nuclear energy utilisation have been developed, and have brought continuous breakthroughs in nuclear innovation.

Chinese Practice

In the 1980s – along with a supportive policy for the closed fuel cycle – China introduced a "three-step" strategy for nuclear energy development, encompassing thermal, fast, and fusion reactors. Since then, China's thermal reactors have seen significant improvement, including serialisation, standardisation, and large-scale development for nuclear power. With improved safety measures and reduced costs, nuclear energy's versatility and applications have been further extended. Complemented by the construction of experimental fast reactors, a robust scientific research system has been established for fast reactors. Also, China has intensified its efforts in the research and development of controllable nuclear fusion technology.

Since the 1980s, China has – in leveraging the technological strengths and foundational research capabilities of the entire nuclear industry chain – introduced a series of PWRs with electric outputs of 300 MWe, 600 MWe, 1,000 MWe, 1,200 MWe, and 1,400 MWe. These include CNP, CP, ACPR, HPR, and CAP models. As PWR technology has been standardised for mass production, the National Science and Technology Major Project for Advanced Large PWRs and HTGRs, has received approval and funding, and the CAP1400 model demonstration project is already underway.

Drawing upon over 40 years of expertise in designing, constructing, and operating nuclear power projects, China has successfully developed its proprietary HPR1000 Generation III nuclear power technology with independent intellectual property rights. As per schedule, the first global demonstration project of HPR1000 was completed and commenced operations in 2021. With mass production capacity, HPR1000 has become the major model for newly constructed nuclear power units in China and has also gained traction internationally. The HTGR demonstration project has already been successfully integrated into the grid, and the multipurpose SMR demonstration project under construction in Changjiang (Hainan Province) is expected to be put into operation in 2026.

With a number of overarching goals, including ensuring a sustained supply of nuclear energy, enhancing the utilisation rate of uranium resources, and transmuting long-lived radionuclides, efforts have been dedicated to advancing fast reactor nuclear energy systems. China has not only built the CEFR but is also actively engaged in the development of LFRs and integral fast reactor nuclear energy systems. Looking ahead, the country is committed to fostering the coordinated development of thermal and fast reactors, bolstering the capabilities of the closed fuel cycle system, optimising the recycling of uranium resources, and minimising radioactive waste through the application of transmutation technology.

Focusing on the primary objective of controlled thermonuclear fusion, research in nuclear fusion has achieved noteworthy advances. China joined the ITER project in 2006. The country has also established experimental devices for fusion research, such as the HL-1, HL-2A, HL-3, and EAST, and made new breakthroughs in experimental fusion science and plasma physics research.

French Practice

Innovation is the very essence of EDF R&D, which is motivated by two missions: improving performance in all today's activities and preparing for the future by working on breakthrough technologies. To this end, it actively contributes to nuclear research with its academic and industrial partners in various projects at French and European levels.

EDF R&D is strongly involved in several fields of research related to innovation in the nuclear sector. These fields include the design of new generations of generating units, improving the maintenance and operation of existing power plants, guaranteeing safety and extending the lifespan of power plants.

EDF R&D has launched a far-reaching programme designed to identify technology barriers to the extension of NPPs' operating lifespans beyond 60 years. More broadly, the EDF Group (EDF and Framatome) conducts R&D in partnership with the CEA as part of the Institut Tripartite and is developing the Nuclear Plant of Tomorrow Initiative which is structured in technological blocks for existing plants and nuclear new builds. EDF R&D is also working to hybridise NPPs with other technologies. The EDF R&D researchers are also involved in work on several innovations aimed at improving the design of future NPPs.

EDF R&D plays an important role in the Sustainable Nuclear Energy Technology Platform (SNETP), the international association dedicated to R&D in the field of nuclear power which is made up of 108 members.

Collaboration within the SNETP provides the possibility of benefiting from an international network to form complete and complementary research teams on different topics. The main areas are nuclear safety, the development of future reactors, their hybridisation for co-generation, the production of radioisotopes for the medical field and hydrogen production.

EDF R&D's scientific partnerships in France, internationally and particularly in China

To conduct its research and development programmes, EDF R&D nurtures a large number of partnerships both in France and internationally. The goals are to attain the highest international levels in the disciplines at the heart of the EDF Group's key challenges and to supplement its in-house skills and direct academic research towards R&D that is relevant for the EDF Group. EDF R&D's partnership policy is embodied in a variety of ways, both nationally and internationally. Countries include China, Germany, Italy, Singapore, the United Kingdom and the United States.

In France, EDF R&D has entered into framework agreements with major public research organisations. The main academic partner in France is the French national research agency CNRS. Over the past few years, EDF R&D has also set up about twenty laboratories and teams on a joint basis with academic partners and technical or industrial centres. The EDF Group is the driving force behind ConnexITy, an R&D programme aimed at connecting players in the nuclear sector, using digital technologies. EDF R&D has also set up the Materials Ageing Institute (MAI), an international research centre on materials ageing that brings together, alongside EDF, most of the world's major nuclear operators.

In China, the centre based in Beijing is a valuable asset for taking part in partners' large-scale Chinese demonstrator projects for smart grids and nuclear facilities. It also benefits from China's highly advanced additive manufacturing ecosystem. In 2022, the centre delivered the electricity trading platform established by the EDF China subsidiary with a local partner as part of the market deregulation decided by the Chinese government. The centre also actively supports EDF China's commercial activities in the field of local multi-energy projects combining electricity, biomass, and heating and cooling networks.

5.2. Innovation in Nuclear Reactor Technology

While fostering the development and deployment of SMRs, China and France have both developed Generation III PWR technology through iterative optimisation. Extensive research has been dedicated to exploring diverse variants of Generation IV nuclear reactors. The two countries are actively participating in the ITER project and making substantial contributions to the ongoing advances in controlled nuclear fusion research.

5.2.1. Generation III reactors

China's HPR1000

The HPR1000 is an independently developed Chinese Generation III PWR technology. It is based on progressive designs of mature PWRs and is supported by over 40 years of engineering practice in the design, construction, commissioning, and operation of NPPs. Inspired by international Generation III nuclear power concepts, the technology uses insights from past NPP incidents worldwide to enhance its safety features. Ensuring its safety, cost-effectiveness, and operational performance, the HPR1000 features a 177-fuel-assembly core, an integration of active and passive safety design that offers enhanced protection against external events, and demonstrates remarkable capabilities for preventing and mitigating severe accidents; it also meets the latest IAEA safety standards and the requirements set by international users of advanced light water reactor technologies such as the European Utility Requirement (EUR) and the United States Utility Requirements Document (URD).

(1) R&D process

In 1999, CNNC began the conceptual design of the CNP1000, a GW-class PWR. This design, comprising 177 assemblies, was an enhanced iteration of Generation II nuclear power technology. Including the adoption of a single-reactor layout and a double-layer safety containment system, CNNC has since made 22 significant technical enhancements to the original 177-assembly design. These improvements effectively transformed the original model into the CP1000, incorporating key technical features of Generation III PWR. Building upon this foundation, CNNC began in 2010 to try to fulfill Generation III nuclear power technology requirements by initiating R&D efforts for the ACP1000. Following the Fukushima nuclear accident in Japan in 2011, CNNC subsequently expedited these efforts. Embracing a technical approach that integrates both active and passive safety design, the organisation has conducted a comprehensive series of experiments and demonstrations.

(2) Project implementation

The construction of the HPR1000 demonstration project, Fuqing-5, began on 7 May 2015, and was completed within the designated timeframe and budget. This unit began commercial operations on 30 January 2021. Currently, there are five HPR1000 units in operation globally, with additional units being mass-produced in China. As of December 2023, there were 11 HPR1000 units under construction, and 10 HPR1000 units approved for construction. On a global scale, China has successfully exported three HPR1000 units to Pakistan, of which one (Chashma NPP C5) is undergoing preparatory work and two (the Karachi NPP K2 and K3) are already in operation as scheduled. Furthermore, a general contract has been signed with Argentina, and cooperative intentions have been established with many other countries.

(3) Characteristics of design and technological innovation

Adhering to the principles of defence-in-depth, reliability and diversification, the design of the HPR1000 was developed with a balanced consideration of safety, cost-effectiveness, and technical maturity. Aligning with the principles of deterministic design and a quantitative approach to risk-informed safety analysis, the safety systems were meticulously configured. The design is highlighted by technical innovation in the reactor, containment, safety systems, and operational performance.

- The HPR1000 reactor core consists of 177 fuel assemblies (see Figure 5-1), which reduces its average linear power density and increases its operating safety margin. The HPR1000 can be equipped with CF3 fuel assemblies, featuring cladding made of N36 zirconium alloy material, significantly enhancing discharge burnup. This design also allows for 18-month refueling, thus improving the NPP's utilisation rate and reducing operational costs.

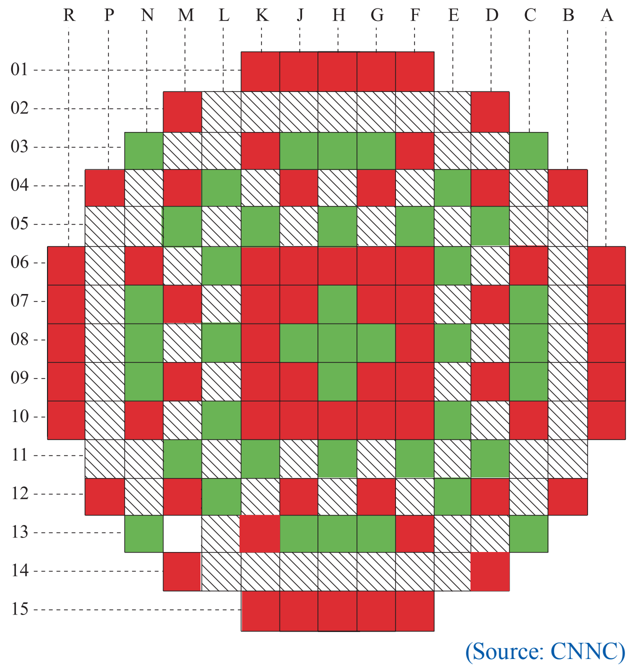


Figure 5-1 The HPR1000 Reactor Core Loaded with 177 Fuel Assemblies

- The HPR1000 adopts a double-layered containment design that integrates both active and passive safety measures (see Figure 5-2). The non-powered passive safety measures complement the active safety measures and provide a diversified safety system for the power plant to achieve defence-in-depth.
- The HPR1000 incorporates advanced measures aimed at preventing and mitigating severe accidents. Additional safety measures have been implemented to prevent core meltdowns under high-risk conditions. Furthermore, comprehensive mitigation measures are in place

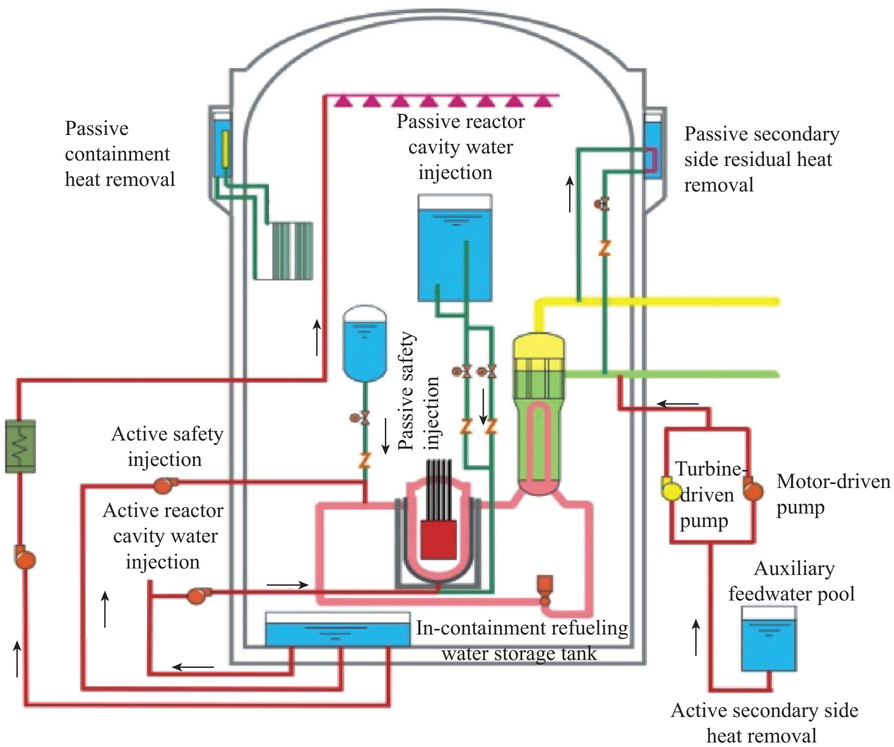
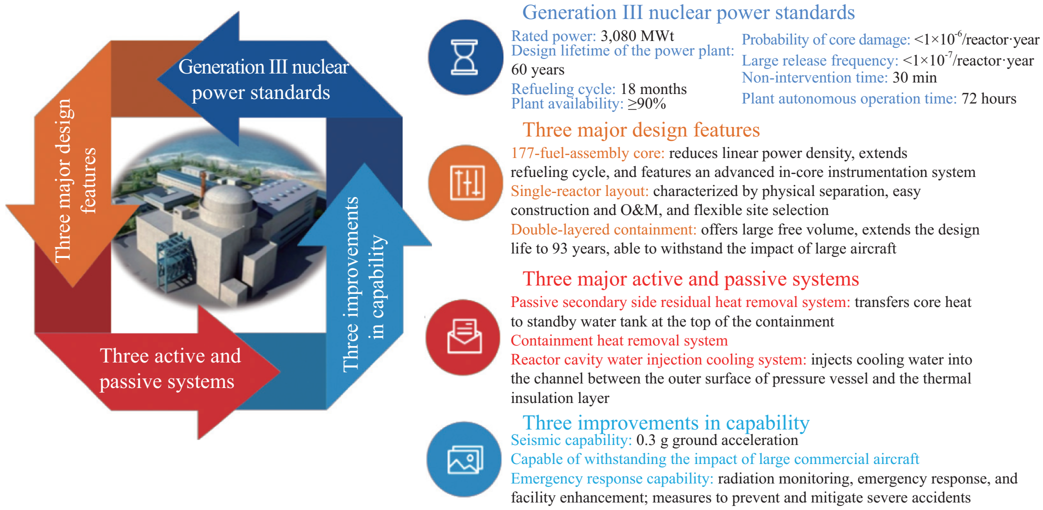


Figure 5-2 Integration of Active and Passive Safety Measures in the Design of HPR1000

to safeguard against incidents that could potentially compromise the integrity of the containment structure. This design effectively minimises the risk of major radioactive release at an early stage.

- The unit is enhanced to withstand extreme external hazards, such as earthquakes, flooding, and impact from large aircraft. The non-intervention period for operators has been extended, and the self-sustainability of NPPs has been improved.
- The service life of NPPs has been extended. Non-replaceable equipment of the HPR1000, such as pressure vessels, can operate for 60 years. Effective ageing management is in place to facilitate the repair and replacement of replaceable components, ensuring that

NPPs will reach their designated 60-year target service life. The main technical characteristics of the HPR1000 are shown in Figure 5-3.



(Source: CNNC)

Figure 5-3 Main Technical Characteristics of the HPR1000

(4) Further improvement

The ongoing enhancement of the HPR1000 encompasses the utilisation of advanced nuclear fuels; optimisation of safety systems; and advances in the construction, operation, and maintenance of smart NPPs, and basic theoretical research. This progress is grounded in both operational unit experience, as illustrated in Figure 5-4, and broader efforts to develop subsequent iterations of HPR1000 designs that prioritise safety, cost-effectiveness, and technological advancement in line with the latest developments in global light water reactor technology. Some of the measures include the following:

- The simplification of peripheral systems through the incorporation of passive safety concepts;
- The introduction of advanced nuclear fuel elements to improve the

intrinsic safety and cost-effectiveness of reactors;

- The adoption of modular design and construction to facilitate standardised construction;
- The utilisation of digital technology in design and construction to enable digital delivery;
- The application of artificial intelligence, 5G, big data, industrial IoT and other technologies to facilitate the transition to smart NPPs.

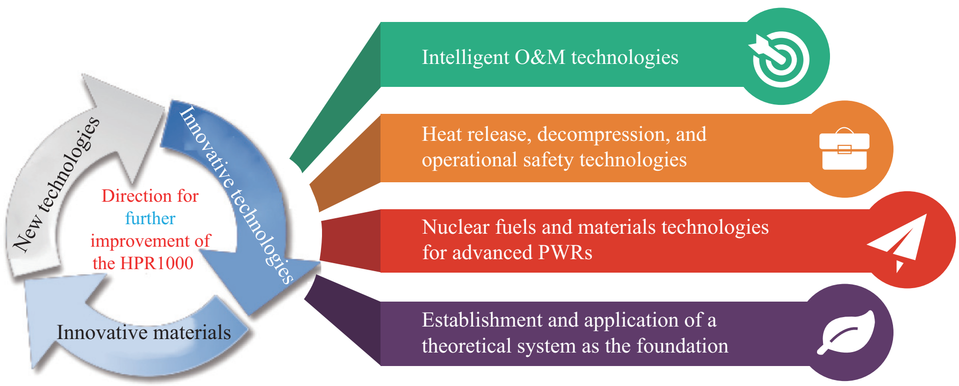


Figure 5-4 Further Improvement of the HPR1000

France EPR Series

The PWR is the most common technology in the world. It is also the technology used by reactors currently in operation in France. It is based on the experience from a standardised French nuclear fleet of 58 reactors, representing more than 2,000 reactor years.

The EPR is a third-generation PWR. The project started in the late 1980s, in the context of a joint project between France and Germany, with the aim of significantly improving the safety and protection of workers from ionising radiation. One of the main advances of the EPR was that the risk of a core meltdown accident was taken into account at the design stage. The EPR design has been approved by four safety authorities (China, Finland, France, and the United Kingdom). There are three units in operation (two in China, one in Finland), one under commissioning process (France) and two under construction (the United Kingdom).

General safety goals for the EPR reactor

- Reduce the individual and collective doses received by workers, in normal operations and during operating incidents.
- Reduce the number of significant incidents with the aim of reducing the possibility of accident conditions as a result of such events.
- Significantly reduce the frequency of core meltdown.
- Significantly reduce radioactive releases that may result from all conceivable accident conditions, including an accident with core meltdown.

(1) General characteristics of the EPR

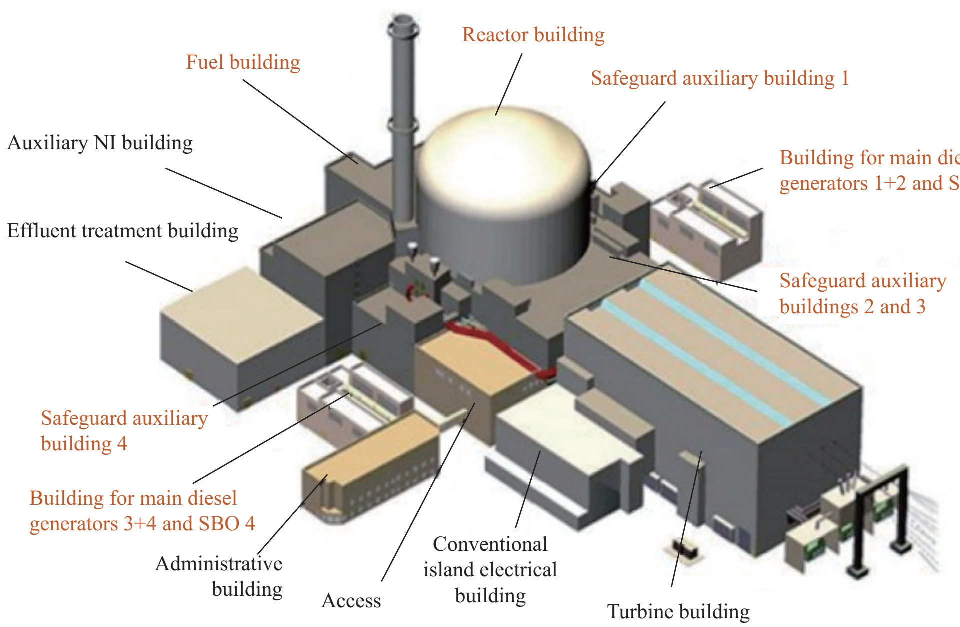
The EPR is referred to as an "evolutionary" reactor as its design is based on that of existing reactors (French *N4* and German *Konvoi* designs). It therefore benefits from proven technologies and the operational experience from its predecessors. It is a high-power reactor with a generating capacity of 1,650 MWe gross, or 1,630 MWe net. It is designed for an operating life of 60 years.

Significant changes have been introduced to strengthen accident prevention and mitigation, in particular accidents that may result from multiple failures, to better protect the facility from the effects of internal and external hazards, and to limit the potential consequences of an accident with core meltdown. In addition, provisions have been made to make severe accident conditions that are likely to lead to significant early releases physically impossible, or, failing that, to make these conditions very unlikely with a high confidence level (these are referred to as “practically eliminated” conditions).

Thus, for the EPR:

- The main safety systems and their support systems (power supply, cooling circuit, instrumentation and control) have four independent and geographically separated safety trains.
- The power supply to the safety systems is ensured by four main generator sets which start automatically in the event of the loss of the normal power supply and by two generator sets of a different design to cope with the loss of the normal power supply combined with the unavailability of the four main generator sets.
- The water reserve used to cool the core in the event of a leak on the reactor coolant system is located inside the reactor building, protected from external hazards.
- The reactor building, the spent fuel assemblies temporary storage building and two of the four buildings housing the first line safety systems are protected from aircraft crashes by a thick concrete structure.
- The water source used for cooling the facility’s systems, called the heat sink, has four identical and separate channels. In addition, two diversified channels (i.e. using equipment with different technology) can cope with a loss of the above four channels through common mode failure.

- A corium catcher to cool the molten core in the event of a severe accident is located at the bottom of the reactor building. It allows the corium (the mixture resulting from the meltdown of the fuel and the internal structures of the reactor vessel) to be collected and cooled.



(Source: EDF)

Figure 5-5 General View of the EPR Reactor

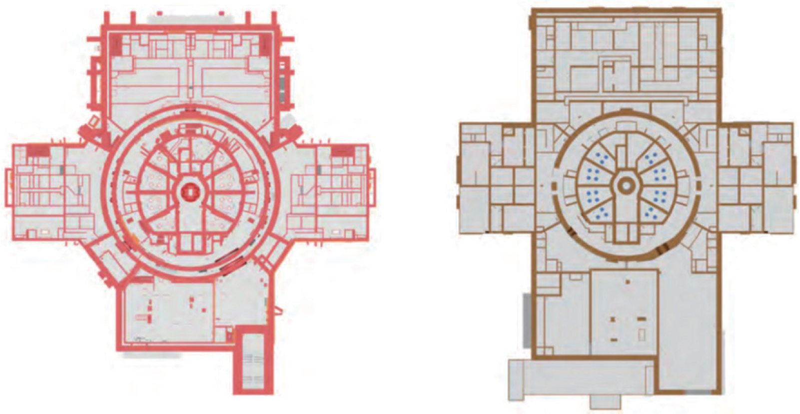
(2) EPR2

The EPR2 takes into account feedback from the design, industrialisation and construction of the various EPR models. Like the EPR, EPR2 is a Generation III reactor, designed to be operated for at least 60 years, with high power output (of the order of 1,670 MWe). It considers the lessons of the accident at the Fukushima Daiichi power plant in March 2011 and the consequences of global warming from the design stage. The EPR2 reactor can also be operated to adapt its power output to electricity supply and demand, particularly in a decarbonised power mix, with a significant share of intermittent renewable energy resources that are priorities in the merit order. The EPR2 is part of the industrialisation logic of the EPR, based on the lessons learned from the construction of other EPRs. The first EPRs constructed in France and worldwide allowed the operational performance of its implementation to be improved.

Its design was guided by the planning for its execution, it was mainly focused on facilitating the construction and control of industrial quality. It incorporated performance optimisations derived from operating experience with the French nuclear fleet. The EPR2 benefits from a wide replication of technical solutions and their implementation frame of reference developed during the construction of the first EPRs in France and around the world. The main levers for this optimisation are listed below.

Main optimisation levers for the EPR2 reactors include:

- Operating experience from EPR projects and the current nuclear fleet. Operating experience comes from the EPR construction projects at Flamanville, Olkiluoto in Finland, Taishan in China, and Hinkley Point in the United Kingdom. It also comes from the involvement of operations and maintenance personnel from EDF's current nuclear fleet.
- Improve constructability. Design simplifications improve the constructability of civil engineering and the installation of electromechanical systems. These points optimise the planning and construction cost, without jeopardising the high safety standards (see Figure 5-6).



(a) EPR (b) EPR2

(Source: EDF)

Figure 5-6 Comparison of Building Structure Between an EPR and an EPR2

- Use factory prefabrication and modularity. Systematic prefabrication of certain large assemblies or modules facilitates work on site, provided that sufficient space is available to organise the site.
- Industrialise the product and rely on good practices from other industries and standardise. The reduction in the number of equipment references in favour of standard industry models, available in supplier catalogues, is a factor in simplifying and securing the quality of production. It is part of a general approach to the design of EPR2, which involves many categories of equipment.
- Digitise nuclear engineering and optimise construction using 3D and 4D models. The EPR2 is the first reactor to be designed by EDF entirely from digital data in a tool that allows all the data used to be capitalised on over the reactor's lifespan. This "data-centric" management limits the sources of error, as the digital data becomes the sole source of data.

(3) EPR1200

The EPR1200 is a mid-size third-generation PWR. It is designed to meet a large variety of safety and regulatory requirements as well as different location-specific conditions. Robust and standardised designs not only contribute to safety in nuclear power, but also to cost reduction throughout the construction process as well as during operation, through the sharing of operating experience, benchmarking and industrial synergies.

The EPR1200 performance is summarised as follows:

• Net power output: around 1,200 MWe (depending on the site conditions)

• Operational lifespan: at least 60 years

• Plant design availability: higher than 90%

• Operation cycle length: 18 months, with potential ability to be adapted to 12 to 24 months depending on customer requirements

• Fuel: UO_2 enriched up to 5%

• Load following: Load following ability takes into account the French fleet's long experience in varying power output to balance generation in the presence of intermittent renewable energy resources, such as wind and solar.

EPR1200 is designed according to the EPR2 design basis (requirements, architecture, manufacturing, quality level, quality control, in-service inspection, etc.). Its design has followed the system engineering principles. EPR1200 takes into account EPR2 design optimisations based on construction and operating experience from all current EPR projects. Most of the main design options have already been reviewed by the French ASN.

The general layout of EPR1200 is identical to EPR2, and replicates all major civil engineering choices in the EPR's common design basis, e.g. the cross-shaped basemat, the choice of a water reserve inside the reactor building, the core-catcher, the exact fuel storage pool location and dimensions, and much more. Most of the major safety-related components remain standard to the EPR's common design basis, e.g. steam generators, pressuriser, and reactor coolant pumps. It inherits all codes and standards used by EPR2, is compliant with the goals of the IAEA, WENRA, EUR recommendations and the European grid code requirements for generators for 50 Hz.

5.2.2. SMRs

SMRs are modularly designed reactors with a power capacity of up to 300 MWe per unit. They offer several technical advantages:

- Advanced design concepts enhance safety, significantly reduce the probability of reactor core damage, and practically eliminate the need for off-site emergency response.
- A small and compact reactor core, often coupled with a passive safety design, results in fewer required equipment and systems.
- Factory fabrication and modular construction streamline large-scale construction, leading to a shorter construction period and lower risk of delays.
- Applicability to combined heat and power (CHP), district heating, desalination, and other applications of nuclear energy contributes to the reduction of GHG emissions.
- A small initial investment mitigates investment risks and lowers financing costs.

SMRs have been hailed as "game changers" in the field of nuclear energy due to their diverse, extra-safe power solutions. In addition to providing low-carbon electricity as a baseload power source, SMRs present low-carbon energy solutions for high energy-consuming industries, including district heating, industrial steam supply, transport, building construction, and desalination. The versatility of SMRs extends to various scenarios, making them applicable even in regions with limited grid capacity or within emerging economies. Making it easier to comprehensively utilise nuclear energy, SMRs can also replace existing small coal-fired or CHP units. SMRs exhibit distinctive advantages in special scenarios such as remote areas, island development, and offshore oil drilling platforms.

Recognising the cruciality of SMR technology in nuclear development, major nuclear-producing countries actively support technological R&D among domestic enterprises. According to the IAEA, there are currently over 80 small reactor designs ongoing worldwide. These designs encompass a diverse array of reactor technologies and fuel types, ranging from both land- and marine-based light water reactors (LWR), HTGRs to liquid metal fast reactors and MSR[1], as shown in Table 5-1 and Figure 5-7.

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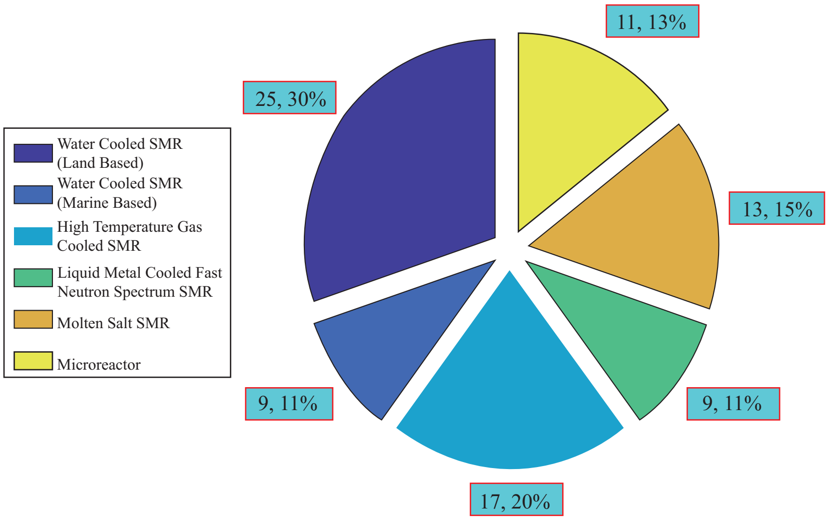
1 IAEA, *Advances in Small Modular Reactor Technology Developments*, 2022 Edition.

Table 5-1 Global Map of SMR Technology Development

Number	Country	Model
1	ARGENTINA	CAREM
2	CANADA	STARCORE, CANDU SMR, IMSR400, ARC-100, SSR-W
3	CHINA	ACP100, ACPR50 S, CAP200, ACP100 S, DHR400, HTR-PM, HAPPY200, HTR-10, NHR200-II, smTMSR-400
4	CZECH REP	TEPLATOR, ENERGY WELL
5	DENMARK	CAWB, CMSR
6	FRANCE	Nuward, Blue Capsule, Calogena, GenF, Hexana, Jimmy, Naarea, Newcleo, Otrera, Renaissance Fusion, Stellaria, Thorizon
7	INDONESIA	PeLUIt/RDE, THORCON
8	ITALY	LFR-AS-200
9	JAPAN	HTTR, IMR, 4S, BWRX-300, FUJI, GTHTR-300, MoveluX
10	KOREA REP	i-SMR, SMART, BANDI-60, microURANUS
11	NETHERLANDS	THORIZON
12	RUSSIA	KARAT-45, ABV-6E, VBER-300, MHR-T, SVBR, RITM-200N, KARAT-100, KLA-40S, SHELF-M, MHR-100, ELENA, VK-300, RUTA-70, RITM-200M, GT-MHR, BREST-OD-300, UNITHERM
13	SANDI ARABIA	SMART
14	SOUTH AFRICA	AHTR 100, PBMR-100, HTMR 100, AMR
15	SWEDEN	SEALER-55
16	SWITZERLAND	STAR
17	UK	Rolls-Royce SMR, SSR-U, LFR-TL-X, U-Battery
18	USA	VOYGR, BWRX-300, SMR-160, Westinghouse SMR, mPower, OPEN20, FMR, EM^2, Xe-100, SC-HTGR, Westinghouse LFR, KP-FHR, MK1 PB-FHR, MCFSR, LFTR, THORCON, AURORA, HOLOS-QUAD, MARVEL, MMR, Westinghouse eVinci



(Source: IAEA Advanced Reactors Information System)

Figure 5-7 Number and Proportion of SMRs around the World

Chinese Practice

China is actively engaged in R&D and the commercial application of SMR technology. On July 13, 2021, China initiated the construction of a multi-purpose SMR technology demonstration project in Changjiang, Hainan Province, as shown in Figure 5-8. This demonstration project leverages ACP100 technology to achieve a reactor thermal capacity of 385 MW and an electrical power output of 125 MW. The construction is scheduled to be completed within 58 months. Marking the peak of the installation of the world's first ACP100 reactor, the reactor core module was successfully installed in August 2023; and the project is expected to be completed in 2026. With a single-reactor and single-unit design, ACP100 will function as a multi-purpose demonstration for trigeneration (i.e., power generation, refrigeration, and desalination). Upon completion, the project is projected to have an annual power output of up to 1 TWh, sufficient for 526,000 households.[2] This will result in an annual reduction

[2] *Technical Scheme and Demonstration Project Progress of ACP100*. Song Danrong.

of CO_2 emissions by nearly 880,000 tonnes, which is the equivalent of planting 7.5 million trees each year. As such, the ACP100 project promises remarkable benefits in GHG emissions reduction.

(Source: CNNC)

Figure 5-8 Construction Site of Multipurpose SMR Demonstration Project at Changjiang in Hainan Province

The ACP100 is an innovative integral reactor design. The coolant system features forced circulation and consists of external steam pressurisers, novel built-in once-through steam generators, and built-in canned motor pumps. The reactor module includes an integral reactor head package, a passive safety system, and a distributed digital instrumentation and control (I&C) system. The power generation system employs condensing steam turbine generator units. Air extraction is utilised for heat supply, and refrigeration is achieved through the use of lithium bromide.

ACP100 technical features

- **The reactor coolant system is integrated into a single reactor module**, with once-through steam generators positioned within the reactor pressure vessel and the canned pump directly connected to the reactor pressure vessel via short nozzles. This configuration eliminates the need for conventional primary circuit piping, as shown in Figure 5-9.

(Source: CNNC)

Figure 5-9 ACP100 Reactor

- **Combination of inherent and passive safety**. The ACP100 incorporates multiple inherent safety features designed to eliminate various design basis incidents. In the event of accidents, the ACP100's fully passive safety system ensures reactor safety through natural forces; this minimises dependence on external water and power supplies, eliminates the need for human intervention, and requires no human involvement in the first 72 hours after an accident.
- **Modular high-efficiency once-through steam generator**

technology. The built-in modular high-efficiency once-through steam generator is compact, ensuring efficient heat exchange with improved economy and enhanced safety.

- **Air-cooled containment**. Requiring no startup signal or complicated air deflectors – and without system capacity limits – the ACP100's air-cooled containment eliminates the risk of overpressure accidents.
- **Underground arrangement**. Isolating radioactivity naturally through rock mass and soil, the reactor, spent fuel, and safety systems are arranged underground. This configuration enhances resistance against earthquakes and potential attacks, contributing to environmental considerations and potentially increasing public acceptance of small-scale nuclear energy.
- **Higher-level modularity**. The reactor and the reactor coolant system are assembled from multiple submodules, allowing for modular fabrication, transportation, and construction, and enabling efficient on-site assembly.
- **High maturity**. The ACP100's main equipment operates on established technologies that have already been verified through engineering practice. Key technological challenges have been addressed, and necessary special equipment has been developed.

Significant progress has been made in the R&D of marine-based small reactors, and nuclear heating reactors. A series of tests, commissioning, and feasibility demonstrations have been completed for the ACPR50S marine-based small reactor; the conceptual and preliminary designs of the pressure vessel and other main equipment for the nuclear heating reactors have been completed.

French Practice

EDF and Nuward positioning

The development of nuclear solutions is part of the EDF industrial strategy, to broaden our range of reactors with an SMR complementary to the large and medium power reactors already available for the new projects of the next decade. EDF strongly believes SMRs have the potential to play a crucial role as part of the global path towards the decarbonisation of our economies, offering interested countries a solution for baseload, dispatchable, affordable and low-carbon power generation. It will usefully expand the range of low-carbon electricity generation solutions offered by the French nuclear sector.

EDF has developed an SMR product called Nuward. Nuward will be a modular solution that will incorporate several major innovations, benefiting the plant operator and improving the competitiveness of the product: simplicity and compactness of an integrated design, flexibility in the construction and operation phases, and an innovative approach to safety in accordance with the highest global standards.

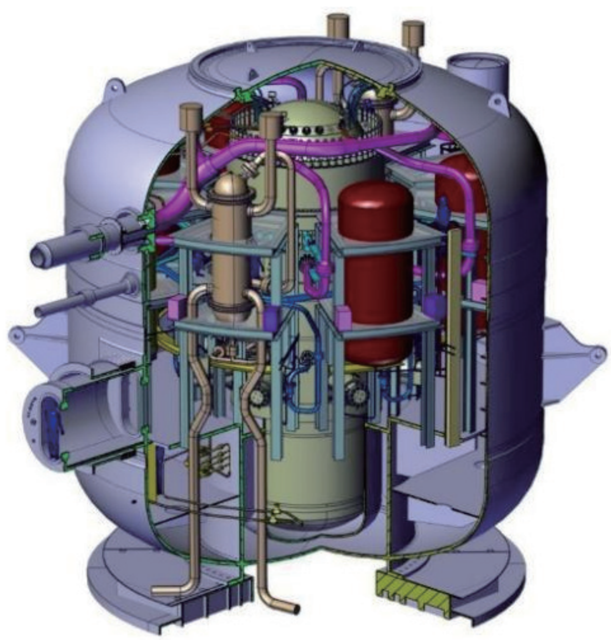
Nuward will be a major asset in decarbonising the world's energy mix, providing a flexible and sustainable energy solution for industrial sites and isolated areas with a restricted electricity grid and highly carbonised electricity supplies. In addition to electricity generation, the design will be able to satisfy multiple usage requirements (hydrogen and heat production, seawater desalination, etc.).

Nuward is targeting the 300-400 MWe segment of the SMR market, which corresponds to palatable needs of replacement of carbon-intensive capacities connected to the grid and, as such, to a tangible and substantial market size. Nuward is also being designed to be adaptable and meet the export market demand for powering industrial sites or less interconnected network infrastructures.

Key features of Nuward

Nuward is a 340 MWe SMR power plant, designed to address the world energy mix decarbonisation challenge with the following key features:

- A Generation III+ integrated PWR technology, with a fine mix of proven and innovative features;
- >90% availability and compatible with ENTSO-E network requirements;
- Safety objectives that meet the best international standards;
- A design developed to support load following;



(Source: EDF)

Figure 5-10 Nuward

- Multipurpose by design: hydrogen production for transport, district heating, desalination, heat & electricity cogeneration, and CO_2 capture and processing;
- Modular approach and simple design targeting 40-month construction duration;
- Designed for export, allowing adaptation to multiple markets without significant redesign;
- Improved landscape integration.

Nuward has been developed through the contributions of strategic partners who leverage their unique expertise: TechnicAtome, Naval Group, CEA, Framatome and Tractebel. Nuward has initiated its basic design phase in early 2023. The goal is to start the construction of the reference plant in France in 2030 and meet the emerging SMR market by the 2030s.

5.2.3. Generation IV advanced nuclear energy systems

The Generation IV nuclear energy systems are characterised by enhanced safety, increased economic competitiveness, reduced nuclear waste, and effectiveness in preventing nuclear proliferation. They represent the forefront of nuclear energy trends and technology, and offer advanced solutions that encompass both reactor technologies and supporting nuclear fuel cycles.

Main objectives of Generation IV nuclear energy systems:

- **Sustainability**: Achieving sustainable energy production aligned with environmental cleanliness goals, promoting long-term safety of the systems, and ensuring efficient utilisation of nuclear fuel. This includes minimising nuclear waste to significantly reduce long-term regulatory burdens.

- **Economy**: Maintaining an overall cost advantage over other energy sources throughout the system's lifespan and possessing a lower financial risk level compared to alternative energy sources.
- **Safety and reliability**: Demonstrating excellent operational safety and reliability, it is characterised by a very low probability and extent of reactor core damage and eliminates the need for off-plant emergency response.
- **Non-proliferation and physical protection**: Protecting against illegal diversion or theft of nuclear materials and enhancing physical protection.

Based on the main objectives above, the GIF Forum has conducted a comprehensive comparison of hundreds of reactor concepts. From this evaluation, six types of reactors have been identified as the most promising Generation IV nuclear energy systems. These include the SFRs, very high-temperature/high-temperature gas-cooled reactors (V/HTGRs)[3], gas-cooled fast reactors (GFRs), lead-cooled or lead-bismuth eutectic-cooled fast reactors (LFRs), MSRs, and supercritical water-cooled reactors (SCWRs), as shown in Table 5-2.

Table 5-2 Generation IV Advanced Nuclear Energy Systems

Type	Neutron Spectrum	Coolant	Coolant Pressure	Coolant Temperature in Reactor Core
GFR	Fast	Gaseous helium	~7 MPa	400-850 ℃
LFR	Fast	Molten lead/ lead-bismuth eutectic (LBE)	~1.5 MPa	400-480 ℃

[3] The Generation IV Nuclear Energy Systems Roadmap Report released in 2002 listed Very High-temperature Gas-cooled Reactors (VHTGR) as one of six technology routes, and the 2010 update of the Roadmap Report changes VHTGR was changed to Very High Temperature/High-temperature Gas-Cooled Reactor (V/HTGR).

Type	Neutron Spectrum	Coolant	Coolant Pressure	Coolant Temperature in Reactor Core
MSR	Fast/thermal	Molten salt fluorides	~0.5 MPa	700-770 ℃
SCWR	Fast/thermal	Light/heavy water	~25 MPa	280-500 ℃
SFR	Fast	Liquid sodium	~0.15 MPa	400-550 ℃
V/HTGR	Thermal	Gaseous helium	~7 MPa	250-1000 ℃

Chinese Practice

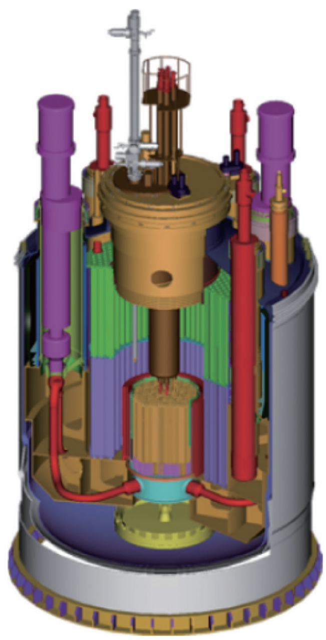
(1) CEFR

The CEFR is China’s first fast neutron reactor and currently the only fast neutron irradiation platform, as shown in Figure 5-11. Approved in 1995, its construction began in 2000. The reactor achieved its first criticality in July 2010 and connected to the grid a year later.

(Source: CNNC)

Figure 5-11 CEFR

The CEFR has a thermal capacity of 65 MW and is capable of generating 20 MW of electrical power. The reactor core, designed in a pool-type configuration, incorporates a sodium-sodium-water triple-circuit primary heat transfer system, as shown in Figure 5-12. For the first time, a passive residual heat removal system is set up in the primary circuit. The fuel elements are compatible with UO_2 and MOX. With a construction area of 44,000 m^2, the project is designed with the main technical parameters and system configurations for small NPPs.



(Source: CNNC)

Figure 5-12 Reactor Core of CEFR

The CEFR is key to China's "three-step" nuclear energy development strategy. This project has provided valuable experience in designing and constructing fast reactor NPPs, as well as operating and maintaining sodium systems and equipment; it has also enabled irradiation tests of fast reactor fuels and materials and gained insights into experimental power generation and operation. These efforts have validated the inherent safety features of fast neutron reactors and fostered a skilled fast reactor technology workforce. The CEFR project has played a significant role in advancing China's fast reactor technology.

(2) Integral fast reactor

The Integral Closed Cycle Advanced Fast Reactor Nuclear Energy System (Integral Fast Reactor, CiFR1000) is comprised of sodium-cooled fast neutron reactors, a fuel regeneration sub-project, and other supporting sub-projects. Combining proliferation, transmutation, and power generation, this system achieves self-sustaining nuclear fuel, improving fuel cycle efficiency through streamlined logistics and recycling of inexpensive depleted uranium. A CiFR1000 consumes only about 100 tonnes of depleted uranium throughout its lifecycle and generates a modest amount of radioactive waste. This waste can be directly disposed of in geological repositories, reducing the management duration to hundreds of years.

CiFR1000 as a disruptive new-generation nuclear energy technology is characterised by its near-zero consumption of natural uranium and near-zero generation of high-level radioactive waste. Supporting the large-scale sustainable growth of fission nuclear energy, this technology offers effective solutions to nuclear energy development's challenges of uranium resource scarcity and nuclear waste management. Therefore, it has been selected as the primary reactor type for China's future commercial fast reactor NPPs. Its design concepts include:

- Establishing technical standards for commercial fast reactor NPPs to ensure high levels of safety, economy, environmental friendliness, and sustainability.

- Utilising a combination of inherent safety and passive technology to enhance safety features.
- Leveraging fast reactor technology to configure more loops, increasing power capacity, and streamlining system and equipment design for improved economy.
- Adopting a metal fuel core and unique fuel regeneration technology to realise a closed cycle in the plant that enhances the utilisation rate of uranium resources.

The typical CiFR1000 layout involves constructing six GW-class SFRs within one plant site, along with one fuel regeneration sub-project and other supporting sub-projects. This configuration delivers a rated thermal capacity of 3,000 MW and electric power of 1,200 MW. It is powered by U-TRU-Zr metal fuel and can be shut down by two sets of shutdown systems and one set of Curie Point passive shutdown rods. The primary heat transport system comprises four loops, each equipped with several integral steam generators. Optimising space utilisation, steam generators are arranged side by side around the reactor vessel. See Table 5-3 for detailed design parameters.

Table 5-3 Main Design Parameters of CiFR1000

Parameter	Unit	Value
Rated thermal capacity	MWt	3,000
Electric power	MWe	1,200
Number of circuits	– –	Sodium-sodium-water triple circuits
Number of loops	– –	4
Availability	– –	>90%
Fuel type	– –	U-TRU-Zr metal fuel
Breeding ratio	– –	>1.2

Parameter	Unit	Value
CDF	per reactor year	$<10^{-6}$
LERF	per reactor year	$<10^{-7}$

Currently, CNNC has completed the conceptual design of its integral fast reactor nuclear energy system and achieved significant breakthroughs in key technologies. Taking into account various factors such as site capacity, safety, and economy, the plan is to construct six fast reactor modules, two fuel regeneration modules, and one waste management module at the same site by 2035, as shown in Figure 5-13.

(Source: CNNC)

Figure 5-13 Conceptual Design of CNNC's Integral Fast Reactor

(3) V/HTGR

The HTGR is a key reactor type for extending the use of nuclear energy beyond electricity generation. It offers a number of unique advantages, including high temperature, versatile application scenarios, high inherent safety, low individual reactor power output, and the ability to combine multiple standard modules for a large-capacity power plant. The

HTGR can provide clean, low-carbon, and high-grade steam and process heat, catering to the needs of industries like steel and petrochemical. In the context of China's goals for carbon peak and carbon neutrality, the HTGR has significant market potential and development opportunities.

A solid foundation has been laid for the development of HTGRs. Research on HTGR technology began in the 1970s. Tsinghua University completed the high-temperature gas-cooled experimental reactor (HTR-10) in 2000 and achieved full-power generation by 2003. On 20 December, 2021, the High-Temperature Reactor Pebble-bed Module (HTR-PM) Demonstration Project was connected to the grid in Shidaowan, Shandong Province, as shown in Figure 5-14. China will continue to promote the large-scale construction of HTGRs and achieve extensive application in non-electric fields. HTGRs will gain momentum in ensuring energy security and promoting clean and low-carbon energy transition. Based on the HTGR demonstration project, research on VHTGRs with higher technical parameters is ongoing.

(Source: CNNC)

Figure 5-14 The HTGR Demonstration Project in Shidaowan, Shandong Province

(4) Other Generation IV advanced nuclear energy systems

China has actively engaged in research on MSRs, LFR, SCWR, and other advanced nuclear energy systems.

MSRs. In 2011, China initiated engineering research for the nuclear energy system of thorium-based MSRs (TMSRs). Currently, a 2 MWt liquid-fueled thorium-based molten salt experimental reactor (TMSR-LF1) is being loaded. There are plans to construct a 10 MWe small modular thorium-based MSR with a maximum design thermal capacity of 60 MWt. This project's systems integration and experimental verification aim to provide the technology, data, and experience necessary for the construction of large commercial reactors.

LFRs, including lead-cooled reactors and lead-bismuth reactors. The fundamental and technological research on LBRs in China began in 1986. Since then, domestic research institutions have established several comprehensive experimental platforms for LBRs of different scales and parameters, enhancing their capacity for technological development in this field. Significant progress has been made in many respects, such as core physics analysis, thermal-hydraulic experiments, system safety analysis, material performance testing, I&C system development, and prototype development of key components.

SCWRs. China initiated research on SCWRs in 2006 and proposed the overall design scheme for a GW-class SCWR (CSR1000). Current SCWR research in China centres on key technological challenges, with breakthroughs achieved in thermal-hydraulics, safety tests, and materials. In the near future, China will proceed with research and design on the engineering experimental SCWR based on the full range of key SCWR technologies it has developed.

French Practice

Historically, France was involved in fuel cycle closure at a very early stage and has developed expertise in the SFR sector, with the commissioning and operation of experimental reactors (Rapsodie: 1967-1983, Phénix: 1973-2010) as well as the European industrial demonstrator Superphénix (1985-1997). The ASTRID programme, launched in 2010 under the direction of CEA to design and build a new SFR industrial demonstrator, was stopped in 2019, due to the forecasted long-term uranium prices, removing the economic need for fuel cycle closure: the launch of a new prototype has been postponed until the second half of the 21st century. Despite the shutdown of the ASTRID project, France maintains a long-term objective of deploying a nuclear fleet combining SFR and PWR.

To be in a position to relaunch the industrialisation of SFR technology when the time comes, the French industry is now committed to maintaining a core of key skills, defining and updating the target reactor model (Industrial SFR), and developing the essential technological topics related to the use of sodium coolant in fast reactors.

While SFR remains the reference solution in France for closing the fuel cycle, there is an increasing interest in alternative technologies. For example, a call for projects launched by the French government, "France 2030", provides for a 500 million EUR budget to support innovative reactor projects and/or those that improve waste management.

The past two years have seen the emergence in France of many companies carrying out very innovative and very ambitious nuclear projects. This trend can also be seen in Europe and the USA, also strongly supported by public authorities.

These projects are not a short-term priority for EDF for electricity production: EDF's priority today is the production of carbon-free electricity. The light water reactors that EDF is currently developing (EPR2, EPR1200 and Nuward) are less expensive (per MWe installed) and use much better proven technologies to produce very low-carbon electricity.

However, most of these projects (sodium, lead, and fast-spectrum molten salt) are of long-term interest to EDF for fuel cycle closure. Indeed, these technologies have the capacity, at various degrees of efficiency, to reduce or even remove the need for natural uranium. As such, they lend credibility to EDF's fuel cycle closure strategy and that the products of our current cycle (depleted uranium, spent MOX fuel) are not waste and can be recovered.

As a potential future operator of GEN IV reactors, EDF participates in the development of SFR (and, to a lesser extent, MSR). EDF ensures that the French industry's R&D programme for fast reactors is consistent with the Group's vision, notably by defining the industrial strategy and specifications for the Industrial SFR.

The rapid development of Advanced Modular Reactors (AMR) deserves to devote at least a technical-economic and competitive watch to it, and even support for AMR projects which include the closure of the fuel cycle in their specifications.

5.2.4. Nuclear fusion

The ultimate goal of controlled nuclear fusion is achieving commercial energy. Currently, magnetic confinement and inertial confinement are the two most promising technologies for attaining fusion energy. The key technological challenge for practical fusion energy through magnetic confinement is steady-state operation of deuterium-tritium burning, while for harnessing fusion energy through inertial confinement, it involves achieving high-frequency ignition and burning of the target capsule.

(1) Tokamak magnetic confinement device: the most likely route to first achieve commercial fusion energy

International research on magnetic confinement-controlled fusion began in the 1950s, with independent and collaborative efforts worldwide. Several large-scale Tokamak devices, including the Tokamak Fusion Test Reactor (TFTR, the United States), Doublet III with D-shaped cross-section (DIII-D, the United States), the Joint European Torus (JET, the EU), Japanese Torus-60 Super Advanced (JT-60SA, Japan), and Korea Superconducting Tokamak Advanced Research (KSTAR, the Republic of Korea), have been successfully built and put into operation. Additionally, multiple countries and regions are jointly advancing the ITER. With notable achievements such as plasma temperatures reaching up to 440 million ℃, pulsed fusion output power exceeding 16 MW, and the equivalent value of the power gain (Q) exceeding 1.25, the scientific feasibility of magnetic confinement controlled fusion technology has been experimentally demonstrated on Tokamak devices. The current focus of research is on achieving long-term fusion burning and eventually establishing a fusion prototype power plant.

(2) Inertial confinement fusion: kind of attractive

Inertial confinement fusion technology utilises laser-induced shock waves to achieve extremely high temperatures and pressures in fuel capsules containing deuterium and tritium, thereby triggering nuclear fusion reactions. It is advantageous in achieving symmetric compression. In recent years, substantial progress has been achieved in various aspects of inertial confinement fusion technology, including theoretical developments, experimental advances, diagnostics, target fabrication, and driver technologies. A significant milestone was reached in December 2022 when the National Ignition Facility (NIF) in the United States achieved net energy gain for the first time. This achievement marks a crucial step forward in the development of inertial confinement fusion technology. The primary focus of inertial confinement fusion is to achieve laboratory-scale ignition for thermonuclear fusion, explore fundamental scientific issues related to extreme physics at high temperature and high density, and gradually master key processes and engineering technologies.

European Practice

The construction of the ITER in Europe holds advantages for the EU in comprehending and mastering fusion technology. As outlined in the EU's 2018 fusion research roadmap, crucial challenges including steady-state operation, plasma physics, and fusion reactor materials for Tokamak fusion reactors, are anticipated to be addressed in the next 30 years. The goal is to lay the groundwork for constructing a steady-state fusion demonstration power plant (DEMO) with a power output of 1,000 MW, comparable to the performance of fission power plants. To accumulate practical experience, the EU primarily relies on projects such as JET, ASDEX Upgrade, Tokamak à Configuration Variable (TCV), W Environment in Steady-state Tokamak (WEST), and the jointly-built project JT-60SA with Japan.

(1) JET

As the largest Tokamak device in Europe, JET has – since its launch in 1983 – been a key player in global fusion research. Consistently setting records in the field, it conducted the first Deuterium-Tritium (D-T) fusion experiment in 1991, generating a fusion power output of up to 1.7 MW and confirming the scientific feasibility of controlled fusion as an advanced energy source on Earth. In 1994, a breakthrough was made in improving confinement research with the discovery of the Central Negative Shear (CNS) mode, which has significant implications for future fusion reactor design and the search for advanced Tokamak confinement configurations. Since 2009, JET has undergone multiple upgrades, including a first wall and tungsten divertor to simulate ITER, and an improved heating system. These advances provide a research platform to address the major issues necessary for the operation of ITER. Currently, JET is the only operating facility licensed to conduct tritium experiments. The results of D-T fusion experiments in JET are crucial in validating the ITER concept and preparing scientists for participation in ITER's operation. In December 2021, JET once again set a new record in controlled fusion energy, heating deuterium, and tritium to 150 million ℃, maintaining stability for 5 seconds, and observing nuclear fusion reactions that released 59 MJ of energy.

(2) WEST

Beginning operations in 2016, the WEST Project – developed by the CEA – is an upgraded version of the Tore Supra device (a Tokamak device that has been in operation since 1988). WEST is the world's first Tokamak device with superconducting magnets and actively cooled Plasma-Facing Components (PFC). The project's primary objective is to validate tungsten divertors and other components under high-heat flux conditions for their final application in the ITER project. In February 2023, WEST was restarted to conduct divertor component tests for the ITER device.

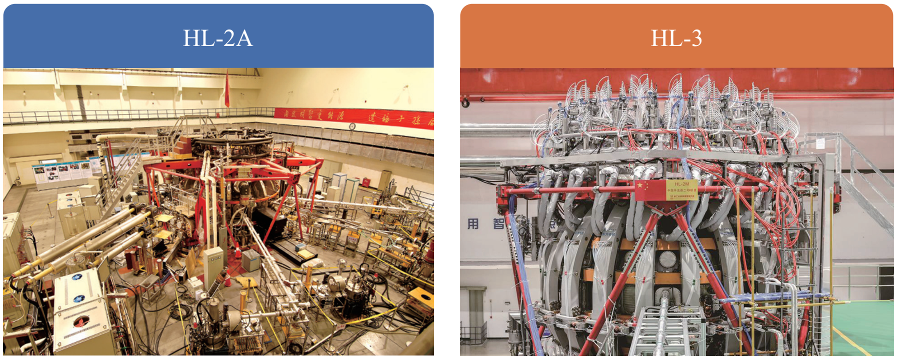
(3) Other fusion research devices

The EU is also supporting the construction of DDT, a new divertor test facility in Italy. DTT is designed to conduct tests on divertor structures, materials, and configurations that differ from those of ITER. Offering new potential solutions for these aspects in fusion demonstration reactors, this is intended to address ITER's limitations in high-heat load control and impurity removal research. The EU has recently put forth a construction plan for DONSE-IFMIF, a separate fusion material irradiation facility. The implementation of DONSE-IFMIF is expected to take place after 2041.

Chinese Practice

China has listed magnetic confinement fusion as a prioritised advanced energy technology for development in the *National Medium- and Long-Term Plan for Development of Science and Technology (2006-2020)*. In June 2012, the MOST of China officially released the *National 12th Five-Year Plan Special for Magnetic Confinement Fusion Development*, reaffirming China's strategic commitment to magnetic confinement fusion development. The roadmap for magnetic confinement fusion research is currently taking shape. To achieve leapfrog development in fusion energy application, China is assimilating the achievements of the ITER project and utilising domestic non-nuclear test facilities to master key engineering technologies for fusion reactors. China has steadily acquired expertise in nuclear materials and the tritium fuel cycle through the development of a nuclear-related fusion research platform.

The Southwestern Institute of Physics (SWIP) is dedicated to the research of magnetic confinement controlled nuclear fusion. It has established 22 controlled nuclear fusion plasma experimental research facilities and conducted a series of physical experiments. The HL-2A is China's first Tokamak device with a divertor configuration. In 2009, it achieved the first high-confinement mode operation in China; and, in 2019, it achieved high-beta and high-confinement mode operation. The HL-2A provides the capability to conduct experimental research related to high-confinement and high-beta modes, relevant to ITER and future fusion reactors. The HL-3, completed in 2020, is China's largest and highest-parameter new generation "artificial sun" to achieve its first plasma discharge. It serves as a scientific research platform capable of core-level burning plasma operation. In August 2023, HL-3 realised high-confinement mode operation with a plasma current of one million amperes for the first time in China. This breakthrough puts the operational level of China's magnetically controlled nuclear fusion device at the forefront of the world, and marks an important milestone in the country's development of nuclear fusion energy. The HL-2A and HL-3 are shown in Figure 5-15.



(Source: CNNC)

Figure 5-15 HL-2A and HL-3

The Institute of Plasma Physics at the Chinese Academy of Sciences (ASIPP) is an important research base for thermonuclear fusion in China. It has successively built conventional magnet Tokamaks such as the HT-6B and HT-6M. The first circular cross-section superconducting Tokamak fusion experimental device in China, and the Experimental Advanced Superconducting Tokamak (EAST), the world's first non-circular cross-section all-superconducting Tokamak fusion experimental device. In recent years, ASIPP has undertaken a series of experimental studies on high-parameter steady-state operation schemes based on research conducted with EAST. In April 2023, steady-state high-confinement mode plasma operation on EAST lasted for 403 seconds.

5.3. Innovative Application of Industrial Technology

Chinese Practice

(1) Deep integration of digital information technology and the nuclear energy industrial chain

A data centre has been built for the nuclear industry to propel accelerated informatisation in construction and facilitate the transition from decentralisation to centralisation, integration, and intelligence. Utilising cutting-edge technologies like big data and artificial intelligence, the nuclear industry is actively developing new core software. Aiming to establish a robust foundation for the digital transformation of the nuclear industry, this development is strategically centred on crucial aspects of both the industrial and innovation chains.

Continuous breakthroughs in the integration of digital information technology and nuclear power research and design. A digital micro-reactor, incorporating technologies like 3D modeling and virtual reality, has been established to create a virtual integrated development environment. The development of "full-process, full-lifecycle, fully-3D, and fully-simulated" digital NPPs has significantly enhanced the efficiency of research and development for NPP models. This includes virtual construction and operation of NPPs, thus improving efficiency and the level of research, design, construction, and operation of NPPs.

Continuous improvement has been achieved in the integration of digital information technology and the nuclear fuel element industry. By systematically developing, integrating, and deploying production line-specific solutions, the industry can simulate manufacturing processes. This simulation enables the anticipation of potential risks, and prevents adverse effects on equipment quality and schedules due to uncontrollable factors. Reinforcing data collaboration and sharing, China has successfully implemented information support and coverage for enterprises' core business operations. This initiative has led to improved business standardisation, convenience, and overall efficiency.

Continuous advancement has been achieved in the integration of digital information technology and uranium mine construction. Various digital information projects have facilitated the digitisation of uranium geology, geophysical, and geochemical exploration processes. Supporting information systems, including the digital uranium exploration system, digital instruments and equipment, and nuclear geological basic database, have been developed and implemented. This increased level of automation and digitisation has significantly enhanced the efficiency, quality, and depth of uranium exploration.

Significant progress has been made in the integration of digital information technology and nuclear power construction. A smart construction site cloud platform has been implemented for nuclear power projects, and "data access standards for smart construction sites" have been established. China has adopted an advanced information technology application architecture for nuclear power project construction that allows smart monitoring across all ongoing nuclear power engineering projects and comprehensive access to data related to personnel, machinery, quality, safety, and green construction. It has completed smart construction site demonstration projects in Xudabu and Changjiang. China has also developed numerous detailed design plans, optimised scenarios and functions, and achieved online management of the construction process for dozens of nuclear power units.

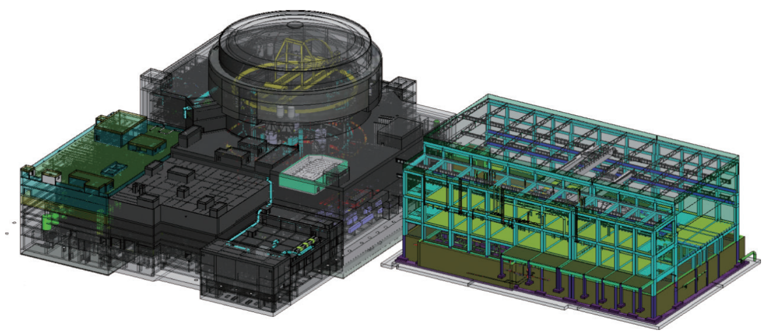
The integration of digital information technology and nuclear logistics has been continuously enhanced. Material classification and coding standards have been established to enhance procurement management through the standardisation of material coding. The application of an integrated platform for procurement, supply, and storage has been advanced to refine procurement management and establish a management model that integrates "planning-execution-monitoring-improvement". Through the optimisation of procurement management processes, a P2P business processing model that significantly shortens business processes and enhances management efficiency has been implemented.

(2) Intelligent engineering construction

To advance the construction of digital NPPs, emphasis has been placed on innovative research and development. This includes the development and application of BIM technology, information system development and integration, and the digital construction of NPPs.

Digitalisation of HPR1000 project management. In the construction of the HPR1000 project, advanced technologies have been studied and promoted, including the multi-project information management system, BIM-based nuclear island construction, construction collision simulation, on-site remote monitoring technology, and automated digital processing equipment. Ushering in the era of digital and intelligent construction for the nuclear power construction industry, these innovations have ensured the timely completion of major engineering projects and greatly enhanced project management capabilities.

Digitalisation of project implementation. In 2019, China initiated the independent development of a smart construction site management platform encompassing 24 functional modules, covering aspects such as personnel management, machine management, green construction, and safety management. Leveraging advanced technologies like 5G, the Internet of Things (IoT), big data, artificial intelligence (AI), and lightweight modeling, the system facilitates real-time and dynamic data collection of elements involved in the construction process, including "humans, machines, materials, methods, and the environment". This integration enables comprehensive and intelligent management of construction sites.



(Source: CNNC)

Figure 5-16 Intelligent Nuclear Power Engineering Construction

French Practice

EDF is committed to achieving carbon neutrality by 2050. Nuclear power is an integral part of the solution to achieve this objective by generating safe, low-carbon electricity, generated on a large-scale, available anytime and flexible. The nuclear industry must therefore be an industry of the future where innovation is paramount. Many innovations concern power plant maintenance, which is essential to guarantee appropriate safety standards while extending their operating life. It is imperative to guarantee the safety of power plants, including when their operating life is extended. The objective is to demonstrate that these power plants can operate safely for up to 60 years without excessive extra cost. Innovations play a crucial role in understanding ageing mechanisms and strengthening methods.

(1) Optimising power plant maintenance and making them last longer (digital focus)

Digital technology has been used by EDF for more than 30 years to improve the performance of the nuclear fleet. To intensify and expand its use, several R&D projects are dedicated to the development of digital innovations for nuclear power and the preparation of their industrialisation. Digital technology allows the design and operation of NPPs to be simplified. It is in this respect that R&D supports the EDF Group in digitising its generating fleet by carrying out several projects that meet important challenges such as increasing reliability, reducing maintenance costs, extending the lifespan of power plants and, above all, making the nuclear sector attractive to new talent.

Through the digitisation of nuclear power, it is possible to visualise the current state of the power plant by digitising more information and analysing it using artificial intelligence. In fact, digital data relating to equipment and installations is becoming increasingly complete, providing real time information on the state of equipment recorded via sensors, as well as the complete history of the means of generation. This provides a comprehensive and up-to-date overview of the physical state of industrial areas thanks to rapid acquisition techniques. This is a key asset for power plant operation and maintenance and their lifespan extension.

The current work involves linking this accessible, up-to-date and usable data with powerful digital simulation tools: digital twins. These twins integrate and centralise data provided by different information sources to predict future behaviour. This requires innovation in many fields such as data management, information transfer and connected objects, statistical analysis tools, visualisation using virtual or augmented reality, high-speed calculations using supercomputers, artificial intelligence algorithms and even blockchain technology for information collection reliability, etc.

Digital twins will eventually provide a true digital copy of components, whether reactors, steam generators, containment, etc., for each power plant. These dynamic models help to understand the behaviour of the equipment, to predict its possible failure and to quickly simulate different operating modes in order to define the best usage scenarios, whether it is a plant main system, components such as the steam generators or the reactor as a whole (e.g. the Vercors project). In short, these innovations allow better prediction and better foresight.

From an operational point of view, digitisation has now taken on many aspects of the plant operator profession in nuclear facilities. By analysing the data available for each reactor, from its design to the present day, plant operators can estimate the failure rate of an item of equipment and thus carry out preventive maintenance, in full knowledge of the facts.

Thus, EDF R&D plays a key role in the digitisation of power plants. It focuses on understanding the needs of those involved in the field in order to respond by providing solutions based on various technological building blocks developed internally or externally by academics or manufacturers in the sector. To do this, it has available expertise and cutting-edge testing methods in digital technologies.

(2) Improving manufacturing and construction

The control of metal equipment manufacture, and the construction of civil engineering works are another area of innovation in the nuclear sector. For the manufacture of large metal parts, two examples of very innovative manufacturing methods are under development: additive manufacturing and hot isostatic pressing (HIP). HIP consists of manufacturing a part via a pressure and temperature cycle (~100 MPa and ~1,000°C) applied to a container filled with metal powder. This results in parts with very homogeneous microstructural, chemical and mechanical properties. Both allow the very demanding quality standards to be reached that nuclear facilities must follow.

Additive manufacturing brings together a whole family of new manufacturing methods. This is a real revolution in production methods, which has been adopted by EDF R&D to meet the maintenance and availability challenges of the group's facilities. It is a method which involves making parts modelled on a computer by adding successive layers of material, the opposite of conventional machining methods where material is removed to reach the desired shape. It can be used for the manufacture of metal, plastic or ceramic parts.

Several applications have already been considered in the different power generation fleets, including the nuclear fleet. For the current fleet, additive manufacturing will be mainly used to deal with problems of obsolescence. Using this method, it will be possible to reproduce parts that the industrial base is no longer able to make. In fact, the nuclear fleet was built about 40 years ago and many manufacturers no longer exist. The idea is therefore to carry out 3D scans of used parts and then recreate them by additive manufacturing. In the context of the future fleet, and in particular EPR2, the idea would be to optimise the design of equipment and to manufacture it using additive manufacturing, which allows much freer geometries to be created compared to conventional techniques. By optimising the design and the material, the costs are optimised as material is expensive, but heat exchange and fluid circulation are improved. Additive manufacturing could therefore lead to not only better efficiency but also better operation.

6 International Cooperation

Nuclear power has its unique characteristics and development modes. Shaped by resource endowments, the conditions and capabilities for developing nuclear power vary among countries and regions. Therefore, international cooperation plays a vital role in fostering the safe and innovative advancement of nuclear energy by facilitating the establishment of an extensive research cooperation network, promoting the coordination of nuclear safety standards, enhancing regulatory systems, and sharing experience feedback.

6.1. Role of International Organisations

A number of international organisations have long promoted and facilitated the safe, secure, and peaceful development of nuclear energy. These organisations include the IAEA, OECD/NEA, ITER Organisation, and GIF Forum, as well as WANO and WNA.

Widely known as the world's "Atoms for Peace and Development" organisation within the UN family, the IAEA serves as the international centre for cooperation in the nuclear field. Working closely with its Member States and multiple partners across the globe, the IAEA promotes the safe, secure, and peaceful applications of nuclear technologies. It provides guidance and support on developing clean and sustainable energy, while advocating the use of nuclear technology in numerous areas including human health, food and agriculture, water resource management, and environmental protection to meet the 17 SDGs, set out in the UN 2030 Agenda for Sustainable Development in 2015. Both China and France – acting as the designated members of the Board of Governors of the IAEA – actively participate in the development and implementation of international legal instruments, and technical standards and guidelines on nuclear safety, security, and emergency preparedness and response.

The OECD/NEA assists its member states to make nuclear energy available for peaceful purposes in a safe, environmentally friendly, and cost-effective way through international cooperation. France, where the OECD/NEA's headquarters is located, is one of the core members of the OECD/NEA. With the signing of a joint statement on cooperation with the OECD/NEA in 2013, China has become an important strategic partner of the OECD/NEA and has conducted extensive cooperation with it in a number of areas such as nuclear fuel cycle, nuclear safety, and nuclear data.

The ITER Organisation aims to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes through international collaboration. Since its establishment in 2007, the ITER has been one of the largest science projects for international scientific and technical cooperation. The ITER device is a superconducting Tokamak for large-scale nuclear fusion reactions, which will make humanity closer to a potentially unlimited source of clean energy. France is where the ITER project's headquarters is located. China, as one of the ITER members, has undertaken 9.09% of the costs for its construction and 10% for its operation and decommissioning.

WANO seeks to maximise the safety and reliability of NPPs across the world by working together to assess, benchmark, and improve performance through mutual support, exchange of information, and emulation of best practices. The Shanghai Center, established in 2020, has grown to be an important member in WANO's global network. The continuous support from WANO and the ongoing efforts of Chinese nuclear power operators have led to a year-over-year improvement in the operational performance of NPPs in China.

International organisations serve as the forums for international cooperation and exchanges in the nuclear field. It is necessary for all countries to promote and strengthen cooperation within the frameworks of international organisations, and participate in their cooperation mechanisms and initiatives, such as the IAEA's Atoms for Net Zero, Nuclear Harmonization and Standardization Initiative (NHSI), and Nuclear Technology for Controlling Plastic Pollution (NUTEC Plastics).

6.2. Bilateral Cooperation

Nuclear power projects and nuclear industry development have greatly benefited from bilateral cooperation. Utilising science and technology for peaceful purposes and conducting relevant international cooperation are inalienable rights of all countries conferred by international law. The development of nuclear power in a country requires comprehensive infrastructure, encompassing well-established laws and regulations, safety regulations, and human resources, to provide institutional and resource assurances for the safe construction and reliable operation of NPPs. Countries with established nuclear power programmes can offer technical expertise and financial support to emerging nuclear power countries, enabling them to achieve their nuclear power programmes.

The process of nuclear power development in many countries underscores the pivotal role of bilateral cooperation in advancing the peaceful use of nuclear energy. For example, since the late 1980s, China has built Daya Bay, Qinshan Phase III, Tianwan, Sanmen, Haiyang AP1000, and Taishan EPR NPPs in cooperation with countries such as Canada, France, Russia, and the United States. These bilateral partnerships have not only fostered the growth of the nuclear power industry, but also spurred innovation in nuclear technology within China.

China has made great contributions to promoting global nuclear power development. The CAEA, in collaboration with the Ministry of Education, has established the Atomic Energy Scholarship of China (AES). This scholarship programme, tailored to meet the needs of the international community, aims to nurture professionals in the field of nuclear power. Initiated in 2017, the AES offers an international professional training platform for nuclear disciplines and employs a diversified and dual-mentor training model. This approach has created a comprehensive training mechanism that involves coordination among the government, universities, and enterprises. Since its establishment, the AES has successfully trained nearly 200 master's and doctoral students from nearly 30 countries across Asia, Africa and the Americas.

These efforts have made positive contributions to the development of nuclear power engineering professionals in these countries. In addition to educational initiatives, China has – through bilateral cooperation – actively supported emerging nuclear power countries in constructing multiple nuclear power projects.

For 60 years, France has promoted and supported the development of foreign nuclear programmes, particularly in Europe and Asia (primarily China) with the training and immersion of international engineers in France. Today, the International Institute of Nuclear Energy (I2EN) is an association that brings together French stakeholders involved in nuclear education and training. With 49 members, including 11 partners (government ministries and agencies, industry, and research) and 38 associate members (academia and E&T associations), the I2EN was inaugurated in 2011 and acquired a legal personality in January 2024.

The I2EN was created to be the single point of contact for countries wishing to develop nuclear education and training programmes, training centres, and comprehensive systems to manage nuclear human resources over the whole lifetime of a nuclear power programme. This expertise is meant to be shared with countries wishing to benefit from France's experience. Six academic institutions offer master's degree programmes especially designed to welcome international students.

6.3. China-France Cooperation

Cooperation between China and France: a long history

Since the signing of the first protocol on cooperation in the peaceful uses of nuclear energy in 1982, China and France have always attached equal importance to scientific, technological, and industrial cooperation. Up to now, 14 protocols have been signed between the two countries in the field of nuclear energy. The CAEA and the CEA have established the China-France Nuclear Energy Cooperation Coordination Committee as an exchange mechanism. This committee promotes the implementation of the Protocols and facilitates exchanges of views periodically on major issues in the nuclear field, the latest developments, and relevant policies in the development of nuclear energy in both countries. The collaboration also extends to nuclear safety regulation, with active cooperation between the French ASN and IRSN, and China’s NNSA and the Nuclear and Radiation Safety Center (NSC) under it. These cooperative efforts have made significant contributions to the economic and social development of both countries. This enduring partnership has yielded fruitful results in the front and back ends of the nuclear fuel cycle, reactor technologies, and nuclear safety. The collaboration between China and France in the field of nuclear energy has evolved into an indispensable and crucial foundation for the overall development of bilateral relations. This success can be attributed to practical cooperation covering various domains, including engineering technology, training, education, and scientific research.

- **Extensive exchange and cooperation in nuclear energy.** In scientific and technological research, seven collaborative laboratories have been established in NPP ageing and lifecycle management, reactor thermal hydraulics, fast reactor technology, radioactive waste management and severe incident management, geological disposal of high-level radioactive waste, and nuclear fusion. Over 500 projects have been implemented, involving the dispatch of more than 1,000 experts for mutual learning, exchange, and discussion. In policy research, the think tanks from both countries have jointly deliberated on the future technological direction of nuclear energy and the trends in the international nuclear power market.

- **Strong supporter for international cooperation and exchanges.** CNNC and EDF have been directly involved in the interactive activities of international organisations, contributing by sending experts to technical teams, engaging in international research projects, and promoting international coordination and standardisation. For example, they have participated in the development of nuclear safety standards of the IAEA, especially the recently launched NHSI and the SMR Regulators' Forum activities to facilitate the development of generic standards for SMRs, harmonise regulatory requirements, and promote the safe and secure deployment of SMRs throughout the world. In addition, the two enterprises have made important contributions to the standards development of the International Organization for Standardization and the International Electrotechnical Commission.
- EDF has had operations in China for over 40 years and is now one of the largest foreign investors in the country's electricity generation and energy services. It has been developing partnerships with leading Chinese electric energy companies and key players in the Chinese nuclear industry, in particular its peers CNNC and CGN. EDF led the design, construction, and commissioning in 1994 of the Daya Bay power plant (with two nuclear reactors of 1,000 MWe each). EDF also assisted CGN in the construction of the Ling'ao Phase I power plant (with two reactors of 1,000 MWe

commissioned in 2002 and 2003), followed by Phase 2 (with two additional reactors of 1,000 MWe commissioned in 2010 and 2011).

EDF China has established its headquarters in Beijing with an extension in Shenzhen. Experts in these offices are working in particular to further promote French codes and standards as well as EDF nuclear safety guidelines.

In 2014, the AFCEN (the French association for nuclear codes and standards) signed MoUs with CNNC, CGN, and CNEA (the largest association in China's nuclear industry). These partnerships led to the creation of Chinese Users Groups and the first technical seminar between the AFCEN and the CNEA, focusing on regulations, codes and standards, qualification of equipment, I&C, etc.

In addition, an agreement between the AFCEN and China's National Energy Administration was signed in 2017. Its objective is to promote mutual recognition of nuclear codes and standards and to establish a basis for cooperation between France and China that would enable both countries to operate on the international nuclear market. EDF also chairs the France-China Partnership for Electricity (PFCE), made up of qualified suppliers of EDF which are seeking to develop in China.

In 2010, EDF signed a partnership framework agreement with CNNC. Aimed at developing their cooperation along deeper, global lines, this agreement was extended in March 2014 and renewed in 2019. Under the Global Partnership Agreement (GPA) between CGN and EDF, a cooperation agreement and a service agreement were signed in 2014 and 2015, respectively, and renewed in 2023. EDF owns 30% of Taishan

Nuclear Power Joint Venture Company Limited (TNPJVC), which was set up to build and operate two EPR nuclear reactors in Taishan, in the province of Guangdong in China. CGN-EDF cooperation contributed, on the one hand, to the commissioning of the first EPR unit in the world and, on the other hand, to the feedback from Taishan to further construction of the EPR model and its O&M. In partnership with CGN, EDF is building two new nuclear units at Hinkley Point in the United Kingdom, based on the EPR technology.

6.4. Future Cooperation

The transition to low-carbon energy and sustainable development is a shared vision of humanity. Nuclear energy is inevitably an important option to achieve these goals. China and France have engaged in extensive and efficient cooperation on nuclear energy. Both countries are beneficiaries and promoters of bilateral cooperation, and strongly support international cooperation and exchanges to advance the peaceful utilisation of nuclear energy. As major global nuclear power companies, CNNC and EDF will continue to work towards the development of nuclear energy and further strengthen research and development cooperation in areas such as:

- **Cooperation in nuclear fields,** including nuclear engineering, nuclear operation, fuel cycle, as described in the chapters above.
- **Synergy between nuclear energy and renewables.** Nuclear energy, especially combined with renewables, can play a more important role in achieving decarbonisation and establishing a safe and reliable power system. Countries should formulate public

policies aimed at fostering low-carbon growth. This includes accelerating the development of renewables like hydropower, wind, solar PV and geothermal power, extending the lifetimes of existing NPPs and launching new programmes. These strategic initiatives will contribute to meeting climate objectives while optimising the economic efficiency of energy transition.

- **Advanced nuclear technologies such as SMRs and nuclear fusion.** SMRs have great potential to make significant contributions to achieving global climate goals and ensuring energy supply security. However, their commercial deployment faces several challenges. As for nuclear fusion, it has witnessed notable advances in recent years, but the complexity and cost of large-scale devices required to address plasma physics and engineering issues underscore the importance of intensified international collaboration in this domain.
- **Multipurpose utilisation of nuclear energy.** Nuclear energy offers versatile applications beyond electricity generation, such as district heating, desalination, and hydrogen production. Nuclear technology can also help monitor the impact of climate change and play a special role in addressing water scarcity, soil erosion, land degradation, increased animal and plant diseases, and insect pests resulting from climate change.

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Abbreviations

ASN	French Nuclear Safety Authority
BNI	Basic Nuclear Installation
BWR	boiling water reactor
CAEA	China Atomic Energy Authority
CEA	French Alternative Energies and Atomic Energy Commission
CEFR	China Experimental Fast Reactor
CGN	China General Nuclear Power Corporation
CHNG	China Huaneng Group
CINIS	China Institute of Nuclear Industry Strategy
CLI	Local Information Commission
CNDP	National Public Debate Committee
CNEA	China Nuclear Energy Association
CNNC	China National Nuclear Corporation
EC	European Commission
EDF	Électricité de France
EU	European Union
EUR	European Utility Requirements
GFR	gas-cooled fast reactor
GHG	greenhouse gas
GIF	Generation-IV International Forum
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IMF	International Monetary Fund
INES	International Nuclear and Radiological Event Scale
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRSN	Institute for Radiation Protection and Nuclear Safety
ITER	International Thermonuclear Experimental Reactor

LEU	low enriched uranium
LFR	lead-cooled fast reactor
MEE	Ministry of Ecology and Environment
MOX	mixed oxide
MOST	Ministry of Science and Technology
NNSA	National Nuclear Safety Administration
NPP	nuclear power plant
NSC	Nuclear and Radiation Safty Center
NUTEC Plastics	Nuclear Technology for Controlling Plastic Pollution
NZE	Net Zero Emissions
OECD/NEA	Organisation for Economic Co-operation and Development/Nuclear Energy Agency
PHWR	pressurised heavy water reactor
PWR	pressurised water reactor
RTE	Réseau de Transport d'Électricité
SCWR	supercritical water-cooled reactor
SFEN	French Society for Nuclear Energy
SFR	sodium-cooled fast reactor
SMR	small modular reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SPIC	State Power Investment Corporation
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
URD	Utility Requirements Document
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association

Note on the sharing of responsibilities for writing the Bluebook

As mentioned in the joint preface to this Bluebook, responsibility for writing the book was shared between EDF and CINIS.

In every chapter each sub-section detailing the case of China or the case of France was solely written and validated by the respective party involved. This is also the case for each of the "Chinese practice" and "French practice" sections in chapters 4 and 5. Apart from these, responsibility for the rest of the book has been allocated as follows:

CINIS is responsible for the following parts:
1, 2.2, 3.1.1, 3.3.1, 3.3.2, 4.2.1, 5.2.4.

EDF is responsible for the following parts:
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