The Path to a New Era for Nuclear Energy

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Abstract

The Path to a New Era for Nuclear Energy is a new report by the International Energy Agency that looks at the opportunities for nuclear energy to address energy security and climate concerns – and at critical elements needed to pursue these opportunities, including policies, innovation and financing. Nuclear energy is a well-established technology that has provided electricity and heat to consumers for well over 50 years but has faced a number of challenges in recent years. However, nuclear energy is making a strong comeback, with rising investment, new technology advances and supportive policies in over 40 countries. Electricity demand is projected to grow strongly over the next decades, including from data centres, further underpinning the importance of having sufficient new sources of stable low-emissions electricity.

Despite the rising momentum behind nuclear energy, various challenges need to be overcome for nuclear to play an important role in the future energy landscape. This report reviews the status of nuclear energy around the world and explores risks related to policies, construction and financing. It provides the long-term outlook for nuclear power in light of policies and ambitions, quantifying nuclear power capacity and the related investment over the period to 2050. The report shows that with continued innovation, sufficient government support and new business models, small modular reactors can play a pivotal role in enabling a new era for nuclear energy. It highlights potential mechanisms to unlock financing while also emphasising the critical importance of adequate planning for the required workforce and supply chains.

Foreword

Some four years ago, the International Energy Agency (IEA) announced that nuclear energy was well positioned to make a comeback after a difficult period following the 2011 Great East Japan Earthquake and the accident at the Fukushima Daiichi plant. Today, this comeback is clearly underway and nuclear now stands on the cusp of a new era, owing to a combination of government policies, technological innovation and private sector interest. At the same time, several major challenges still need to be overcome on the path to this new era.

This new IEA special report provides a comprehensive assessment of the situation, examining how these challenges can be overcome in countries that see it as part of their future energy mix. It is important to note, however, that some countries, including some IEA Members, do not see a role for nuclear energy in their future, and the IEA Secretariat fully respects their position. This report should not be seen as representative of their views.

Globally, nuclear energy is a leading source of clean and secure electricity generation – second only to hydropower among low-emissions sources. In 2025, nuclear is set to produce more electricity than ever before, a clear sign of the comeback that the IEA signalled in 2021. Another sign of momentum is that interest in nuclear energy today is at its highest levels since the oil crises of the 1970s, with support for expanding the use of nuclear power now in place in more than 40 countries. At the same time, innovation is changing the nuclear technology landscape through the development of small modular reactors (SMR), the first of which are expected to start commercial operations around 2030.

These positive developments for nuclear are well timed, as the world is moving towards the Age of Electricity, with global electricity demand for electricity set to grow six times as fast as overall energy demand in the coming decade, driven by the need to power everything from industrial machinery and air conditioning to electric vehicles and data centres. Alongside renewable technologies such as solar and wind, whose electricity output is expanding rapidly, nuclear can play an important role in meeting growing power demand securely and sustainably.

The global map of nuclear is changing. In the 1990s, for example, Europe was a frontrunner in nuclear power, but its nuclear industry has shrunk. Today, half of nuclear power projects under construction are in China, which is set to overtake both the European Union and the United States in nuclear capacity by 2030. The picture may change again, though, as new technologies such as SMRs come to market. For this report, IEA experts spoke with many leading SMR companies to get a detailed understanding of where things stand. Momentum is clearly building for the technology, but SMRs' success will hinge on whether government support, innovation and new business models enable them to bring down their costs quickly enough. If that happens, SMRs could account for 10% of all nuclear capacity globally by 2040. As an innovation leader, the United States alone would account for 20% of the growth in SMRs.

In terms of challenges, financing is a major issue for nuclear. A new era for nuclear energy will require a lot of investment, which won't happen without major efforts from government and industry. Nuclear projects have traditionally been hard to finance due to their scale, capital intensity, long construction lead times and technical complexity. This has meant heavy involvement of governments. But public funding alone will not be sufficient to build a new era for nuclear: private financing will be needed to scale up investments.

The positive news for the nuclear industry is that for the first time in a long time, more and more parts of the private sector now see nuclear as investible thanks to the promise of SMRs. Major technology companies building data centres can also take advantage of their strong credit ratings to facilitate financing for SMR projects.

Reducing the risk of cost overruns and delays is a prerequisite for expanding finance, both public and private, and protecting the interests of consumers. SMRs have the potential to be a game-changer when it comes to financing. They can dramatically reduce the overall investment costs of individual projects.

This report shows that governments have a unique capacity to provide the strategic vision, the policies, the incentives, de-risking mechanisms and the public finance that can move the nuclear sector forward. In doing so, they must pay close attention to ensuring robust and diverse supply chains for nuclear energy. Highly concentrated markets for nuclear technologies, as well as for uranium production and enrichment, represent a risk factor for the future.

While taking these risks into account, the market, technology and policy foundations are in place today for a new era of growth in nuclear energy over the coming decades. Governments and industry now need to build on these foundations if they want to make it a reality.

Finally, I would like to thank my colleagues Brent Wanner and Eren Çam and the team they led that worked extremely hard over almost a year to produce this data-rich report, which I believe will help governments around the world ensure a more secure and sustainable energy future.

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Executive Summary

Multiple signs point towards a new era for nuclear power

The market, technology and policy foundations are in place for a new era of growth in nuclear energy over the coming decades. Demand for electricity is rising fast, not only for conventional uses such as light industry or air conditioning, but also in new areas such as electric vehicles, data centres and artificial intelligence. Electricity use has increased at twice the rate of total energy demand over the past decade and is set to extend this lead as the world enters a new Age of Electricity. Nuclear is a clean and dispatchable source of electricity and heat that can be deployed at scale with round-the-clock availability. It brings proven energy security benefits to electricity markets as well as reductions in emissions, complementing renewable energy. Interest in nuclear energy is at its highest level since the oil crises in the 1970s: support for expanding the use of nuclear power is now in place in more than 40 countries. Moreover, innovation is changing the nuclear technology landscape, including many small modular reactor (SMR) designs under development; the first commercial SMR projects are set to start operation around 2030.

Nuclear generation is set to hit an all-time high in 2025

Generation from the world's fleet of nearly 420 reactors is on track to reach new heights in 2025. Even as a few countries phase out nuclear power or retire plants early, global generation from nuclear plants is rising as Japan restarts production, maintenance works are completed in France, and new reactors begin commercial operations in various markets, including China, India, Korea and Europe. Nuclear power produces just under 10% of global generation and is the second-largest source of low-emissions electricity today after hydropower.

Some 63 nuclear reactors are currently under construction, representing more than 70 gigawatts (GW) of capacity, one of the highest levels seen since 1990. In addition, over the last five years, decisions have been taken to extend the operating lifetimes of over 60 reactors worldwide, covering almost 15% of the total nuclear fleet. A new multi-country initiative was launched that aims to triple global nuclear capacity by 2050, recognising the role of nuclear energy in reaching energy security and climate goals, complementing the leading role played by renewables. Annual investment in nuclear – encompassing both new plants and lifetime extensions of existing ones – has increased by almost 50% in the three years since 2020, exceeding USD 60 billion.

However, the momentum behind nuclear is unbalanced

For the moment, the renewed momentum behind nuclear power is heavily reliant on Chinese and Russian technologies. Of the 52 reactors that have started construction worldwide since 2017, 25 of them are of Chinese design and 23 of them of Russian design. Highly concentrated markets for nuclear technologies, as well as for uranium production and enrichment, represent a risk factor for the future and underscore the need for greater diversity in supply chains.

A shift in market leadership is underway: half of the projects that are under construction today are in China, which is on course to overtake both the United States and European Union in installed nuclear power capacity by 2030. Advanced economies are still home to most of the world's nuclear fleet, but these reactors are relatively old; their average age is more than 36 years, twice the average elsewhere. Rejuvenating this fleet has not been easy: the nuclear industry in long-time market leaders, such as the United States and France, has struggled in recent years with project delays and cost overruns for all new large-scale reactors.

A brighter outlook for nuclear power can be unlocked, as regional outcomes vary widely in a scenario based on today's policy settings and market dynamics. In advanced economies, the rise in SMRs and new construction of large-scale reactors only just offset the effects of an ageing fleet, meaning that capacity is slightly higher in 2050 than today. In the European Union, the share of nuclear power in the electricity mix peaked at 34% in the 1990s but has already fallen to 23% today and continues to fall steadily in this scenario. By contrast, in China, installed capacity more than triples to mid-century, and it also doubles in other emerging and developing economies.

Small modular reactors can be the catalyst for change

Cost-competitive SMRs, boosted by government support and new business models, can help clear the path to a new era for nuclear energy. Demand for firm, dispatchable and clean power from the private sector is a major driver of interest in these emerging technologies, and there are plans of varying maturity for up to 25 GW of SMR capacity, in large part to meet growing electricity demand for data centres. Under today's policy settings, total SMR capacity reaches 40 GW by 2050, but the potential is far greater. In a scenario in which tailored policy support for nuclear and streamlined regulations for SMRs align with robust industry delivery on new projects and designs, SMR capacity is three times higher by mid-century, reaching 120 GW, with more than one thousand SMRs in operation by then. This rapid growth scenario would raise required investment in SMRs from less than USD 5 billion today to USD 25 billion by the end of this decade, with cumulative investment of USD 670 billion by 2050.

If construction costs for SMRs are brought down over the next 15 years to parity with large-scale reactors built on budget, this could see the cost-effective uptake of SMRs increase by a further 60%, with deployment reaching 190 GW by 2050. This trajectory for cost reductions – to USD 2 500/kW of capacity in China and USD 4 500/kW in the United States and Europe by 2040 – is faster than we have in our main scenarios but less ambitious than the cost levels being targeted by today's SMR project developers. Cumulative global investment in SMRs in this case totals USD 900 billion to 2050.

Diversifying technology leadership and supply chains

The rise of SMRs, alongside a new wave of large-scale reactors built on time and on budget, can open the possibility for Europe, the United States and Japan to reclaim technology leadership. In a rapid growth scenario, nuclear capacity in advanced economies grows by over 40% to 2050, helping to meet energy security and emissions goals. The share of large-scale nuclear construction starts using designs from advanced economies rises from less than 10% in recent years to 40% by 2030 and over 50% thereafter, spurred by new projects in Europe, the United States, Japan and Korea. The widespread deployment of SMRs reinforces this trend, with over half of new construction starts to 2050 using designs from the United States or Europe. A more competitive and diverse market brings broad benefits for countries seeking to step up deployment of nuclear technologies.

Greater diversity of uranium supply and enrichment services is essential for a secure and affordable expansion of the nuclear sector. Uranium production is highly concentrated in four countries, which jointly account for more than three-quarters of global uranium production from mines. Enrichment capacity is also highly concentrated, with more than 99% of the enrichment capacity in four suppliers, with Russia accounting for 40% of global enrichment capacity. This area needs to be given much greater attention, particularly for countries that import enriched uranium.

Mobilising new sources of finance

A rapid growth scenario requires a major expansion in annual investment, which doubles to USD 120 billion already by 2030. Nuclear projects have traditionally been hard to finance due to their scale, capital intensity, long construction lead times, technical complexity and risk liability in some countries. This has meant heavy involvement of governments, and typically a major role for state-owned enterprises (SOEs) as owners and operators of nuclear plants. SOEs can often obtain large amounts of financing at relatively competitive rates, close to those of sovereign entities.

Public funding alone will not be sufficient to build a new era for nuclear: private financing will be needed to scale up investments. However, the long timelines for permitting and construction make nuclear a tough proposition for commercial lenders, as they can push the breakeven point for a new large reactor to 20-30 years after the project start. These factors also limit the use of project finance structures, which are often used to support other large infrastructure projects.

Ensuring better visibility on timelines and cash flows

Reducing the risk of cost overruns and delays is a prerequisite for expanding finance, both public and private, and protecting the interests of consumers. This requires a multifaceted approach. Adopting well-established reactor designs and then building them in series can greatly help to build up capacity, supply chains, and a strong and skilled workforce. Standardisation allows for a streamlined construction process, reducing the time and cost associated with building each reactor, and lowering costs over time through learning.

The predictability of future cash flows is key to bring down financing costs and attract private capital to the nuclear sector. Financial institutions lend based on reliable future cash flow expectations, so a supportive regulatory framework that increases visibility, including limiting liabilities, in this area is crucial for debt financing. In markets with volatile prices, de-risking instruments such as long-term power purchase agreements, contracts for difference and regulated asset base models are indispensable. Long-term power purchase agreements can also be underwritten by large consumers, who can lock in future supplies of electricity at average cost. These arrangements can also open the door to proven commercial financing instruments, such as green bonds, supported by accommodating regulations and taxonomies.

SMRs bring new business models into play

SMRs can dramatically cut the overall investment costs of individual projects to levels similar to those of large renewable energy projects such as offshore wind and large hydro. This makes SMRs less risky for commercial lenders, once first-of-a-kind projects are established and technologies are proven. The more modular design of SMRs significantly cuts construction times, with projects expected to reach cash flow break-even up to 10 years earlier than for large reactors. The strong credit rating of the technology players behind data centres can also facilitate financing for SMR projects targeting this sector.

A leading role for governments in a new era for nuclear

Governments have a unique capacity to provide the strategic vision, and the policies, incentives and public finance that can move the nuclear sector forward. Not all countries see a role for nuclear technologies, and nuclear power is only one of multiple fuels and technologies that are required globally for a safer and more sustainable energy future. But nuclear can provide services and scale that are difficult to replicate with other low-emissions technologies. Taking advantage of this opportunity requires a broad approach from governments, encompassing robust and diverse supply chains, a skilled workforce, support for innovation, de-risking mechanisms for investment as well as direct financial support, and effective and transparent nuclear safety regulations, alongside provisions for decommissioning and waste management. There are multiple signs pointing towards a new era for nuclear; the task now is to build it.

Introduction

Nuclear energy is a well-established technology that has provided electricity and heat to consumers for well over 50 years and is envisioned to play an important role in secure and affordable energy supply in over 40 countries in the world. Innovation in nuclear is also gaining momentum, particularly for small modular reactors (SMRs). However, the nuclear industry has faced a number of challenges in recent years. For those countries pursuing nuclear energy, these factors invite a close look at what nuclear energy can deliver and what is needed to achieve it.

This report provides an update of recent developments and the long-term outlook for nuclear energy based on the latest policy, technology and cost information, and then takes a deep-dive into the financing of nuclear energy. The work builds on our previous IEA analysis on the role of nuclear energy in energy systems, including a special focus in the World Energy Outlook 2014, and dedicated reports in 2019, Nuclear Power in a Clean Energy System, and most recently in 2022, Nuclear Power and Secure Energy Transitions.

The first chapter provides an overview of the current status of nuclear energy worldwide, recent market trends and the drivers of renewed interest in nuclear energy. It provides a country-by-country review of government policy support and takes stock of recent technology developments, with a focus on SMRs. It highlights the rising interest in nuclear energy from the private sector, in particular to meet the growing energy needs of artificial intelligence (AI) and data centres. The chapter also outlines the main challenges to overcome for nuclear to play its envisioned role.

The second chapter provides the global outlook for nuclear energy, with scenario projections for installed capacity and investment under different policy settings. Regional trends, potential shifts in technological leadership and nuclear energy competitiveness are discussed. The chapter also looks at the potential role for SMRs, depending on future cost reductions, the need for efficient nuclear supply chains, including building a sustainable workforce, and reviews developments in safety, decommissioning reactors and managing radioactive waste.

The third chapter focuses on financing nuclear energy, highlighting the key challenges and needs to deliver timely investment. It identifies the special nature of financing nuclear, including the types of risks associated with building reactors. The type of key players in nuclear energy investments and the important role of governments are discussed. The chapter outlines how projects are financed and who is providing this capital in different markets and regions. It then reviews ways in which the large amounts of capital that will be needed could be mobilised, notably from private investors, through new approaches and instruments.

1. Status of nuclear energy

Highlights

- **Nuclear bolsters energy security and contributes to addressing climate concerns. In 2023,** more than 410 reactors were in operation in over 30 countries, with nuclear energy providing 9% of global electricity supply. Nuclear was the second-largest source of low-emissions electricity after hydropower, producing 20% more than wind and 70% more than solar PV, and also providing heat for industry, district heating and desalination in several countries. Since 1971, nuclear energy has avoided 72 Gt of CO_2 emissions by reducing the need to build power plants that run on coal, natural gas or oil, and has strengthened energy security in many countries by reducing their need to import fossil fuels.
- **Nuclear energy plays a bigger role in the advanced economies, which are home to more than 70% of the reactors in operation worldwide today, but this fleet is relatively old.** Their average age is over 36 years, compared with 18 years in the emerging economies. The share of nuclear in electricity generation is highest in France, at 65%, and the Slovak Republic, at over 60%. The European Union (EU) share has declined from a peak of 34% in 1997 to 23% today. In the United States, which has the largest fleet of nuclear reactors in the world, it is less than 20%.
- **Emerging economies are moving towards market leadership in nuclear energy**. Of the 52 reactors that have started construction worldwide since 2017, 48 are of either Chinese or Russian design. As of the end of 2024, there were 63 nuclear reactors (71 GW) under construction, of which three-quarters are in the emerging economies and half in China alone. China now has the third-largest nuclear fleet in operation in the world.
- **The last few years have seen renewed interest in building new nuclear plants and extending the lifetimes of existing ones, and 2025 is set to see generation from nuclear plants reaching an all-time high.** This is being driven by energy security concerns, a strengthening of policy support, technological advances and growing needs for dispatchable low-emissions power. Global ambitions to expand nuclear energy now encompass an initiative to triple nuclear energy capacity by 2050 and supportive policies in over 40 countries. Investment in nuclear has risen to about USD 65 billion in 2023, nearly double the level a decade ago. Small modular reactors (SMR) are attracting particular interest, with investors planning up to 25 GW of SMR capacity, mainly to power data centres.
- **The nuclear industry will need to overcome several hurdles for it to achieve a true comeback and contribute fully to clean energy transitions.** In particular, the construction of large-scale reactors in advanced economies has seen in recent years substantial delays and large cost overruns. The highly concentrated market for nuclear technology providers could hinder development.

Current role of nuclear energy

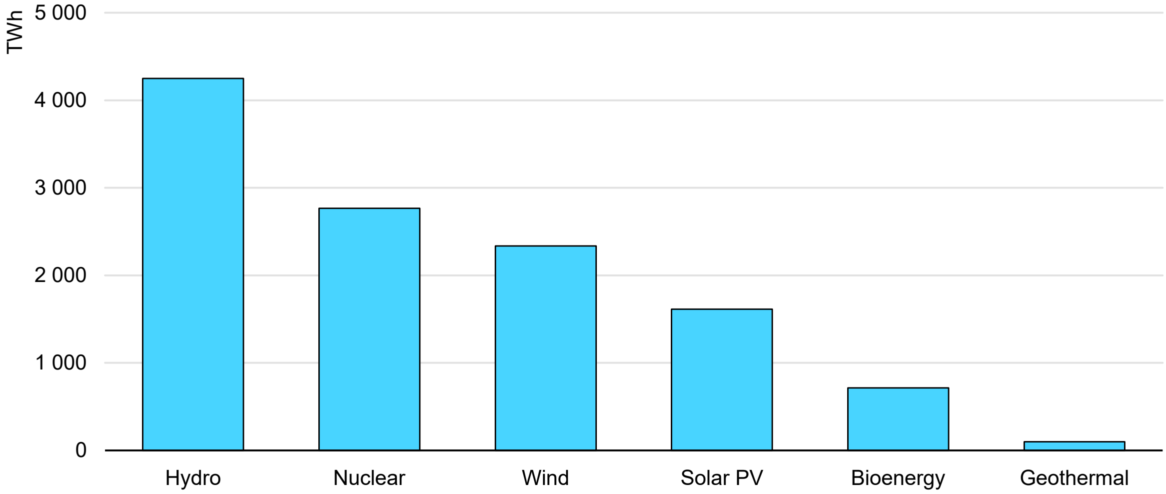
Nuclear power has been a major component of energy systems in many countries for more than half a century, though its contribution to meeting energy needs has evolved considerably over time in response to developments in power generation technologies and to changes in energy demand and energy policies. Over the past decade, global electricity demand has grown twice as fast as overall energy demand as we enter the Age of Electricity, driven by the emergence of new uses of power including electric vehicles (EVs) and data centres, as well as rapid growth in demand from conventional ones such as appliances and air conditioning. At the same time, the deployment of solar photovoltaic (PV) and wind power has soared. These developments are reshaping electricity systems around the world and the market and policy context for nuclear energy.

Global investment in nuclear energy was in decline around the turn of the century, notably in the advanced economies, due to high costs, long construction times, an unfavourable electricity market and policy environment, and ongoing concerns about the safe operation of nuclear power plants and secure disposal of high-level nuclear waste. As a result, the contribution of nuclear energy to meeting rising electricity needs has dwindled. But there has been a resurgence in interest in nuclear energy in recent years, driven by energy security concerns, the growing need for dispatchable low-emissions power capacity and advances in nuclear technology.

Nuclear energy is the second-largest low-emissions source of electricity worldwide

Nuclear energy made up just over 9% of global electricity generation in 2023, with more than 410 reactors in operation in over 30 countries. That share has declined from its peak of around 18% in the late 1990s. Although nuclear power generation has crept upwards in absolute terms over the last decade, electricity demand has increased faster, reducing the share of nuclear in total electricity supply. Nuclear energy was still the second-largest source of low-emissions electricity in 2023 after hydropower, producing about 20% more electricity than wind power, 70% more than solar PV and four times as much as bioenergy (Figure 1.1). Since 1971, nuclear energy has avoided 72 gigatonnes (Gt) of carbon dioxide (CO_2) emissions by reducing the need to build power plants that run on coal, natural gas or oil. It has also strengthened energy security in many countries by reducing their need to import fossil fuels. The fleet of reactors in operation today avoids emissions of around 1.5 Gt CO_2 each year.

Figure 1.1 Global low-emissions electricity generation by source, 2023



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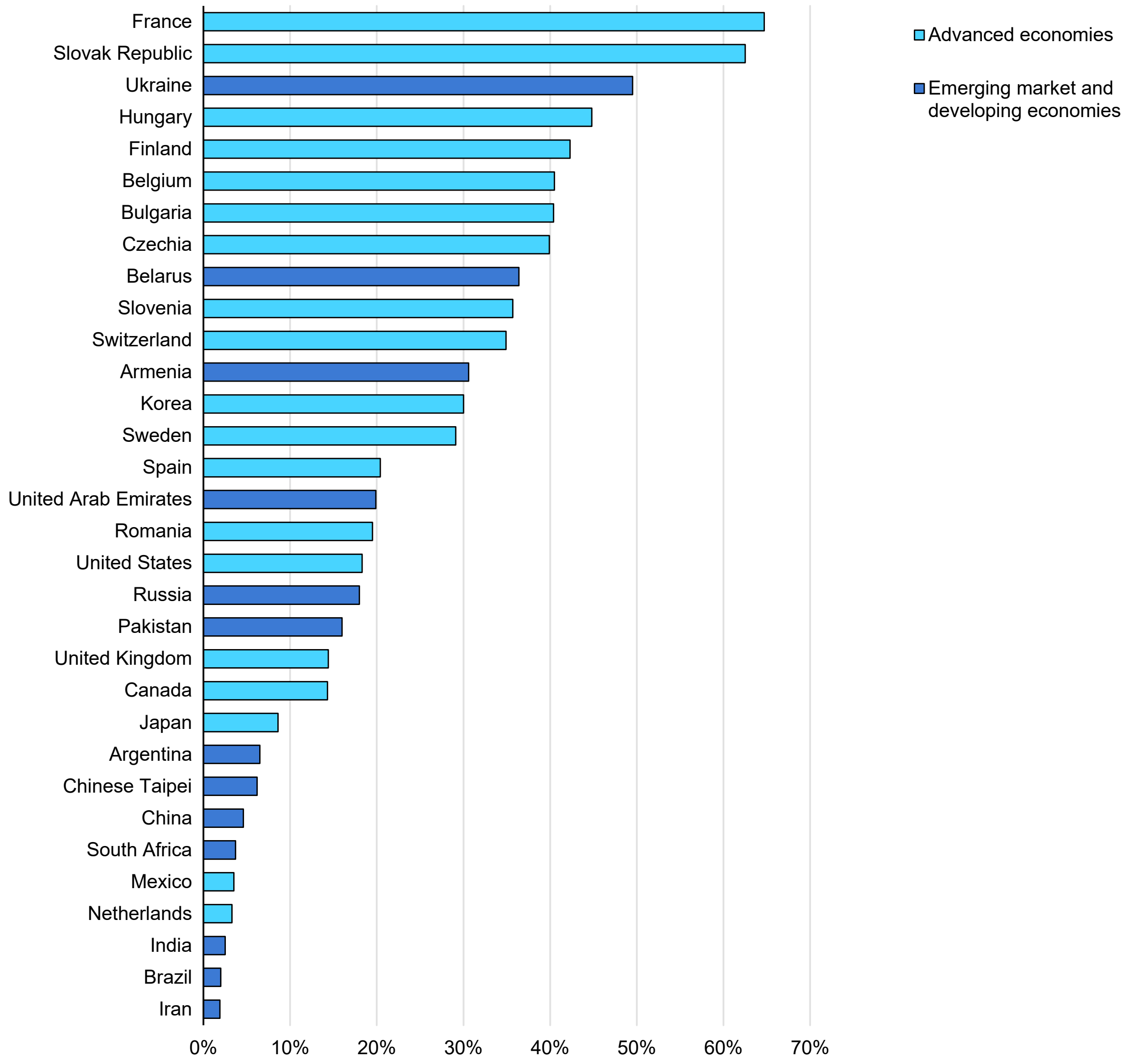
Notes: TWh = terawatt-hour. Other low-emissions sources not shown generate smaller amounts of electricity. They include concentrating solar power, marine power, and plants equipped with carbon capture, utilisation and storage.

Nuclear energy plays a bigger role in advanced economies, accounting for 17% of total electricity supply in 2023. Reactors are currently in operation in 19 advanced economies. Nuclear energy is the largest single source of low-emissions electricity in those countries as a group, well ahead of hydro, wind or solar PV. Eight of the ten countries with the highest nuclear share of total generation worldwide are advanced economies, including the top two: France, with 65%, and the Slovak Republic, with over 60% (Figure 1.2). While the United States has the most nuclear reactors in operation of any country worldwide, with 94, nuclear represents less than one-fifth of electricity supply.

In emerging market and developing economies (EMDE), nuclear energy accounted for just 5% of total electricity generation in 2023, with reactors operating in 13 countries. Among those countries, Ukraine had the highest nuclear share, at about 50%, and Belarus the second-highest, at over 35%. Only four others – Armenia, the United Arab Emirates, the Russian Federation (hereafter, "Russia") and Pakistan – had a share of more than 10%.

Figure 1.2 Share of nuclear energy in total electricity generation by country, 2023



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Nuclear has long been an important source of heat in several countries too

Nuclear combined heat and power (CHP) harnesses the dual benefits of electricity generation and thermal energy utilisation from nuclear reactors. Nuclear CHP enhances the efficiency of primary energy use by avoiding waste, while the direct use of fission heat decreases conversion losses when heat is the desired output. Today around 70 nuclear reactors are used for nuclear co-generation.

Opportunities for nuclear CHP are constrained by the required temperature of the heat output and the types of nuclear reactors in use. Most nuclear power plants operating today are light water reactors (LWRs) or heavy water reactors, which can supply process heat at under 150 °C. As a result, nuclear CHP is used mainly for district heating, seawater desalination and certain industrial processes such as pulp and paper production.

Nuclear district heating has been a proven technology since the 1960s, when Swedish Ågesta and the United Kingdom's Calder Hall nuclear power plants started generating electricity and co-generating heat for local district heating networks. Nuclear district heating is now well-established in several other countries, including Bulgaria, Canada, the Czech Republic, Hungary, Romania, Russia, Switzerland and Ukraine. The first nuclear district heating project in the People's Republic of China (hereafter, "China"), connected to the Haiyang power plant, began operation in 2020. When fully completed, with a 23-kilometre pipeline from the Haiyang plant, it will provide heating for up to one million residents. The cost-effectiveness of this project was demonstrated in 2021, when surging fossil fuel prices drove up heating costs in many cities across northern China, while costs in Haiyang fell. The new Dukovany II power plant in the Czech Republic is designed to supply district heat to the city of Brno, meeting half of its total heating needs and reducing heating costs for consumers by up to 15%. Construction of the heating infrastructure is scheduled to begin in 2027, with first heat deliveries to begin by 2031. The project is expected to cost around USD 800 million.

Nuclear co-generation has the potential to power seawater desalination, the need for which is expected to rise rapidly in the coming years as global demand for fresh water continues to grow and shortages of natural fresh water worsen. In 2023, approximately 2 000 petajoules of energy was consumed globally for seawater desalination, with demand projected to nearly double by 2030. Several countries, including China, India, Egypt, Japan, Jordan, Kazakhstan, Pakistan and Russia, have already implemented nuclear-based seawater desalination systems. India currently operates the world's largest nuclear desalination plant, but it is due to come to end of its 25-year lifespan by 2028. Two new nuclear-based desalination plants are planned to replace it. China's Tianwan nuclear power plant has also been used for desalination.[1] Pakistan's KANUPP-1 reactor, which had been retrofitted to provide heat for seawater desalination in 2010, shut down in 2021.

In addition to district heating and seawater desalination, some nuclear power plants have been providing heat to low-temperature industrial processes. For example, Switzerland's Gösgen plant supplies steam at 220 °C to a nearby cardboard manufacturing facility. Nuclear co-generation can be competitive with competing fossil-based technologies. In addition, several advanced reactor

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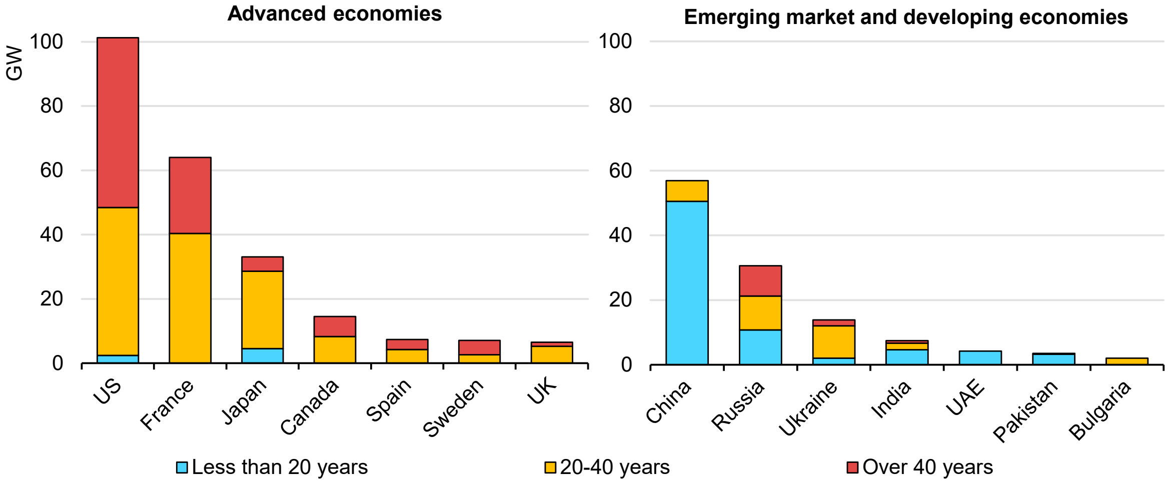
[1] It also began supplying steam to a chemical industrial facility in 2024 and could supply heat for hydrogen production later. Similarly, the Qinshan nuclear power plant provides heat to industrial parks, public facilities and residential district heating, with the projects due to be completed in 2025.

designs are currently under development and can supply heat at a temperature of over 800 °C, offering a wide range of possible applications (see Box 1.1).

Nuclear fleets are oldest in the advanced economies

The average age of a nuclear reactor in operation at the end of 2023 was over 36 years in advanced economies, compared with less than 18 years in EMDE. Over one-third of the fleet in the advanced economies has been in operation for over 40 years, more than half for between 20 and 40 years, and under 10% for less than two decades. The average age of the fleet in the United States (US) – the leading nuclear power producer worldwide – is 41 years, while that in France is 37 years and that in Japan 32 years (Figure 1.3). Most of these reactors in the advanced economies operate under 40-year licences, therefore, many will either shut down or need to undergo lifetime extension projects within the next decade to allow them to operate for another 10 to 20 years.

Figure 1.3 Installed nuclear power capacity by country and age, end-2023



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Notes: GW = gigawatt; UK = United Kingdom; UAE = United Arab Emirates.
Source: IEA analysis based on IAEA PRIS database (Accessed 10 January 2025).

Rapid growth in China means it now has the third-largest nuclear fleet in operation in the world, with an average age of just nine years. The fleets are also relatively young in India, the United Arab Emirates and Pakistan. By contrast, about one-third of the nuclear fleet in Russia is over 40 years old, while that in Ukraine is well over 30 years old.

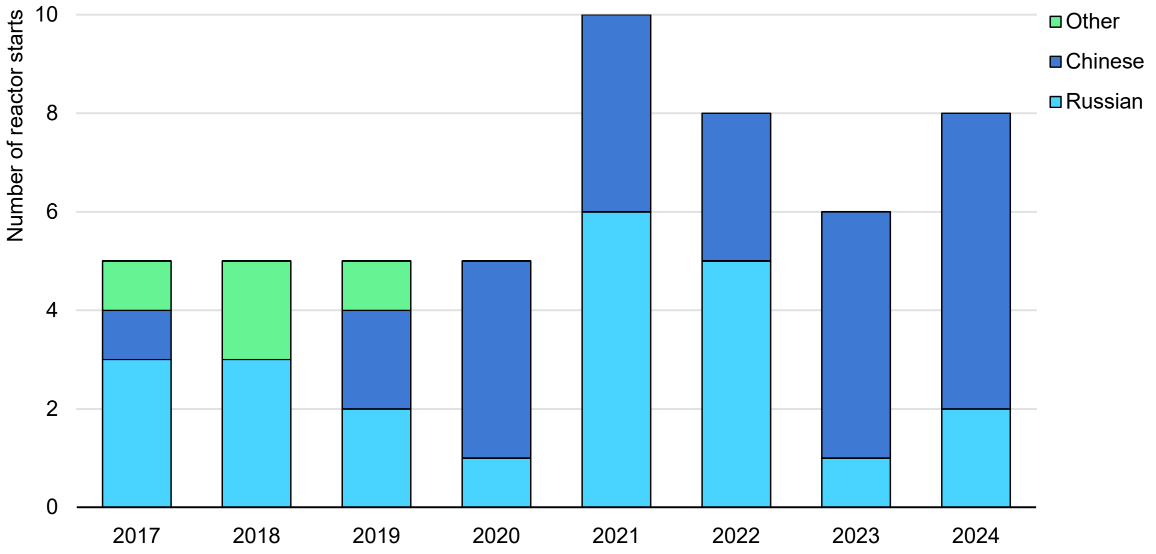
Recent market developments

The landscape of the nuclear industry has changed markedly in recent years, as the construction of new large-scale reactors has shifted away from the advanced economies and the diversity of nuclear designs for large-scale reactors has declined. This reflects in large part the growing leadership of Chinese and Russian developers and the difficulties the industry has faced in the advanced economies in bringing new projects online in a timely manner.

Technological leadership has shifted towards China and Russia

Nuclear market leadership has continued to shift away from advanced economies and towards China and Russia. Although advanced economies hold two-thirds of global nuclear capacity, the vast majority of new construction is in EMDE, based on Chinese or Russian technology (Figure 1.4). Between the beginning of 2017 and end of 2024, 52 nuclear reactors began construction, of which all but four were either Chinese designs (25) or Russian designs (23). The construction of just four reactors were started in the advanced economies – two in the United Kingdom based on European designs, and two in Korea using national technology. Such a high concentration among nuclear technology providers could hinder future development.

Figure 1.4 Nuclear power plant construction starts by national origin of technology, 2017-2024

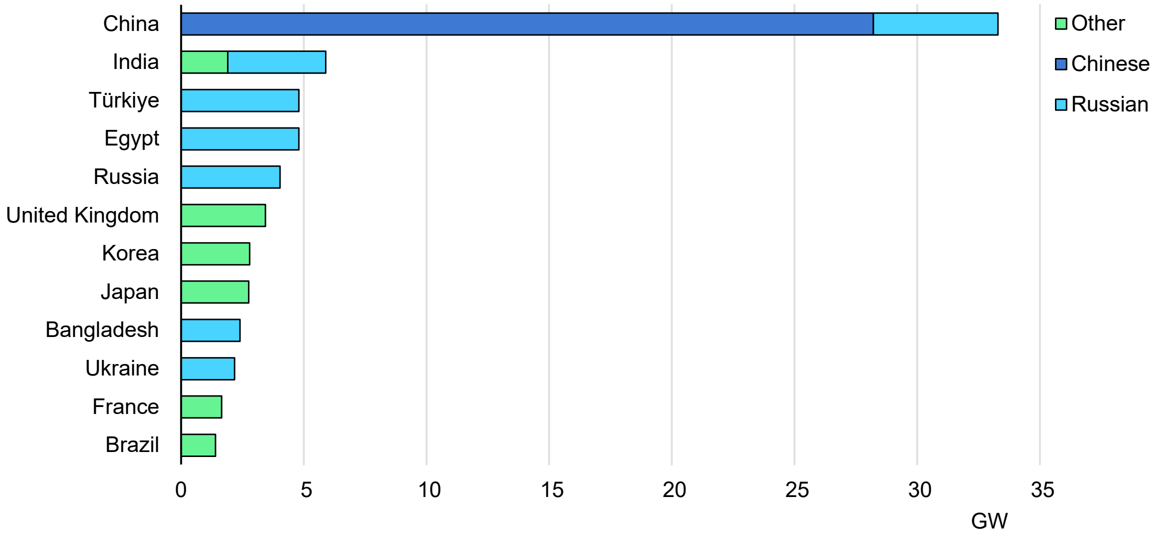


IEA. CC BY 4.0.

Source: IEA analysis based on IAEA PRIS database (Accessed 10 January 2025).

As of the end of 2024, there were 63 nuclear reactors under construction globally, with a combined power capacity of 71 GW. China has the most under construction by far – 29 reactors with a total capacity of 33 GW – accounting for almost half the global total (Figure 1.5). The majority of these reactors are of Chinese design, with four of Russian design. India, Russia, Türkiye and Egypt all have around 5 GW of nuclear capacity currently under construction, the majority of which is of Russian design. Reactors under construction in Bangladesh and Ukraine also use Russian designs, making Russia the leading exporter of nuclear technology, with a total of 23 GW of reactors under construction in six countries (another 4 reactors with capacity of 4 GW are being built domestically). Reactors under construction in Japan, France and Brazil, as well as Korea and the United Kingdom, are based on domestic designs or those from other advanced economies.

Figure 1.5 Nuclear power capacity under construction by region and national origin of technology, as of January 2025



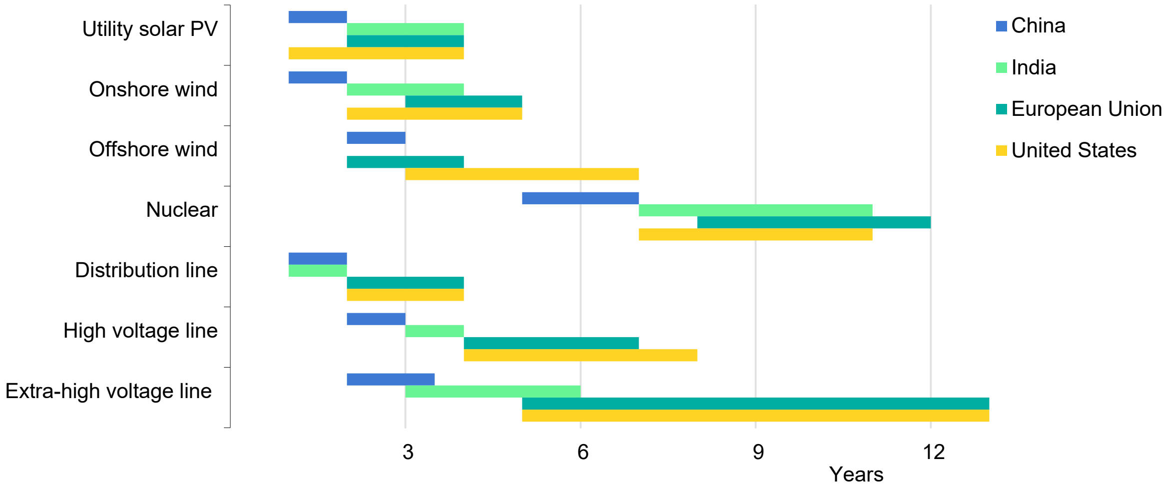
Source: IEA analysis based on IAEA PRIS database (Accessed 10 January 2025).

In advanced economies, the lack of new nuclear construction, combined with the ageing fleet and decisions to shut down reactors, has resulted in a decline in the contribution of nuclear energy to total electricity generation from a high of 24% in 2001 to around 17% in 2023. In the European Union, the share peaked at 34% in 1997 but has since declined by 11 percentage points. In the United States the share has remained at about 20% for many years, though the absolute level of nuclear power generation is just 3% higher today than 20 years ago. In Japan, the nuclear energy share declined from 25% in 2010 to zero following the accident at the Fukushima Daiichi nuclear power station, recovering to 10% in 2023 as several reactors were gradually brought back online.

Nuclear power plants are taking longer to build in the advanced economies

Construction times for nuclear power plants have a direct impact on total costs. Delays in bringing a new plant online typically lead to cost overruns. Nuclear plants often take much longer to build than power stations that burn fossil fuels or renewables-based power plants due to their much larger scale, the complexity of the technology and more stringent regulations. Globally, since 2000, building a nuclear reactor has taken an average of seven years, but has exceeded a decade in some cases, notably in some advanced economies. Most other low-emissions power technologies can be built much quicker; for example, utility-scale wind and solar PV capacity can usually be built in less than four years and sometimes less than two years (including planning), although extra-high voltage transmission lines have development times that can extend beyond a decade (Figure 1.6).

Figure 1.6 Typical development time for selected power plants and electricity grids



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Nuclear power plant construction times vary widely across countries and regions. Europe and the United States have recently been characterised by long construction times. Even in Korea, where the vast majority of their nuclear reactors took four to six years, the last three reactors took ten years each to complete. By contrast, China has been able to bring its large nuclear reactors into operation more quickly, averaging just seven years per project between 2017 and 2023 including several first-of-a-kind designs, with several being completed in just five years.

The last decade has seen a significant increase in the time it takes to build a nuclear reactor in the advanced economies. Most recent projects have been plagued by substantial delays and cost overruns (Figure 1.7). In the United States, the Vogtle Units 3 and 4 – the first new nuclear project in the United States in over three decades – have experienced extensive delays and cost overruns. The initial capital cost estimate of about USD (2023) 5 600 per kilowatt (kW) (gross capacity) rose to USD (2023) 14 700/kW with the timeline extending significantly beyond initial projections to around ten years. Delays have been attributed to a variety of factors, including workforce management and a change in the engineering, procurement and construction contractors after construction had started.

European projects have provided additional examples of large delays. The Olkiluoto 3 project in Finland was initially planned to be operational by 2009, but was connected to the grid in 2022. The original budget was about USD (2023, MER[2]) 3 300/kW, but costs escalated to USD (2023, MER) 7 200/kW due to design modifications, regulatory hurdles and supply chain disruptions.

In the United Kingdom, the Hinkley Point C project has struggled with escalating costs and timelines. Initially estimated at about USD (2023, MER) 8 700/kW, the budget has risen to almost USD (2023, MER) 16 000/kW[3], with the completion date being pushed back several times from 2025 initially to 2029-2031, with around 1.5 years of the delay attributed to the Covid pandemic by Electricité de France (EDF).

The Flamanville 3 project in France experienced a significant cost escalation, with initial estimates of USD (2023, MER) 3 200/kW rising to USD (2023, MER) 11 000/kW by the time it became operational in 2024, following a delay of 12 years.[4] In all three projects, the use of a new generation of reactors, the European Pressurised Reactor (EPR), which was not built in series, played a part in the cost overruns. Another important aspect is that although these three countries were not newcomers to nuclear energy, no new reactors had been built over the last 10 to 20 years, which meant that the nuclear industrial base and skills had to be rebuilt.

Some recent nuclear projects have been completed with relatively moderate delays and limited cost overruns. For example, Korea's Saeul 1 and 2 reactors[5] became operational after delays of two and five years, respectively, with

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[2] MER = market exchange rate.

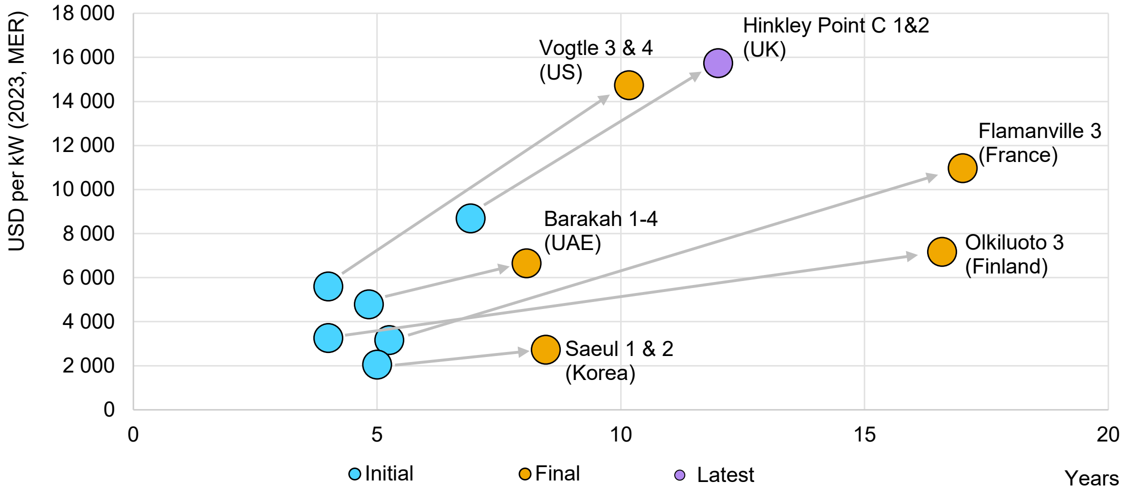
[3] The estimates provided here are in 2023 currency and are based on the initial and current cost estimates provided by EDF in 2015 currency.

[4] The estimates provided here are in 2023 currency and are based on the initial and current cost estimates provided by EDF in 2015 currency.

[5] The reactors Saeul 1 and 2 were previously named Shin Kori 3 and 4.

construction costs rising by about 30% compared with initial estimates, with cost per capacity reaching USD (2023, MER) 2 700/kW. Similarly, Barakah nuclear power plant in the United Arab Emirates was completed with comparable schedule delays to those experienced by Saeul 1 and 2, while incurring limited cost overrun.

Figure 1.7 Initial and latest capital cost estimates and construction time for selected recent nuclear projects



Notes: kW = kilowatt; MER = market exchange rate. The cost estimates do not include interest. Gross installed capacity is considered. Construction time refers to the time period between the start of the construction until grid connection. For plants shown here with multiple reactors, the average construction time is taken. The construction of Hinkley Point C is ongoing.

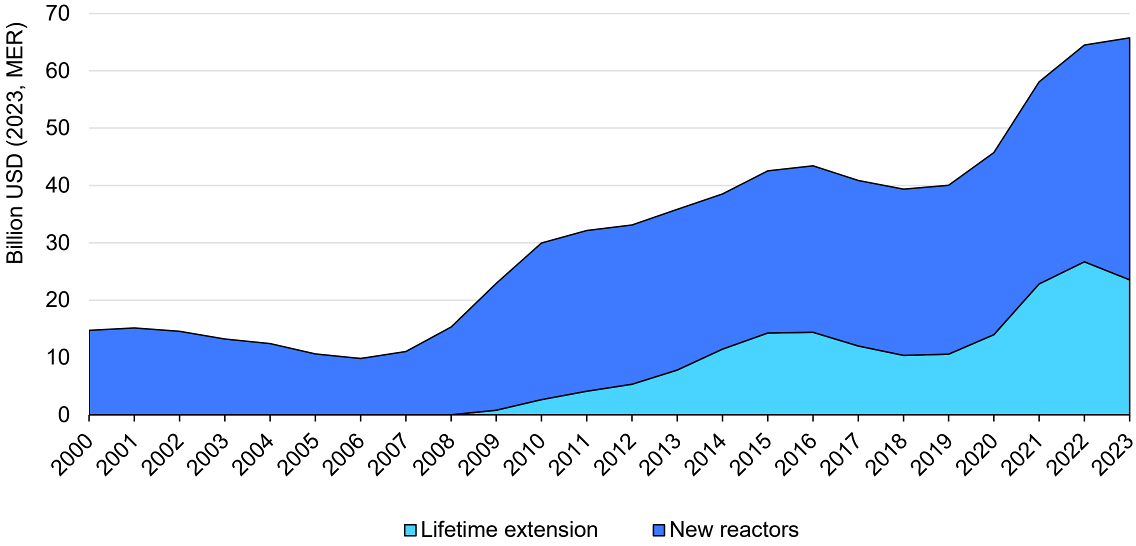
Source: IEA analysis based on publicly available sources. The latest cost estimates for Hinkley Point C considered in this analysis are based on EDF (2024), Hinkley Point C Update.

Nuclear investment has been rising in recent years

Investment in nuclear energy surged in the 1980s, as several advanced economies sought to reduce their dependence on fossil fuel imports following the oil shocks of the 1970s. This wave of new investment was almost halted following the Chernobyl accident in 1986 as several countries decided to abandon their nuclear programmes. Interest in developing new plants in other countries also fell because of higher costs related to more stringent safety regulations. Capital spending gradually ramped up again during the next decade and reached about USD 15 billion in 2000 (in 2023 dollars), but levelled off again after that as nuclear programmes reached maturity and few new units were added, falling to less than USD 10 billion in 2006. Investment then rebounded towards the end of the 2000s with the start of a new wave of construction of nuclear plants as well and the need for refurbishment of older plants that had come to the end of their operating lifetimes. Investment in new capacity levelled off again after the Fukushima Daiichi accident in 2011, with overall investment experiencing sluggish growth of less than

3% per year on average over the decade, mostly supported by lifetime extensions in advanced economies and new capacity additions in EMDE, notably China.

Figure 1.8 Global nuclear energy investment by type, 2000-2023



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Notes: MER = market exchange rate. Cost overruns account for a marginal portion of the investment increase, with the majority driven by new capacity additions. Values are presented in constant 2023 US dollars.

The increasingly pressing need to decarbonise energy systems and renewed concerns about energy security have rekindled interest in nuclear generation in recent years. Total investment in nuclear energy reached about USD 65 billion in 2023 (Figure 1.8), nearly double the level a decade before, as investment in new nuclear facilities surged to USD 35 billion in 2021 and to USD 42 billion in 2023. The overall increase in investment was also underpinned by spending of about USD 25 billion annually in refurbishing ageing infrastructure and upgrading facilities.

Drivers of renewed interest in nuclear energy

The last few years have seen increased interest in building new nuclear plants and extending the lifetimes of existing ones, pointing to a possible comeback of the industry (see Chapter 2). This is being driven by a strengthening of policy support, technological advances and growing needs for around-the-clock power, including for data centres.

Policy support for nuclear energy is strengthening in many countries

The changing policy landscape is setting the conditions for nuclear energy to continue making an important contribution to power systems around the world. Governments are increasingly recognising the benefits of nuclear energy as a low-emissions source of dispatchable electricity and heat that can make a valuable contribution to clean energy transitions and to energy security, by bolstering the stability and reliability of power systems.

Growing policy support is reflected in recent policy decisions in several countries to authorise extensions to the operating lifetimes of existing nuclear reactors (Table 1.1). Decisions taken during the past five years cover lifetime extensions at 64 reactors in 13 countries, with a total capacity of about 65 GW – around 15% of that of the current global nuclear fleet.

- In the United States, the Inflation Reduction Act extended clean energy tax incentives to nuclear energy, drastically improving the economics of all operating reactors. In the last 5 years, a total of 22 operational reactors have applied for lifetime extensions. As of 2024, all US reactors that have been in operation for at least 30 years have applied for an additional 20-year operating licence and over one-fifth of them for a second 20-year extension.
- In Japan, the Electricity Business Act was revised in 2023 as a part of the country's Green Transformation (GX) initiative, allowing reactors to remain in operation beyond 60 years by excluding periods when reactors were offline due to reasons unforeseeable by operators as defined by the act. The country also introduced a new investment promotion scheme, Long-Term Decarbonised Capacity Auction in 2023, to promote investments for decarbonised power sources including nuclear energy. The auction scheme guarantees fixed income for 20 years, covering the fixed cost of operation and enhancing the predictability of the revenue to increase the investment of new decarbonised power sources in the country.
- In France, plans have been confirmed to carry out the Grand Carenage project, including a decision in 2021 to extend operations at all 1 300 MW reactors (20 in total).
- Several other European countries have also recently announced decisions to extend operations at existing reactors, including in Belgium (involving a total capacity of 2.2 GW), Hungary (2.0 GW), the Czech Republic (2.0 GW), Finland (1.1 GW), Spain (1.1 GW), Romania (0.7 GW) and the Netherlands (0.5 GW).
- New decisions have been announced in Mexico and South Africa to extend the operations of nuclear reactors, in both cases representing half of the country's total nuclear capacity.

Table 1.1 Recent decisions on lifetime extensions of existing reactors by country, 2019-2024

Country	Decision	Total operating capacity (GW)	Recently extended capacity (GW)	Long-term plans
Armenia	A plan to extend lifetime of Armenian Unit 2 by 2036	0.4	0.4	Expansion
Belgium	Lifetime extensions of the Doel 4 and Tihange 3 reactors for 10 years (to 2035)	4.1	2.2	Phase-out
Czech Republic	The four reactors at Dukovany are expected to obtain 20-year operating lifetime extensions to 2045-2047	4.2	2.0	Expansion
Finland	Approval to extend the lifetime of the two-unit Loviisa power plant to the end of 2050	4.6	1.1	Expansion
France	The Grand Carenage programme to extend the lifetime of all nuclear reactors beyond 40 years	64.0	27.4	Expansion
Hungary	Parliamentary approval of plans to further extend the lifetime of the four units of the Paks nuclear plant by 20 years	2.0	2.0	Expansion
Japan	The revised Electricity Business Act allows over 60 years of operation in some cases by excluding periods when reactors were suspended for safety reasons	13.3	3.5	Restart
Mexico	Plans to extend the lifetime of the 775 megawatt (MW) Unit 2 of the Laguna Verde nuclear power plant by 30 years to April 2055	1.6	0.8	Expansion
Netherlands	Possible extension of the lifetime of the Borssele nuclear power plant	0.5	0.5	Expansion
Romania	Planned refurbishment of Cernavoda unit 1 to extend its operating lifetime to 60 years	1.4	0.7	Expansion
South Africa	Granting of licence for Koeberg unit 1 to continue operating for another 20 years to 2044 (Koeberg unit 2 is still under assessment)	1.9	1.0	Expansion
Spain	Extension of the operating licence of the Trillo nuclear power plant for 10 years to 2034	7.4	1.1	Phase-out
United States	The Inflation Reduction Act provides a production tax credit to the existing fleet	102.4	22.7	Expansion

Policy support is playing a critical role in driving the expansion of nuclear energy. At present, more than 40 countries plan to build new reactors or are considering doing so, including around 10 that do not as yet have any nuclear capacity (Table 1.2). In December 2023, more than 20 countries pledged to triple global nuclear capacity collectively by 2050. At COP29 in 2024, an additional 6 countries have joined the pledge. Support for SMRs, in particular, has grown in recent years. While the level of interests varies, over 30 countries have been developing SMRs or are considering deploying them. Notable policy developments to support SMRs include the Enabling Small Modular Reactors Program in Canada, which provides up to CAD 5 million (Canadian dollars) (or USD 3.7 million) of funding for SMR research and development (R&D) projects, the France 2030 Investment Plan to invest EUR 1 billion in innovative reactors including SMRs in France, and the Advanced Reactor Demonstration Program in the United States with over USD 3 billion of funding to support the deployment of advanced reactors, including SMRs.

Table 1.2 Recent policy decisions and nuclear energy developments in selected countries

Country	Recent policy decisions and nuclear energy developments	SMR included
	Countries with operational reactors	
Argentina	CAREM (SMR) is currently under construction with a capacity of 25 MW	🟡
Armenia	The construction of a new nuclear power plant by 2036 is under consideration	🟡
Belarus	Belarusian Unit 2 started operation in 2023 and the country is considering additional reactors depending on future electricity demand growth	N/A
Brazil	After a public consultation about the Angra 3 nuclear power plant, construction can restart after several stops in recent years	🟡
Bulgaria	A plan to construct two AP1000 reactors with a total capacity of 2.3 GW, due to start operation from mid-2030s A memorandum of understanding (MoU) to explore the construction of an SMR in Bulgaria signed by NuScale Power (a US developer) and Kozloduy Nuclear Power Plant New Build (KNPP-NB)	🟡
Canada	Announced up to CAD 50 million investment for Ontario's new large-scale nuclear plant The Enabling Small Modular Reactors Program, which provides up to CAD 5 million of funding for R&D projects for SMRs	🟢
China	The 14th Five-Year Plan (2021-2025), which targets nuclear capacity of 70 GW The development of the ACP100 SMR by China National Nuclear Corporation (CNNC), with completion by 2026	🟢
Czech Republic	Updated National Energy and Climate Plan, which includes a plan to continue the construction of a new nuclear plant in Dukovany by 2036 and consider other possible sites The Czech SMR Roadmap, which explores potential SMR deployment	🟢
Finland	A total of 10 to 20 SMRs are currently under consideration in the country to produce both electricity and heat, with total thermal output of 1 GW to 3 GW	🟢
France	A plan to build six EPR2 reactors and consider the need for an additional eight EPR2 reactors France 2030 investment plan, which provides funding of EUR 1 billion to develop innovative reactors including SMRs, with the aim of building a first SMR in France by 2035	🟢
Hungary	The Paks II nuclear power plant, comprising two reactors (1 200 MW each), is due to start construction in mid-2020s and come online in the early 2030s	N/A
India	National Electricity Plan 2023, which expects a total of about 13 GW of new nuclear capacity by 2032, with several reactors currently under construction The government has announced plans to develop SMRs in co-operation with the private sector	🟡
Iran	The Atomic Energy Organization of Iran (AEOI) has announced the start of construction of a nuclear plant with a total of 5 GW	N/A

Country	Recent policy decisions and nuclear energy developments	SMR included
Japan	The country is progressively restarting reactors; TAKAHAMA-1 and TAKAHAMA-2 (with a combined capacity of about 1.7 GW) restarted commercial operation in 2023; ONAGAWA-2 and SHIMANE-2 (with a combined capacity of about 1.6 GW) restarted in 2024	🟡
Korea	Shin Hanul Unit 2 started its operation in 2024 with a capacity of 1.4 GW 10th Basic Plan for Long-term Electricity Supply and Demand, which aims to increase the share of nuclear in total electricity generation to over 30% by 2036	🟢
Netherlands	A total of EUR 14.5 billion allocated by the government to the Climate Fund, including EUR 65 million to support the Dutch SMR programme	🟢
Pakistan	Country is finalising to start construction of new plant, expecting to start operation by 2030	N/A
Romania	Integrated National Energy and Climate Plan Change, which confirms plans for two new Candu units with a combined capacity of 1.4 GW at Cernavoda by 2032 The Romanian and US governments signed an agreement on the front-end engineering and design study for a SMR using NuScale technology	🟢
Russia	The development of several SMR designs, including the country's first land-based SMR, which is due to be commissioned by 2028 Draft plan for electric power facilities, in which the share of nuclear in total electricity generation is targeted to rise from 18.9% in 2023 to 24% by 2042	🟢
Slovakia	Government approval of a plan to build a new nuclear reactor with a capacity of up to 1.2 GW at the Jaslovske Bohunice site Draft update of the Integrated National Energy and Climate Plan, in which nuclear energy, potentially including SMRs, is expected to dominate its electricity sector by 2050	🟡
Slovenia	Draft update of the Integrated National Energy and Climate Plan, which supports the continued expansion of nuclear energy and the consideration of SMRs	🟡
South Africa	The development of two SMR designs (HTMR-100 and A-HTR-100)	🟢
Sweden	A roadmap for new nuclear energy in Sweden, which aims to add new capacity of 2.5 GW by 2035 and foresees further expansion thereafter	🟢
Switzerland	Energy Strategy 2050 aims to phase out nuclear energy by 2050, though the government has announced its intention to lift a ban on the construction of new nuclear plants	N/A
Ukraine	Draft National Energy and Climate Plan of Ukraine 2025-2030, which discusses potential development of SMRs	🟡
United Arab Emirates	Updated Energy Strategy 2050, which aims to promote nuclear energy and encourages investments in the country's renewable and clean energy sector	N/A
United Kingdom	British Energy Security Strategy (2022), which targets eight new large reactors as well as SMRs to achieve nuclear power capacity of 24 GW by 2050 Great British Nuclear (GBN), launched in 2023 to support the 2050 target	🟢
United States	A federal government plan to add new capacity of 35 GW by 2035 (including plants under construction), with deployment of 200 GW capacity by 2050 to at least triple the country's nuclear capacity The Advanced Reactor Demonstration Program, which provides over USD 3 billion in funding for SMRs and other advanced reactor designs	🟢
Countries with reactors under construction or considering introducing nuclear energy		
Bangladesh	Integration Energy and Power Master Plan (IEPMP) 2023, which discusses the potential of nuclear energy including SMRs, targeting future capacity of between 4.8 GW and 7.2 GW by 2050	🟡
Estonia	Draft update of the National Energy and Climate Plan, which consider the potential of SMRs and highlights their advantages given limited generation capacity that can be integrated in the Estonian electricity system	🟡

Country	Recent policy decisions and nuclear energy developments	SMR included
Ghana	Long-term National Development Plan of Ghana (2018-2057), which envisions its first nuclear power reactor to come online by 2030	🟡
Jamaica	MoU signed with Canadian organisations in 2024 to explore the potential of nuclear energy to diversify the country's energy mix	🟡
Jordan	Jordan Atomic Energy Commission is exploring the potential for deploying SMRs, including for desalination, by shortlisting the most viable SMR designs from internationally recognised vendors	🟡
Morocco	Morocco has been reviewing opportunities to introduce nuclear in its energy mix by 2030	N/A
Poland	State-owned Polskie Elektrownie Jądrowe (PEJ) signed an agreement in 2023 with Westinghouse for the latter to build three AP1000 reactors, with the first unit to be online by 2033 Several MoUs signed by leading companies to start SMR projects in the country	🟢
Singapore	Deputy Prime Minister announced that the country will pave the way to deploy nuclear technologies and plans to launch a roadmap in late 2024	🟡
Türkiye	Long-term National Energy Plan, which aims to add 7.2 GW nuclear capacity by the end of 2035 and 20 GW by 2050 including potentially SMRs	🟡
Uzbekistan	Concept note for ensuring electricity supply in Uzbekistan in 2020-2030, which envisions the introduction of 2.4 GW of nuclear capacity by 2030 The government adopted a decision on the construction of SMRs, aiming to start operation around 2030.	🟢
Countries that previously phased out nuclear or currently have phase-out plans		
Italy	The National Energy and Climate Plan, released in 2023, discusses the possible contribution of SMR and fusion technology in dedicated nuclear scenarios, reaching 8 GW to 16 GW by 2050	🟡
Kazakhstan	The National Strategy for Achieving Carbon Neutrality, which aims to affect a transition to a low-carbon economy by 2060, discussing potential for nuclear power to contribute to the generation mix	🟡
Lithuania	A renewed National Energy Independence Strategy, which aims to analyse the option of using advanced SMR technologies	🟡
Spain	In 2023, the government announced plans to phase out four of the country's seven reactors by 2030 and the other three by 2035	N/A

🟢 SMR planned 🟡 SMR potential under discussion N/A SMR not mentioned

Nuclear technology development is accelerating and could reshape nuclear market leadership

Innovation in nuclear fission technologies, notably SMRs, has the potential to reshape the nuclear market industry. SMR R&D has been stepped up in recent years, with upwards of 80 designs under development around the world. By reducing scale, SMR technologies hold the promise of reduced upfront costs, shorter development times and less construction risk, in turn opening up new applications for nuclear energy. Many of the leading companies in developing SMRs are based in advanced economies, potentially rebalancing the global leadership of the nuclear industry. In addition, efforts to develop advanced large-scale reactors, including both Generation III+ and Generation IV reactors, aimed at improving their safety, economics and sustainability, are being strengthened.

SMR development is moving fast

SMRs are a central focus of innovation in the nuclear industry, with several leading companies having made important technological advances in recent years (Table 1.3). The first SMR projects that will come online are expected to take a variety of forms, with a wide range of maximum power capacities – with most designs ranging from 10 MW up to 350 MW. Smaller micro reactor concepts are also under development, and they may have significant potential for niche applications such as supplying power to remote communities and industries, including desalinisation, drilling and mining.

SMR designs with capacities at the upper end of the range are under development in the United States and United Kingdom in particular. Medium-sized reactors are the focus of R&D in China, Japan and Korea. Several countries are working on smaller SMRs, for example in Canada to provide power to remote areas and in India to power steel mills. Various EU countries are interested in deploying SMRs with a wide range of sizes under consideration depending on policy, agreements with SMR developers and energy security needs. Romania and Bulgaria are looking to deploy small to medium-sized reactors, whereas bigger reactors are being considered in the Czech Republic and Poland. Some African countries, including Kenya and Ghana, are also looking into building SMRs. In August 2024, Nuclear Power Ghana signed a commercial agreement with the Regnum Technology Group, a US developer, to develop SMRs of less than 100 MW scale using technology developed by NuScale Power, a US developer. Kenya is targeting the start of construction of its first SMR with a capacity of 300 MW in 2027 and commissioning in 2034.

SMRs can also serve as a source of heat for low-temperature applications such as district heating and desalination. For instance, NuScale's light water reactor is designed to generate sufficient heat for these applications. In Finland, there are plans to build an SMR dedicated to district heating, developed by Steady Energy, a local company. The LDR-50 (low-temperature district heating) reactor, designed specifically for urban district heating, aims to reduce reliance on fossil fuels and support Finland's energy transition. In 2024, Sweden's Kärnfull entered into a partnership with Steady Energy to deploy the technology in Sweden. Another example is the NHR-200 in China, a 200 MW reactor under feasibility study for district heating and desalination.

There are upwards of 80 SMR designs currently under development, with some companies working on several of them. While some companies have advanced their technologies to the near-commercial stage, many others are still at the early conceptual or design phases. Companies that are on the leading edge of SMR development, having completed their primary SMR design, development plans and agreements, include the following:

- NuScale Power, a US-based company, has been actively pursuing SMR projects in several countries. In Romania, a 462 MW six-module VOYGR-6 SMR is planned, with a target completion date of 2029. NuScale has also signed MoU and co-operation agreements with Bulgaria, Canada, the Czech Republic, Ghana, Indonesia, Korea, Poland, Ukraine and the United States.
- Westinghouse Electric Company, another US firm, is ready to deploy its AP300 (330 MW SMR) technology in the United Kingdom. In September 2024, its SMR project was shortlisted for the final phase of Great British Nuclear's (GBN) competitive SMR technology selection process, with the first unit expected to be built by the early 2030s. Westinghouse is active in several other countries and has signed MoUs in Canada, the Czech Republic, Romania and Ukraine.
- TerraPower, a US company, plans to build a 345 MW demonstration plant in Kemmerer, Wyoming. The Natrium project is scheduled to begin operation five years after the start of construction, which is expected to begin in 2025.
- GE Hitachi Nuclear signed a contract with Ontario Power Generation (OPG) in January 2023 to build the first BWRX-300 SMR at OPG's Darlington site in Canada. It will have a capacity of 300 MW. Three other 300 MW units are also planned. Early site preparation work has been completed with construction expected to start in 2025 and commercial operation by the end of 2029. Additional units are planned in Saskatchewan. GE Hitachi Nuclear has also progressed to the next stage of GBN's SMR competition and has signed MoUs in the Czech Republic, Estonia, Poland and Sweden.
- Rolls-Royce SMR, a UK company, is developing a 470 MW SMR design, the first UK reactor design submitted for consideration by the Nuclear Industry Association to the government. It has signed an MoU in Netherlands and it has been selected as preferred supplier in Sweden, Poland and in the Czech Republic, where early construction works are expected to start as soon as 2025. The company aims to complete its first unit in the United Kingdom in the early 2030s.
- NUWARD, a French company owned by (EDF), is developing a 200 MW to 400 MW multipurpose SMR project based on proven pressurised water reactor (PWR) technology, with the first construction to begin in France by around 2030. NUWARD and EDF have also signed an MoU or co-operation agreement to build SMRs with utilities in Finland, India, Italy, Poland, Slovakia and Slovenia.
- X-energy, a US company, expects that the first project using its 320 MW Xe-100 reactor technology will be completed in Texas by end of the 2020s. Three other such reactors are planned as part of a 960 MW project in Washington, as part of its goal of reaching almost 5 GW of installed SMR capacity in the United States by 2039. X-energy has recently completed the pre-licensing process to develop projects in Canada.

- Oklo, a US start-up, is targeting the construction of its first SMR by 2027 at the Idaho National Laboratory using recycled fuel from the US Department of Energy (DOE). Other projects in Ohio and Alaska are on the drawing board.
- Moltex Energy, a Canadian company, has signed an MoU to build its first reactor at the Point Lepreau site in New Brunswick, with a target operation date in the early 2030s.
- The CNNC is developing SMRs primarily for domestic use in China. Its ACP100 SMR, known as Linglong One, has a capacity of 125 MW. Construction of the first ACP100 began in 2021 on the island province of Hainan, with operation expected to start in 2026. This reactor could be the world's first commercial land-based small modular PWR.
- Kairos Power is the first US company to receive a construction permit for a Generation IV SMR in December 2023. The works started in July 2024 with a target to be operational by 2027. This test reactor will be used for thermal use only but a second unit will then follow for electricity generation. Recently, Google signed a contract with Kairos Power to ensure a SMR online by 2030 and up to 500 MW by 2035.
- Newcleo, an Italian start-up based in France, is working on lead-cooled fast reactor (LFR) technology and aims to commission the first 30 MW LFR in France by 2031, followed by a 200 MW commercial unit in the United Kingdom by 2033.
- Korea Hydro & Nuclear Power (KHNP) is developing a 170 MW i-SMR (innovative SMR) under a government-funded project. It has reached the basic design phase and is currently undergoing the standard design phase, aiming for a Standard Design Approval (SDA) by 2028.

Table 1.3 Leading SMR companies plan and technology

Company	SMR development plan	Technology
NuScale	Romania: 6-module plant (462 MW) planned operation by 2029 MoU/agreement in Bulgaria, Canada, Czechia, Ghana, Indonesia, Korea, Poland, Ukraine and US	VOYGR SMR: 77 MW per module, 4, 6 or 12 modules per plant. Integral PWR design with passive safety features
Westinghouse	UK: advanced approval stage for the AP300 (1st reactor online in early 2030s) MoU/agreement in Canada, Czechia, Romania and Ukraine	AP300 SMR: 330 MW single-loop PWR. Based on AP1000 technology. Ultra-compact footprint, modular construction
TerraPower	US: Natrium reactor planned for Wyoming, US, with operation target 2030	Natrium: 345 MW sodium-cooled fast reactor with molten salt energy storage
GE Hitachi Nuclear	Canada: contract for building the first SMR with OPG by 2029 MoU/agreement in Czechia, Estonia, Poland, Sweden and UK	BWRX-300: 300 MW water-cooled, natural circulation SMR based on Boiling Water Reactor (BWR) design

Company	SMR development plan	Technology
Rolls-Royce	UK: government funding for SMR development, deployment in early 2030s MoU/agreement in Czechia, Netherlands, Poland and Sweden	UK SMR: 470 MW PWR design, 60-year service life
NUWARD	France: 200-400 MW SMR, with the construction start planned around 2030 MoU/agreement in Finland, India, Italy, Poland, Slovakia and Slovenia	NUWARD: 200-400 MW multipurpose SMR, based on proven PWR technology
X-energy	US: selected for Advanced Reactor Demonstration Program with 320 MW SMRs online by 2030. MoU in Canada	Xe-100: 80 MW high-temperature gas-cooled reactor, modular design for 320 MW plants
Oklo	US: Aurora SMR first lab-plant to be ready by 2027	Aurora: 15 MW fast neutron reactor, potential for larger versions
Moltex Energy	Canada: agreement with New Brunswick Power for first reactor by early 2030s	SSR-W: 300 MW molten salt reactor design, reusing spent nuclear fuel
CNNC	China: ACP100 SMR under construction in Hainan, operation expected by 2026	ACP100 (Linglong One): 125 MW integral PWR design
Kairos Power	US: first Generation IV SMR online by 2027	Hermes Low-Power Demonstration Reactor: 35 MW molten salt reactors
Newcleo	UK: developing LFR design. First 200 MW commercial unit expected in the UK by 2033	LFR-AS-200: 200 MW LFR design
KHNP	Korea: simulator reactor completed by the second half of 2027 and SDA by 2028	i-SMR: 170 MW integrated PWR SMR

Brownfield investments as an option to reduce costs

Repurposing or replacing former coal or gas power plants with SMRs may offer a promising solution for transitioning to low-carbon energy systems by making use of existing infrastructure. SMRs, with capacities around 300 MW, are well-suited to replace retired coal facilities due to their comparable power output and the availability of existing infrastructure, such as grid connections and water resources. Such brownfield projects would not only lower land acquisition costs but also facilitate permitting processes. A US DOE study shows that converting former coal power plants to nuclear ones could save up to 35% of the cost of building the nuclear plant and that more than 300 existing or retired coal plants are suitable for conversion. TerraPower's planned Natrium reactor is due to be built near a coal plant in Wyoming in order to benefit from existing infrastructure. In Romania, a coal plant site in Doiceşti has been identified as an attractive location for the country's first SMR.

Development of advanced large reactors

The field of nuclear science and technology is showing increasing vitality. In recent years, many innovative nuclear reactors, advanced nuclear fuel cycles and various solutions for nuclear energy utilisation have been developed, which has enabled continuous progress in nuclear innovation. The Generation IV nuclear reactors – the latest generation of reactors, which are envisaged to replace current Generation III designs – are at the forefront of these trends. Nevertheless, when unproven features are introduced in reactor designs, the construction risks increase accordingly, since there is less or no operating experience. Many designs aim to reduce this risk as much as possible.

The main objectives of these advanced systems are to improve sustainability (for example, through more efficient utilisation of nuclear fuel and minimising nuclear waste), economics (e.g. by lowering construction and operating costs) and safety (e.g. by eliminating the need for off-plant emergency response) and reducing the risk of proliferation. There are several dozen varieties of design under development worldwide, including water-cooled, gas-cooled, liquid metal-cooled and molten salt-cooled reactors, as well as different fuel cycles.

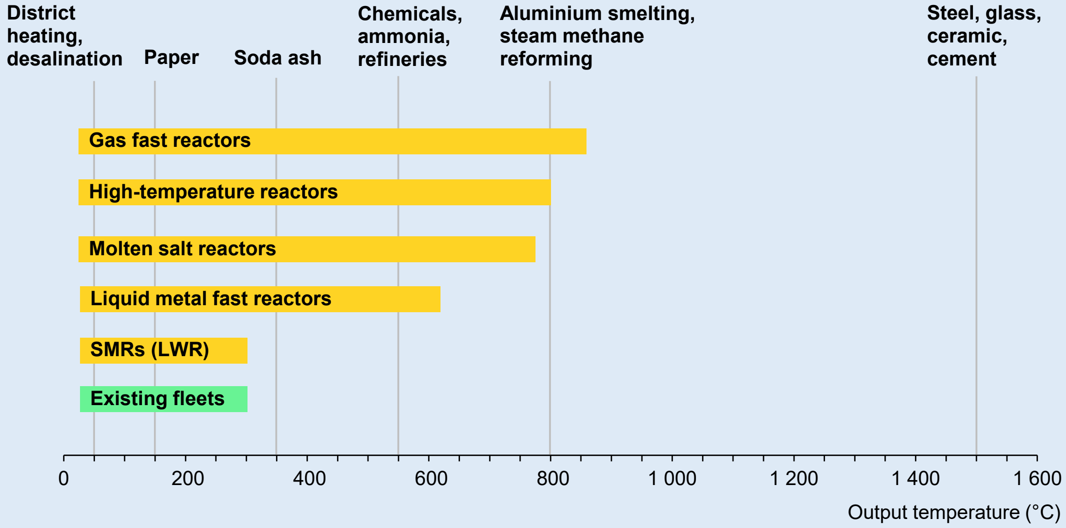
In the United States, the federal government is supporting a few major initiatives. In particular, the Infrastructure Investment and Jobs Act of 2021 includes numerous nuclear-related provisions, such as funding for the US DOE’s Advanced Reactor Demonstration Program, designed to accelerate the demonstration of advanced reactors through cost-sharing partnerships with US companies. In 2023, the European Commission included advanced nuclear reactors in the list of strategic technologies eligible for financial support in the Net Zero Industry Act, which came into force in 2024. China has built the China Experimental Fast Reactor (CEFR) and the high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration project (along with a supporting nuclear fuel supply system), endorsed the demonstration of the sodium-cooled fast reactor (SFR) project, and initiated R&D of the Integral Closed Cycle Advanced Fast Reactor Nuclear Energy System to create an advanced closed fuel-cycle system.

All these advanced designs still need to address major technological and economic barriers. The extent to which costs can be lowered will determine the degree to which these are able to produce low-emissions electricity, heat or hydrogen in the long term (Box 1.1). Outside of China and Russia, no design has yet reached the construction stage. And even in those two countries, they have not achieved series production with corresponding integrated supply chains.

Box 1.1 Opportunities for nuclear power plants to provide high-temperature heat for hard-to-abate sectors

Generation IV reactors, which are able to supply heat at above 800 °C, offer a much broader range of possible applications for use as nuclear CHP. The higher temperatures of Generation IV reactors mean they could be used for supplying heat in the most energy-intensive industrial sectors, such as chemicals, oil refining, aluminium smelting and steam methane reforming (Figure 1.9). SMRs can supply heat and electricity to end users located in close proximity, minimising heat transmission losses.

Figure 1.9 Nuclear CHP applications by temperature ranges and reactor types



Sources: IEA analysis based on NEA (2021), Small Modular Reactors and IAEA (2017), Opportunities for Cogeneration With Nuclear Energy.

Several advanced designs that could produce high-temperature heat are under development. The world's first modular high-temperature gas-cooled reactor pebble-bed module (HTR-PM) entered operation in China in 2023, while the BREST-OD-300, a lead-cooled fast-neutron reactor, is under construction in Russia. Other notable SMR projects under development with technology suited for high-temperature applications include the X-energy (Xe-100) and Kairos (a molten-salt reactor) in the United States, and Terrestrial (a molten-salt reactor) in Canada.

High-temperature steam electrolysis, particularly when paired with high-temperature reactors, may prove to be a more economically viable option than hydrogen produced through low-temperature electrolysis. This technology is at a relatively early stage of development stage, though various studies that have been carried out, such as those at Idaho National Laboratory, demonstrate that it is theoretically feasible.

Data centres are emerging as a new dedicated market for nuclear power

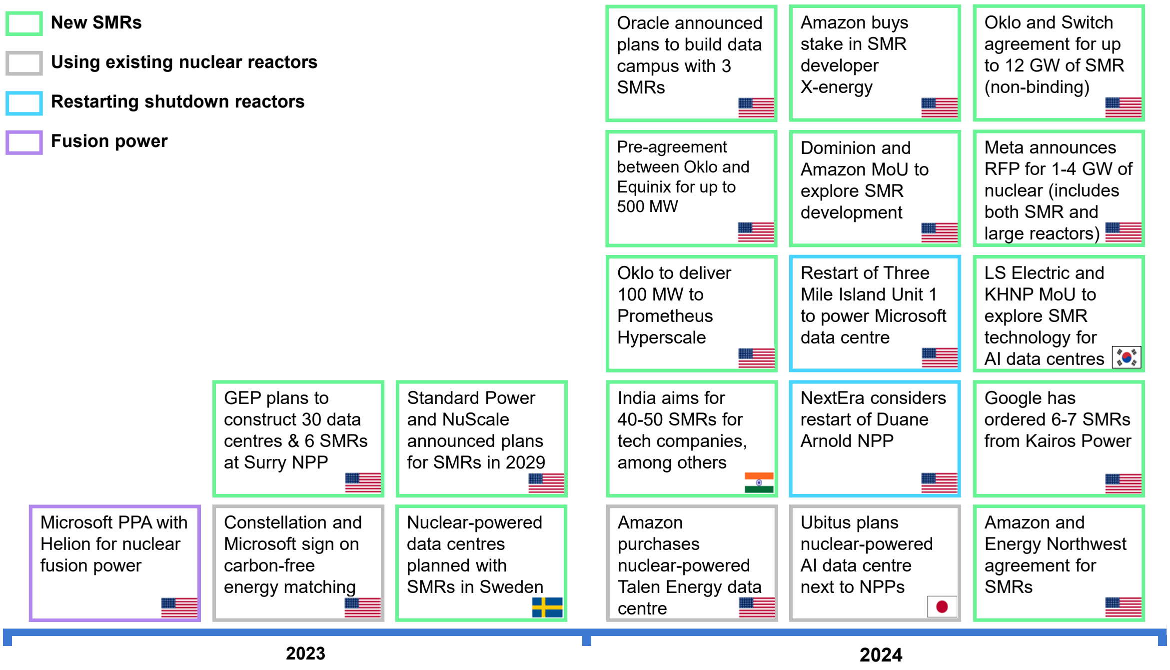
Technology firms are increasingly turning to nuclear energy and specifically SMRs as the source of the electricity needed for their data centres. Electricity demand from data centres is expected to increase rapidly, driven by digitalisation and the boom in AI. To date, plans to build up to 25 GW of SMR capacity associated with supplying the data centre sector have been announced worldwide, almost all of them in the United States, though projects are at varying stages of maturity and certainty.

Globally, electricity consumption of data centres currently accounts for only around 1% of electricity demand. While this share is expected to increase, data centres' share of the growth of global electricity consumption will remain limited compared with that in other end-use sectors, especially EVs and air conditioners. Nevertheless, the local impact of data centres is becoming increasingly noticeable. Data centres already make up a sizeable portion of electricity demand in some countries and regions, causing local grid and supply bottlenecks. In Ireland, for example, data centres accounted for 20% of national electricity consumption in 2023. In the US state of Virginia, the share exceeds one-quarter.

A study published in December 2024, which was commissioned by the US DOE, estimates that electricity consumption of data centres in the United States increased from 58 TWh in 2014 to 176 TWh in 2023, accounting for 4.4% of total electricity consumption. Their projections show that the electricity use of the sector could rise by about an additional 150 TWh to 400 TWh out to 2028, reaching 325 TWh to 580 TWh to make up 6.7-12% of the total electricity demand.

The first half of 2024 saw a marked surge in announced new data centres in the United States, with their associated power capacity needs totalling close to 24 GW – more than triple that for same period in 2023. A growing number of US data centre projects are looking to secure their electricity supplies from a dedicated source of nuclear energy, notably SMRs. The number of announcements of nuclear-powered data centre projects grew substantially in 2024 compared with the previous year (Figure 1.10). The most recent projects are mainly based on SMRs, while others involve the procurement of nuclear energy from existing plants in operation or that would need to be reopened. Since SMRs are expected to become commercially available only towards the end of the current decade, restarting shut-down reactors is seen as a way of meeting more immediate power needs. Nuclear-powered data centres are also planned in India, Japan and Sweden. A significant change that has occurred over the last two years is that data centres are now more actively supporting the development and commissioning of new nuclear projects rather than merely purchasing nuclear energy.

Figure 1.10 Recent announcements and agreements related to the procurement of nuclear energy for data centres



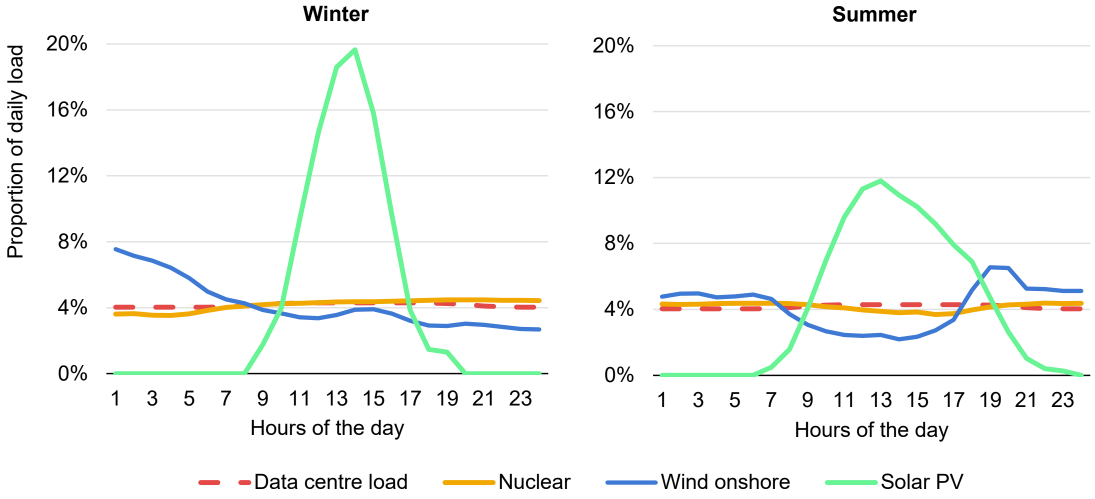
IEA. CC BY 4.0.

Notes: PPA = power purchase agreement; RFP = request for proposals; NPP = nuclear power plant.

Source: IEA analysis based on publicly available sources such as company press releases, journalistic coverage and government statements.

The increasing interest of data centres in nuclear energy reflects both their growing electricity demand and their need for clean, firm power to meet their decarbonisation targets. Data centres generally have very high uptime rates – the percentage of time a system is up and running. They generally aim for a rate of 99.999% (known as the “5 Nines”), i.e. downtime is limited to less than five minutes per year. As a result, they typically have a relatively flat baseload profile, which matches well the load profile of nuclear power plants (Figure 1.11). Both technologies are highly capital-intensive, so they need to run at close to full capacity most of the time throughout the year to recuperate their investment costs. Similarly, the data centre sector is also interested in geothermal power, including next-generation geothermal technologies.

Figure 1.11 Representative daily load curves of data centres and selected clean power sources in winter and summer in France



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Notes: The data on hourly electricity generation refer to the representative days of 2 January 2023 and 11 June 2023. The generation profiles shown are derived from the total generation of the selected technologies on these days.
Sources: IEA analysis based ENTSO-E transparency and E3 Whitepaper (2024).

This need for firm, stable clean power means that data centre operators may be willing to pay a premium for nuclear power supplies. One notable example is the Microsoft-Constellation Energy deal. External estimates indicate Microsoft would pay about USD 100 per megawatt-hour (MWh) to USD 110/MWh under a deal announced in September 2024 – indicating about USD 40/MWh of a premium compared with wind and solar energy – for power from Constellation's 835 MW Three Mile Island unit 1, which was shut down in 2019.

In some cases, data centres are securing nuclear-powered energy under PPAs. Of the up to almost 27 GW of projects announced in 2023-2024 involving both SMRs and large nuclear reactors, about 15 GW have been associated with PPAs, though not all of them have been finalised yet. For instance, Microsoft and Constellation Energy have opted for a 20-year PPA for the restart of the Three Mile Island plant, while AWS and Talen Energy are aiming to agree to a 10-year PPA for 300 MW to 960 MW of nuclear energy. In addition, data centre operators, power generators and utilities are designing new tariff formats. Google and NV Energy signed an agreement that includes a novel market rate structure called Clean Transition Tariff (CTT) aimed at supporting investment in nuclear energy, among other clean energy technologies, via enabling large customers to pay higher rates for advanced clean energy technologies without passing costs on to ratepayers. The CTT allows customers to pay a fixed price per MWh for clean energy delivered hourly, with a variable rate for additional grid energy. Google, Microsoft and the North American steelmaker Nucor announced in March 2024 that they are working on a demand aggregation model to facilitate first-of-a-kind projects for advanced clean electricity technologies, including advanced nuclear.

Opportunities for restarting nuclear plants

The heightened focus on energy security and the rising need for clean, firm power in the face of rising electricity demand have led to growing interest in restarting reactors that have been shut down for economic reasons in some regions, notably the United States. As discussed above, expectations of soaring data centre electricity demand have led to plans to restart several decommissioned US reactors. There have also been discussions on the possibility of restarting recently shut-down reactors in Germany.

Reopening nuclear reactors is a technically complex process that requires thorough safety and environmental assessments. First, the technical condition of the reactor, cooling system and other critical infrastructure must be evaluated. Following this, necessary maintenance and repairs are carried out. In many cases, components such as wiring or turbines, which are prone to corrosion after the power plant has been shut down, need to be replaced. Regulatory approval then needs to be sought, requiring the plant to meet current licensing and permitting requirements.

Training and preparing qualified personnel to ensure safe operations is a critical factor. In countries with limited remaining nuclear production, staffing might be a barrier to recommissioning nuclear power plants. Engaging with the local community and other stakeholders is also necessary to gather feedback and foster transparency and social acceptability about the reopening process. Before the reactor can be fully recommissioned, extensive system testing must be performed once approval has been obtained. Finally, a phased commissioning process needs to be undertaken, gradually increasing the plant's capacity to ensure a safe return to full operational status.

Experience in restarting nuclear reactors is limited worldwide. Japan has the most experience, as all the country’s reactors were shut down following the Fukushima Daiichi accident in 2011. But while the recommissioned units in Japan were maintained to allow them to be restarted in the future, this is not always the case elsewhere. Where reactors were shut down due to political or market-related reasons and were not well-maintained, restarting them can involve considerable technical difficulties and costs, especially if dismantling has already started. The cost of reopening a reactor can reach several billion US dollars, irrespective of the reactor's size or age.

Japan has been recommissioning its nuclear reactors in a gradual manner aimed at maximising safety, ensuring energy security and meeting its environmental pledges. Of the 54 commercial reactors shut down in 2011, 14 nuclear reactors have since resumed operations while 11 are awaiting reopening as of 2024 (Table 1.4). The New Regulatory Requirements, adopted in 2013, introduced stringent safety protocols and oversight, including upgrades to withstand tsunamis and earthquakes, improved backup cooling systems, anti-terrorism measures, and enhanced flood prevention measures for reopened reactors. Public acceptance for reopening the plants, particularly among local communities, is an important factor in Japan, which can lead to longer development times, coupled with stricter regulations.

Table 1.4 Status of Japan's nuclear reactors

Unit name	Reactor type	Gross capacity (MW)	Status
Genkai-3	PWR	1 180	Operational
Genkai-4	PWR	1 180	Operational
Hamaoka-3	BWR	1 100	NRA permission pending
Hamaoka-4	BWR	1 137	NRA permission pending
Hamaoka-5	BWR	1 380	NRA not applied
Higashi Dori-1 (Tohoku)	BWR	1 100	NRA permission pending
Ikata-3	PWR	890	Operational
Kashiwazaki Kariwa-1	BWR	1 100	NRA not applied
Kashiwazaki Kariwa 2	BWR	1 100	NRA not applied
Kashiwazaki Kariwa -3	BWR	1 100	NRA not applied
Kashiwazaki Kariwa -4	BWR	1 100	NRA not applied
Kashiwazaki Kariwa -5	BWR	1 100	NRA not applied
Kashiwazaki Kariwa -6	BWR	1 356	Passed NRA review
Kashiwazaki Kariwa -7	BWR	1 356	Passed NRA review
Mihama-3	PWR	826	Operational
Ohi-3	PWR	1 180	Operational
Ohi-4	PWR	1 180	Operational
Ohma	BWR	1 383	NRA permission pending (under construction)
Onagawa-2	BWR	825	Operational
Onagawa-3	BWR	825	NRA not applied
Sendai-1	PWR	890	Operational
Sendai-2	PWR	890	Operational

Unit name	Reactor type	Gross capacity (MW)	Status
Shika-1	BWR	540	NRA not applied
Shika-2	BWR	1 206	NRA permission pending
Shimane-2	BWR	820	Operational
Shimane-3	BWR	1 373	NRA permission pending (under construction)
Takahama-1	PWR	826	Operational
Takahama-2	PWR	826	Operational
Takahama-3	PWR	870	Operational
Takahama-4	PWR	870	Operational
Tokai-2	BWR	1 100	Passed NRA review
Tomari-1	PWR	579	NRA permission pending
Tomari-2	PWR	579	NRA permission pending
Tomari-3	PWR	912	NRA permission pending
Tsuruga-2	PWR	1 160	NRA permission pending

Notes: BWR = boiling water reactor; PWR = pressurised water reactor; NRA = Nuclear Regulation Authority.
Source: IEA analysis based on data from METI (accessed 2024).

In the United States, there are plans to restart three plants. In addition to the Three Mile Island plant (see above), there are plans to reopen the 850 MW Palisades Nuclear Plant, which was shut down in 2022, in late 2025, underpinned by a USD 1.5 billion loan commitment from the US DOE. NextEra Energy is also considering restarting the Duane Arnold nuclear power plant to meet growing data centre electricity demand. In Germany, opposition parties in November 2024 called for an expert assessment to check whether it is technically and economically feasible to restart the country’s recently closed reactors, though the former nuclear power plant operator, E.ON, stated that it would not be economical to do so.

2. Outlook for nuclear investment

Highlights

- **Global investment in nuclear energy increases in all three scenarios set out in this report**. From around USD 65 billion per year today, investment rises to USD 70 billion per year by 2030 in a scenario reflecting today's policy settings (the STEPS), putting global nuclear capacity on track to rise by more than 50% to nearly 650 GW by 2050. Nuclear investments could rise more rapidly with stronger government policy interventions. In the Announced Pledges Scenario (APS), in which all energy and climate policies are met in full and on time, investment hits USD 120 billion in 2030 and nuclear capacity more than doubles by mid-century. In the Net Zero Emissions by 2050 Scenario, investment exceeds USD 150 billion by 2030 and installed capacity rises above 1 000 GW by 2050.
- **While large reactors are set to capture the majority of nuclear investment, SMRs are poised for rapid growth.** In the STEPS, SMR capacity reaches 40 GW in 2050. Stronger government support in the APS sees more than 1 000 SMRs deployed by 2050, with a total capacity of 120 GW. This involves a rise in investment in SMRs from USD 5 billion today to over USD 25 billion in 2030, with cumulative investment of USD 670 billion by 2050.
- **The outlook for nuclear energy and investment differs markedly across regions and countries.** In advanced economies, nuclear capacity rises thanks to new plants and lifetime extensions at existing ones; in the APS, capacity jumps by 40% to 2050. China accounts for over half of all capacity added to 2050, and the size of China's nuclear fleet overtakes that of the United States by 2030 to become the largest in the world. In other markets, nuclear grows more rapidly after 2035, reaching 25% of global nuclear capacity by 2050 in the APS.
- **Advanced economies have the opportunity to take a larger part of the nuclear market.** The share of new large-scale nuclear projects using their designs rises from less than 10% in recent years to 40% by 2030 and over half thereafter in the APS, thanks to new construction starts in Europe, the United States and Japan. Widespread deployment of SMRs could accelerate the shift in market leadership, with over 60% of new construction starts to 2050 in the APS using designs from the United States or Europe.
- **Expanding and diversifying nuclear supply chains, including investment in a larger qualified workforce, will be key to making nuclear energy secure and affordable.** Uranium production is highly concentrated in four countries, with Kazakhstan accounting for 43%. Enrichment capacities are also concentrated in only four suppliers. Several countries have introduced policy measures to promote greater diversity of nuclear fuels supply, and various projects are in development.

Global outlook

Government policy will play a critical role in the future of nuclear energy

Global investment in nuclear energy and installed capacity are projected to increase in all three scenarios set out in the International Energy Agency's (IEA) World Energy Outlook 2024. Those scenarios incorporate different assumptions about government policies, climate ambitions, and also economic and demographic context, technology costs and learning, energy prices and affordability, corporate sustainability commitments, and social and behavioural factors (Box 2.1). In the Stated Policies Scenario (STEPS), which reflects today's policy settings, nuclear investment increases slightly from about USD 65 billion in 2023 to about USD 70 billion in 2030 (Figure 2.1). About 80% of the investment in 2030 goes to the construction of new large-scale reactors, 10% to small modular reactors (SMRs) and the remaining 10% to lifetime extensions of and uprates at existing nuclear reactors. Beyond 2030, annual nuclear investment declines somewhat, especially after 2040, reaching just USD 45 billion in 2050. This is due to a downturn in the construction of new reactors, especially in the People's Republic of China (hereafter, "China"), as well as declining costs for both large-scale reactors and SMRs.

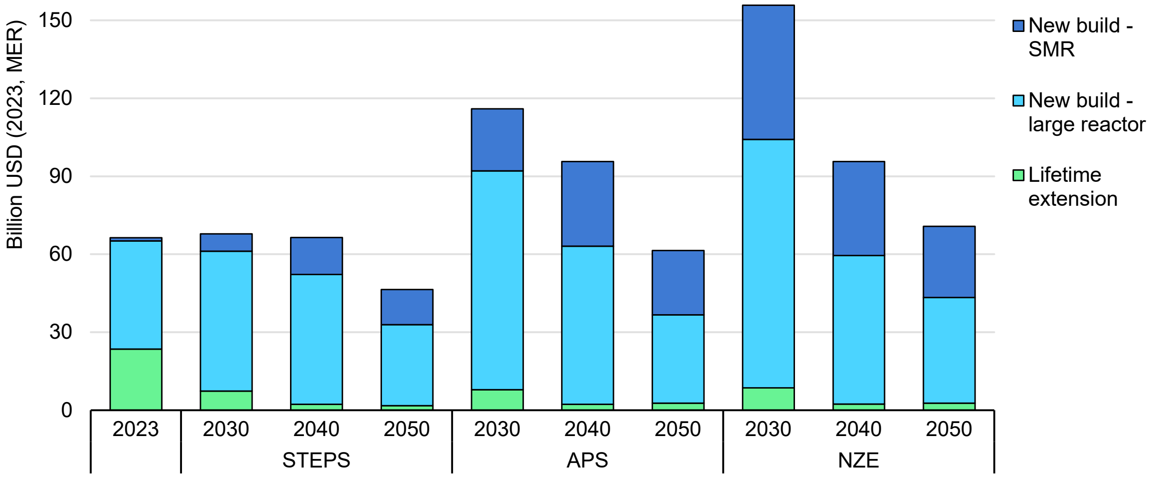
Box 2.1 IEA scenarios

IEA scenarios illustrate several different pathways that the energy sector could follow, the levers that decision-makers can use to reach them, and their implications for energy markets, security and emissions:

- The Stated Policies Scenario (STEPS) is an exploratory scenario which reflects today's policy settings based on a sector-by-sector and country-by-country assessment of the energy-related policies that are in place as of the end of August 2024, as well as those that are under development. The scenario also considers currently planned manufacturing capacities for clean energy technologies.
- The Announced Pledges Scenario (APS) is an exploratory scenario which assumes that all climate commitments made by governments and industries around the world as of the end of August 2024, including nationally determined contributions (NDCs) and longer-term net zero targets, as well as targets for access to electricity and clean cooking, will be met in full and on time.

- The Net Zero Emissions by 2050 (NZE) Scenario is normative, setting out a pathway for the global energy sector to achieve net zero carbon dioxide (CO_2) emissions by 2050. It does not rely on emissions reductions from outside the energy sector to achieve its goal. Universal access to electricity and clean cooking are achieved by 2030. The scenario was updated with the latest data in 2024.

Figure 2.1 Global investment in nuclear energy by scenario and type, 2023-2050



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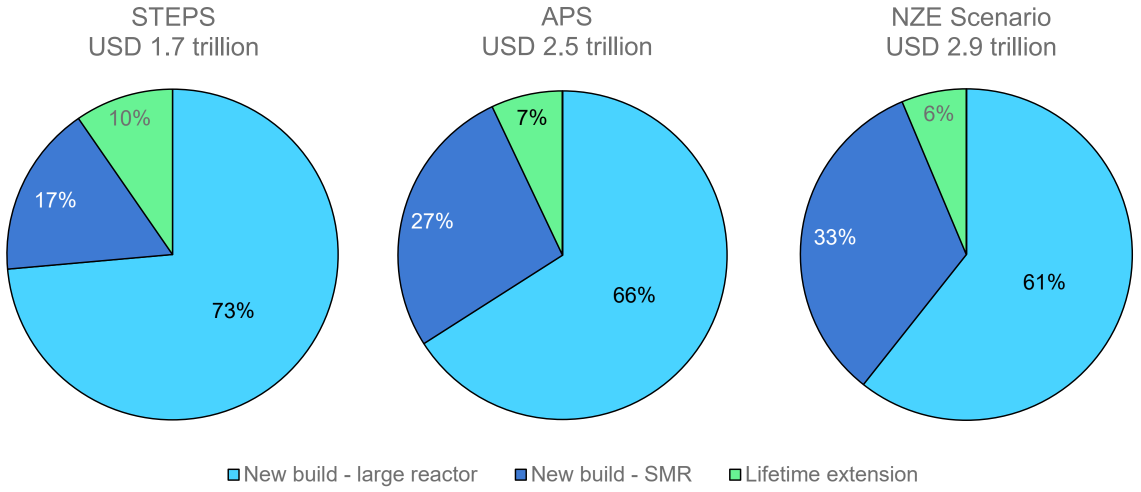
Notes: MER = market exchange rate; SMR = small modular reactor; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.
Source: IEA (2024), World Energy Outlook 2024.

Nuclear power plays an even more prominent role in delivering secure and affordable clean energy transitions in the APS. Global nuclear investment nearly doubles to about USD 120 billion in 2030, including about USD 25 billion for SMRs. It then goes into decline, in large part due to cost reductions for both large-scale reactors and SMRs, reaching around USD 60 billion in 2050. Many power systems approach or achieve full decarbonisation before 2050, so require less investment in new sources of low-emissions electricity. After 2040, more than one-third of total nuclear investment goes to SMRs. Near-term investment is even higher in the NZE Scenario, as accelerated timelines to decarbonise power systems by 2040 bring forward investment in nuclear energy and other low-emissions sources. Investment hits USD 155 billion in 2030, before falling back to around USD 70 billion in 2050. In all scenarios, stronger-than-projected growth for electricity demand could lift the prospects for more sustained nuclear investment in the longer term.

Over the period from 2024 to 2050, cumulative investment in nuclear energy reaches USD 1.7 trillion in the STEPS, USD 2.5 trillion in the APS and about USD 2.9 trillion in the NZE Scenario (Figure 2.2). Large-scale reactors account for the majority of investment in all scenarios, though SMRs start to gain a rising share once introduced in greater numbers from the 2030s onwards (see below). For example, in the APS, cumulative investment in SMRs is about USD 670 billion by 2050, representing more than 25% of total cumulative investments in nuclear energy. Cumulative investment in lifetime extensions of existing reactors counts for less than 10% of the total in the APS, though the share is higher in advanced economies (13%) given the age of the nuclear fleet.

Figure 2.2 Cumulative investment in nuclear energy by scenario and type, 2024-2050



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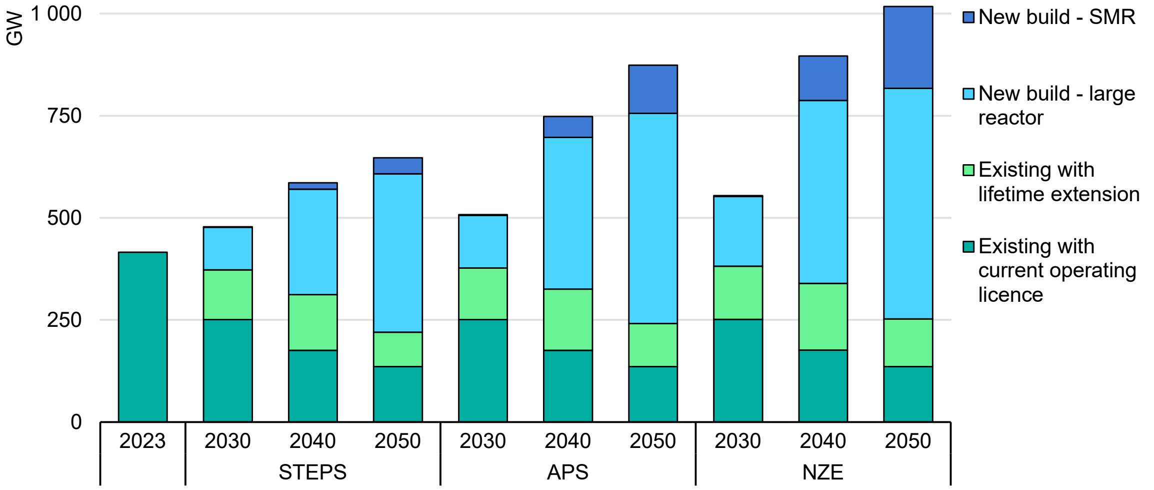
Notes: Investment is in 2023 dollars. STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050; SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

The global nuclear fleet expands in each of the three scenarios. Capacity rises by around half from 416 gigawatts (GW) at the end of 2023 to 650 GW by 2050 in the STEPS, more than doubles to 870 GW in the APS, and exceeds 1 000 GW in the NZE Scenario (Figure 2.3). Lifetime extensions play an important role in each case. For example, they account for around 150 GW, or 20% of global capacity, in 2040 in the APS. Large-scale reactors make up most new nuclear capacity in all scenarios; in the APS, over 500 GW of them are built from 2024 to 2050.

Figure 2.3 Global nuclear power capacity by scenario and type, 2023-2050



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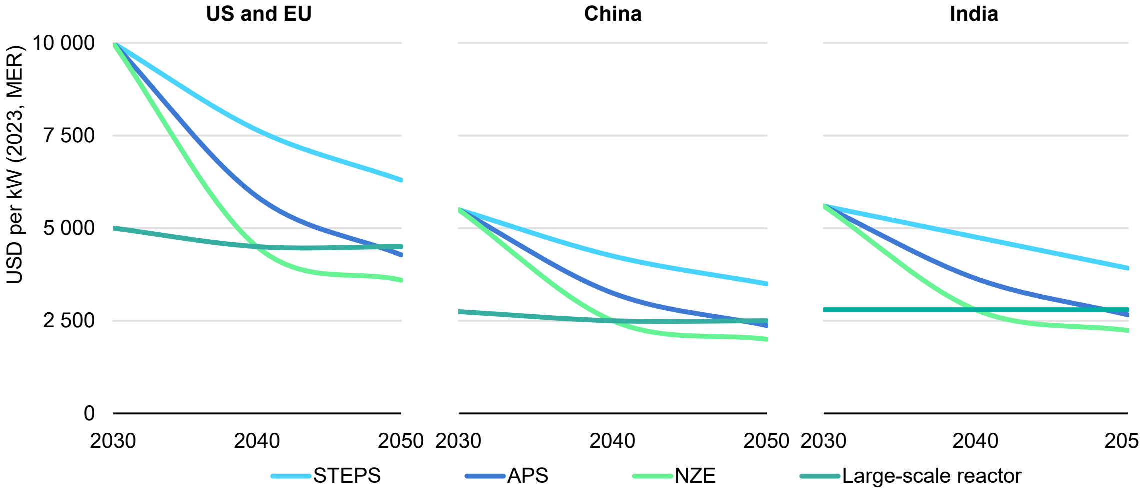
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

A growing share of investment is set to go to SMRs

SMRs are projected to account for a rising part of nuclear investment over the next 25 years in all three scenarios. In the APS, with consistent support of technology innovation and deployment, more than 1 000 SMRs with a total capacity of 120 GW, accounting for about 20% of all nuclear capacity additions, are deployed by 2050. The stronger commitment to decarbonising the power sector in the NZE Scenario drives even faster development of SMRs, reaching almost 200 GW, or over 1 500 reactors, by 2050. Deployment is slower in the STEPS, reaching just 40 GW in 2050, as current policies are insufficient to provide a solid basis for rapidly scaling up the technology, leading to higher costs.

The cost of building SMRs will be critical to the pace of deployment of the technology. Future costs are highly uncertain as the first-of-a-kind projects are still to be completed in most markets. In our analysis, we assume that the first-of-a-kind SMR projects have construction costs (per unit of capacity) that are double those of large-scale reactors that are completed on time and on budget, yielding a cost of around USD 10 000 per kilowatt (kW) in advanced economies and less than USD 6 000/kW in China and India (Figure 2.4). We project those costs to decline as deployment and experience increases, and as a greater portion of each nuclear project can be built off-site, offering significant efficiency gains. In the APS, SMR costs fall significantly in the 2030s and reach parity with large-scale reactors in the 2040s, at under USD 5 000/kW. Costs fall even faster in the NZE Scenario, thanks to faster deployment. Less policy support for innovation and deployment, as assumed in the STEPS, leads to less development and limited cost reductions.

Figure 2.4 Capital costs of SMRs in major markets by scenario, 2030-2050



Notes: MER = market exchange rate; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; SMR = small modular reactor. The cost of large-scale reactors is projected to be same in all three scenarios.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

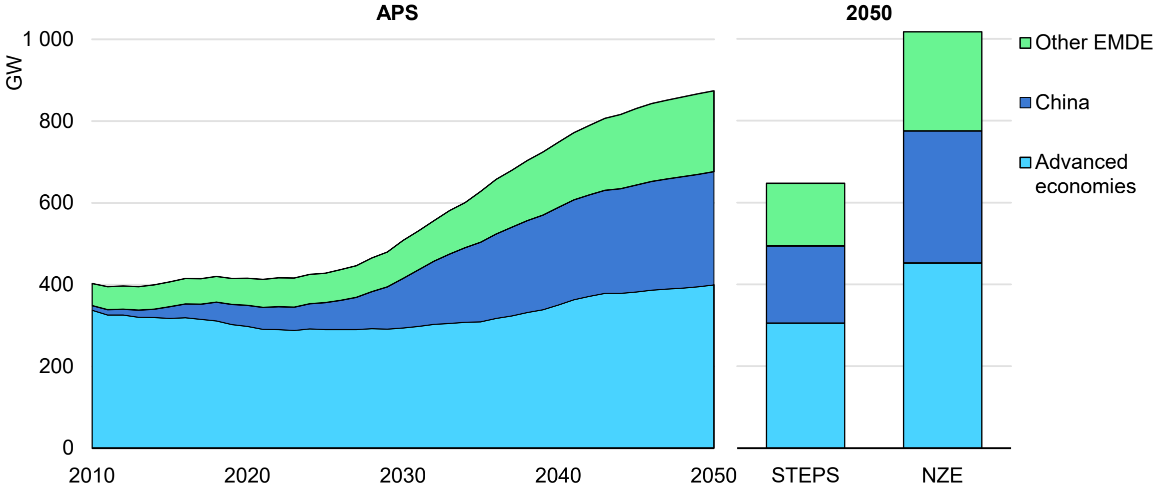
While the costs projected for SMRs in the United States and Europe in 2050 in the APS and NZE Scenario are less than half of the first-of-a-kind SMR projects, they are still well above the targets of several leading SMR developers. For example, GE Hitachi is targeting a cost of USD 2 250/kW, Moltex Energy USD 2 000/kW and Westinghouse USD 3 400/kW.

Regional outlook

China is set to account for the bulk of the growth in global nuclear capacity to 2050

The rate of deployment of nuclear energy is set to continue to diverge across the advanced economies, China and other emerging market and developing economies (EMDE). In advanced economies, the ageing fleet and limited new construction are set to keep nuclear capacity broadly flat to 2030. In the longer term to 2050, nuclear power capacity is 40% higher than in 2023 in the APS (Figure 2.5 and Table 2.1) and 60% higher in the NZE Scenario. Capacity increases by less than 10% from 2030 to 2050 in the STEPS.

Figure 2.5 Nuclear power capacity by scenario and region, 2010-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; Other EMDE = Emerging market and developing economies excluding China.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

Capacity in China is set to grow much faster than in the advanced economies, with installed capacity overtaking that of the United States to become the largest in the world by around 2030 in all three scenarios. By 2050, the nuclear fleet in China expands from 57 GW in 2023 to 190 GW in the STEPS, 280 GW in the APS and 320 GW in the NZE Scenario. In other EMDE, the development of nuclear capacity takes off after 2035, accounting for about one-quarter of the global nuclear fleet in 2050 in all three scenarios.

A major increase in investment is needed in the coming decade

The prospects for investment across the three main regional groupings reflect the differences in the outlook for capacity and costs. The amount of investment needed in China and the other EMDE is 10% lower than in the advanced economies in all three scenarios, despite bigger increases in capacity, thanks to lower construction costs.

In advanced economies, investment in nuclear energy amounted to about USD 35 billion in 2023, with more than half going to extend the lifetimes of existing reactors. In the STEPS, investment falls through to 2030 due to fewer lifetime extensions. In the APS and the NZE Scenario, new construction more than offsets reduced spending on extensions (Figure 2.6). Large-scale reactors, with more proven designs, account for the bulk of investment, with SMRs accounting for a small but rising share. Investment rises strongly through to 2040 across the board, as new large and small reactors are needed to compensate for the retirement of a growing number of ageing reactors. Nuclear investment falls back after 2040 in all three scenarios as electricity demand slows and their power sectors are mostly decarbonised by then. However, if electricity demand were to grow faster than projected in the long term, more sustained investment in nuclear energy would be needed to maintain its role.

Nuclear investment sees a higher pace of growth in China. It has been rising in recent years, nearing USD 15 billion in 2023, and continues to increase sharply to 2030 in all three scenarios. In the APS, it reaches around USD 40 billion in 2030, with about 20% going to SMRs. By 2040, investment in nuclear slows substantially, with capacity reaching 240 GW. That would require fully utilising all the currently identified coastal sites for reactors and developing new sites with access to water for cooling, constraining future developments. Overcoming the limitations for new sites could expand further the opportunities for nuclear energy in China. For example, converting coal-fired power sites to host SMRs could increase the potential for nuclear energy in China by several times.

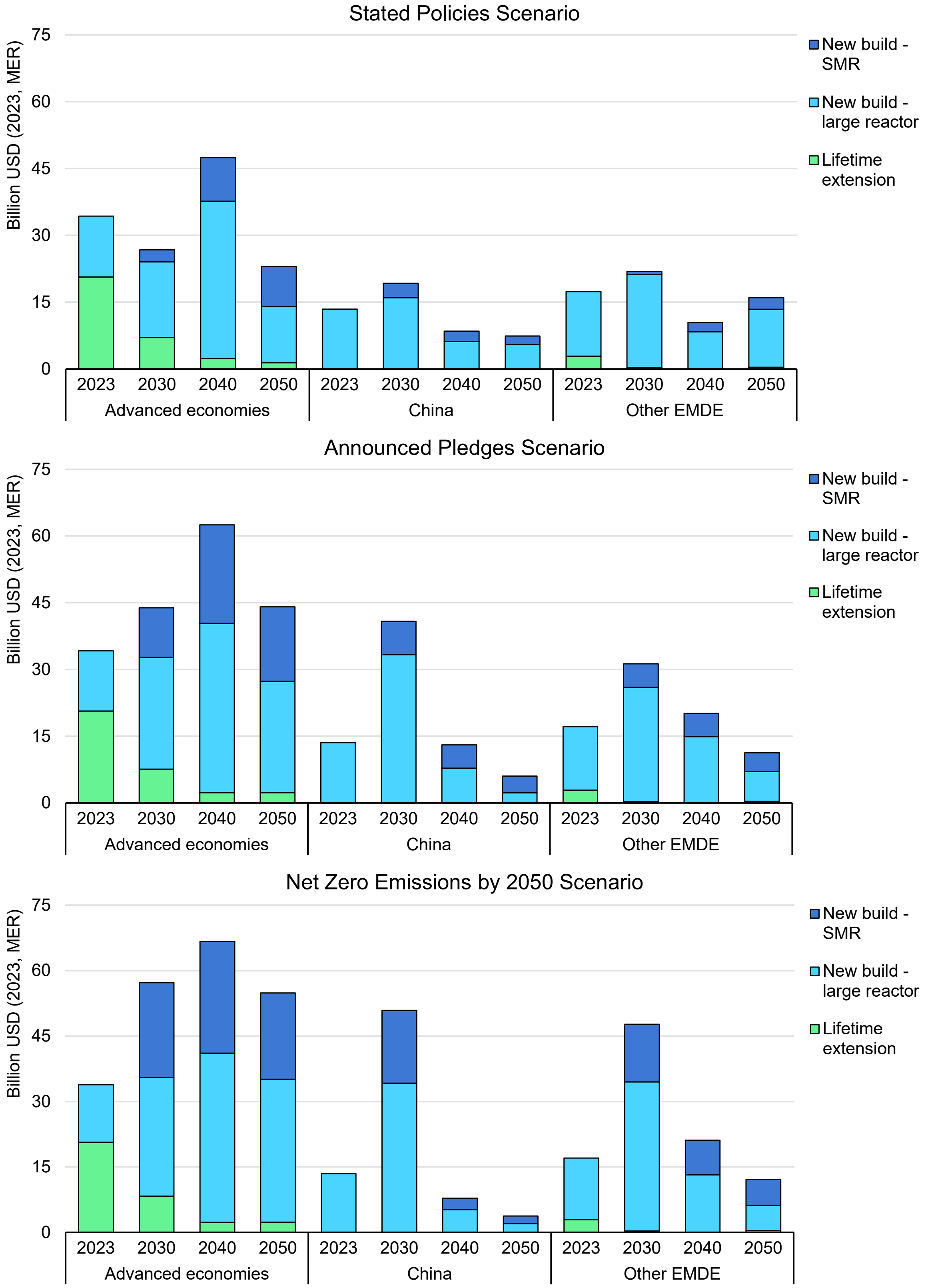
Table 2.1 Installed nuclear capacity by region/country, scenario and type (GW)

		STEPS			APS			NZE		
	2023	2030	2040	2050	2030	2040	2050	2030	2040	2050
Advanced economies										
Existing	288	266	222	142	270	235	163	273	245	175
Of which: lifetime extensions		114	133	79	118	146	100	120	156	112
New SMRs		0	6	19	0	21	60	0	39	98
New large		20	69	144	24	95	176	30	105	180
China										
Existing	57	57	57	55	57	57	55	57	57	55
Of which: lifetime extensions		0	0	0	0	0	0	0	0	0
New SMRs		1	8	13	1	19	35	1	43	53
New large		43	95	121	63	162	187	88	210	224
Other EMDE										
Existing	71	50	34	23	50	34	23	52	38	23
Of which: lifetime extensions		8	3	5	8	3	5	10	8	5
New SMRs		0	2	7	0	11	23	0	27	49
New large		41	94	123	42	114	151	53	142	170

Notes: Other EMDE = Emerging market and developing economies excluding China; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

In other EMDE, nuclear investment surpassed USD 15 billion in 2023 and is set to increase in all scenarios. In the APS, it doubles to well over USD 30 billion in 2030, with SMRs beginning to gain market share. As elsewhere, investment in nuclear drops off thereafter, reaching around USD 10 billion in 2050. Again, stronger-than-projected electricity demand could raise the prospects for maintaining a higher level of nuclear investment in the long term.

Figure 2.6 Investment in nuclear energy by scenario, region and type, 2023-2050



Stated Policies Scenario

Announced Pledges Scenario

Net Zero Emissions by 2050 Scenario

Notes: MER = market exchange rate; Other EMDE = Emerging market and developing economies excluding China; SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

Cutting construction and financing costs is key to making nuclear competitive with other dispatchable options

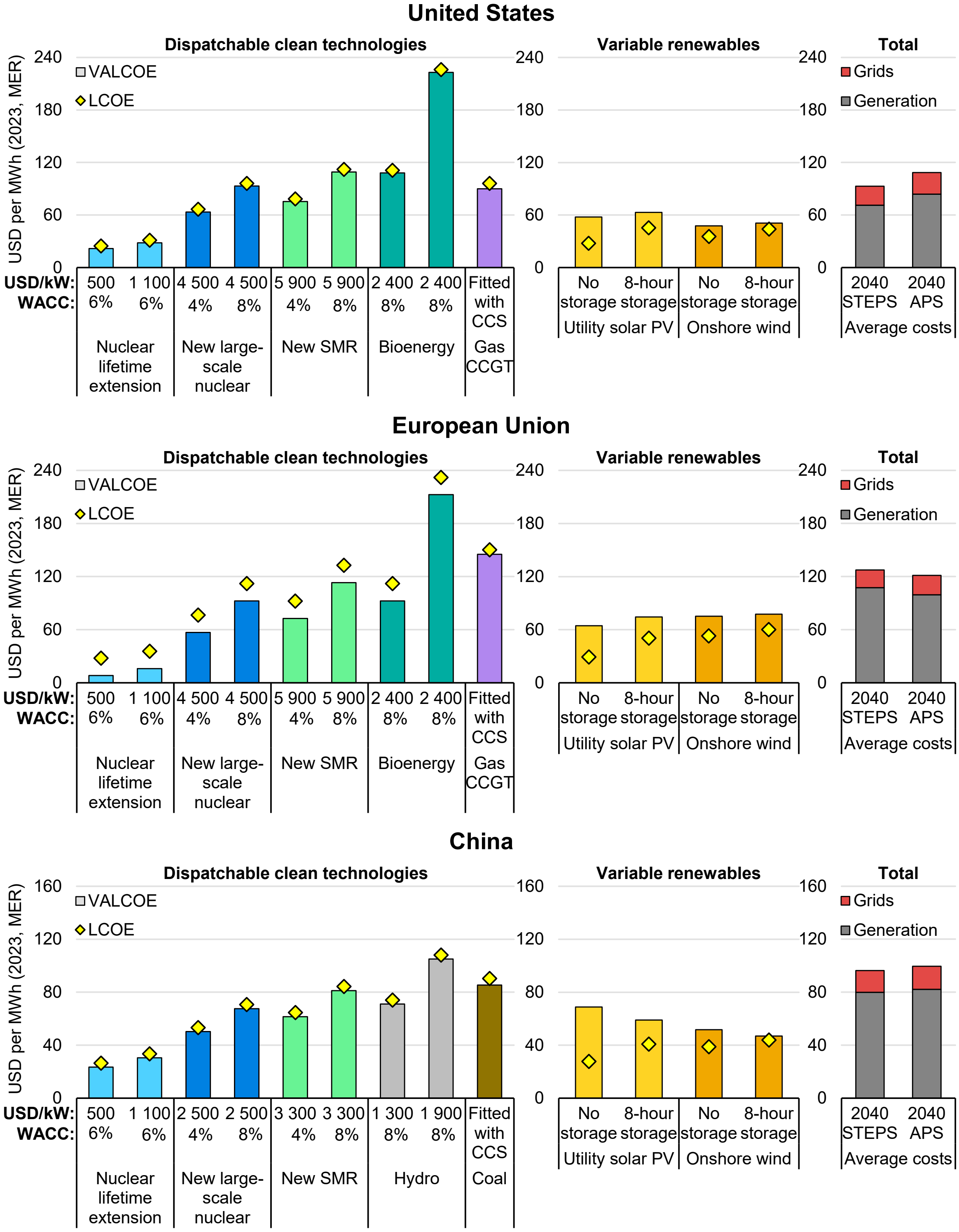
The prospects for the nuclear industry depend critically on whether both large- and small-scale reactors can be built on time and on budget. Capital and financing costs make up a large share of total generating costs for nuclear energy, so any construction cost overruns or delays can significantly undermine the competitiveness of the technology. The higher the risks associated with construction costs, the less attractive investing in nuclear will be.

The competitiveness of nuclear energy depends on both the cost of building and running nuclear plants and that of alternative technologies. For power technologies that operate in similar ways, such as dispatchable sources providing bulk power, the levelised cost of electricity (LCOE) is a useful measure of competitiveness. The LCOE is defined as the average cost of electricity generation for a generating asset over its economic lifetime, including capital costs, operation and maintenance costs, fuel costs, carbon costs, and decommissioning costs. Nuclear plants are highly capital-intensive, but generally have low fuels costs compared with other technologies that generate dispatchable baseload power, including fossil fuels. In addition, nuclear energy is characterised by high capacity factors, often around 75% or more, which also helps to lower the LCOE.

The prospects for LCOE for each generating technology vary across the three scenarios according to the level of policy support for each technology and their rate of deployment. For new large-scale nuclear reactors, the projected LCOE in 2040 in the APS ranges widely between regions, reflecting differences in both construction costs and the weighted average cost of capital (WACC). In China, the LCOE amounts to USD 50 per megawatt-hour (MWh) to USD 70/MWh depending on financing costs (Figure 2.7). In the United States and the European Union, higher construction costs result in higher LCOEs of USD 60/MWh to USD 100/MWh in the United States and USD 75/MWh to USD 110/MWh in Europe. The LCOEs for lifetime extensions are significantly lower.

Projected LCOEs for SMRs are higher in 2040 in the APS, reflecting higher per unit construction costs. On average, they are around 20% higher than large-scale reactors in many regions, reaching USD 85/MWh in China, USD 110/MWh in the United States, and USD 130/MWh in the European Union assuming the same capacity factors as for larger reactors. The lower upfront investment costs of SMRs and other advantages, including shorter construction periods, may nonetheless make them attractive to investors (see Chapter 3).

Figure 2.7 LCOE and VALCOE of nuclear and other selected technologies in selected regions in the Announced Pledges Scenario, 2040



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Notes: LCOE = levelised cost of electricity; VALCOE = value-adjusted LCOE; USD/kW = USD costs per kilowatt for construction; CCS = carbon capture and storage; CCGT = combined-cycle gas turbine; WACC = weighted average cost of capital; SMR = small modular reactor. The average nuclear capacity factor is assumed to be 75-90%. Biomass capacity factor was assumed to be 50% and 25% for hydro. The WACC for solar PV is assumed to be 4-5%. Fuel costs for biomass range from USD 5 per gigajoule (GJ) to USD 20/GJ. Coal capacity factors were assumed to be 50% and 30-50% for gas CCGT. Technology costs and VALCOE for solar PV are from IEA (2024), World Energy Outlook 2024.

In general, the projected LCOEs for nuclear energy in 2040 in the APS are competitive with other low-emissions dispatchable generating options, including hydropower (in China) and bioenergy (in the United States and the European Union). Considering multiple levels of financing costs, we find this is true even in the case where financing costs are relatively high (e.g. 8% WACC) for nuclear.[6] In addition, the LCOE of both large-scale reactors and SMRs is broadly in the same range as the system average cost of generation, which includes the entire fleet of power plants in operation at the time and provides a useful indicator of relative costs, especially where lower financing rates are achieved, but also at higher financing costs for large-scale reactors in China and the European Union. This suggests that new nuclear could be added to electricity systems in those countries without raising the average cost of generation. Furthermore, IEA analysis of the cost-effective pathway to net zero emissions found that less nuclear energy than envisioned would raise total electricity costs, as replacing the contributions of nuclear energy without compromising energy security requires additional sources of generation (mainly wind and solar PV), energy storage (e.g. batteries) and other dispatchable sources such as fossil fuel plants fitted with carbon capture.

The projected LCOEs for nuclear energy are also competitive with the LCOE of new unabated fossil fuel power plants in the APS in 2040, including coal-fired power (in China) and natural gas-fired power (in the United States and European Union). In this scenario, prices on CO_2 emissions are significant in each region, in part reflecting the ambitions to decarbonise electricity. These ambitions also indicate that the comparison with unabated fossil fuels is not highly relevant for new investment decisions in 2040.

In practice, assessing the competitiveness of different generating technologies needs to take account of their operational characteristics and their relative value to the overall electricity system. This is particularly the case in comparing nuclear energy or other dispatchable sources with variable renewables such as solar PV and wind power. The IEA has developed the VALCOE to quantify several of the key considerations, taking account of the energy mix at a given point in time and the specific contributions to energy, capacity and flexibility of each technology (Box 2.2). In the APS, both large-scale reactors and SMRs are competitive with utility-scale solar PV without storage in 2040 in China and the European Union when low financing is achieved based on VALCOE. When comparing the VALCOE of nuclear with battery-paired solar PV in the same year, nuclear is even more competitive, especially for large-scale reactors at low financing rates. Another advantage of the VALCOE is that it can reflect rational operational changes that

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[6] If next-generation geothermal achieves the cost reductions required to enter the market and expand rapidly, it would add another low-emissions dispatchable technology to compete with, potentially up to 400 GW of new capacity by 2040 in the APS.

otherwise appear only as cost increases. For example, if dispatchable power plants including nuclear reactors are operated more flexibly, resulting in lower capacity factors, the LCOE can increase substantially, but this can be offset partially or in full by higher value to the system.

Box 2.2 The value-adjusted LCOE as a metric of competitiveness

The LCOE is a commonly used metric for comparing the cost of generating electricity using different technologies. However, the LCOE takes no account of the differences in value that technologies provide to the overall power system. In addition to comparing total power system costs, the IEA has developed the value-adjusted LCOE – a more comprehensive measure of competitiveness for technologies that combines the LCOE with the value of three central system services: energy, flexibility and capacity. It draws on the detailed hourly modelling of electricity demand and supply carried out for the annual World Energy Outlook. Energy value reflects the average value of output over the course of a year, evaluated from simulations of the output profile and marginal value of electricity in each hour. Flexibility value reflects the value of ancillary services provided by each technology per unit of output. Capacity value reflects the ability for each technology to contribute to the adequacy of power systems at all times. The three value streams were designed and parameterised based on real-world data.

Each power system is unique, with different characteristics, including demand patterns and the generation mix. As the shares of solar PV and wind in the generation mix rise, the value of energy provided by these sources tends to decrease in relation to the system average, while the value of flexibility tends to increase. As a result, the VALCOE of dispatchable generating technologies such as nuclear diverges from the LCOE over time with increasing penetration of renewables. Consequently, the VALCOE becomes a more useful measure of the competitiveness of each technology.

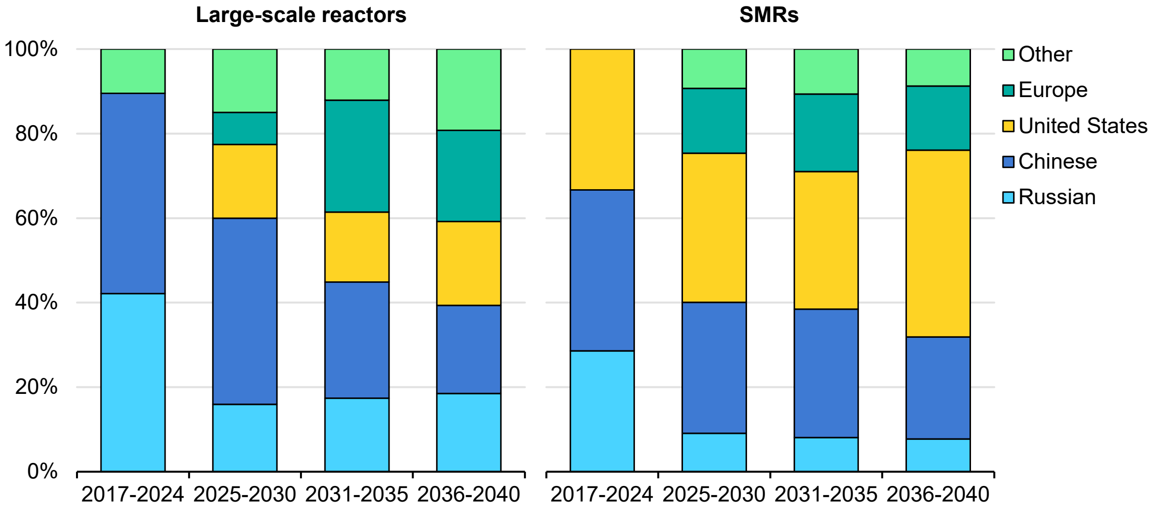
The VALCOE is part of a broader family of metrics that go beyond the LCOE, including the System LCOE and traditional measures of profitability and cost-benefit analysis. Although the VALCOE provides a broader metric of competitiveness than LCOE, it does not include the cost of emissions from power generation that are not priced in the market, nor does it include grid-related costs, as they are highly site-specific.

Grid-related costs are an important element to consider in total power system costs and are strongly influenced by the power generation mix. Grid-related costs represent between 10% and 30% of total power system costs in major economies today. All else being equal, analysis indicates that grid-related costs tend to increase as the share of solar PV and wind increases, and that the relationship is non-linear, with costs increasing at a faster rate at higher shares of variable renewables. The additional grid costs include transmission – for extensions to connect new wind and solar PV projects, which tend to be further from existing grids, particularly for offshore wind parks, and for grid reinforcement or upgrades – and distribution grids. For example, a detailed assessment of total grid costs across multiple scenarios for the power system in 2060 in France found that grid-related costs increase by an average of USD 15/MWh of additional output from wind and solar PV when increasing their share from 40% to 55% of electricity supply, and USD 30/MWh on average when increasing from 55% to 90%. Additional grid-related costs are not captured in the LCOE or VALCOE as they can only be captured properly in comprehensive assessments of system costs.

Nuclear market leadership could shift back towards advanced economies

The centre of gravity of the global nuclear industry and market leadership could shift back towards advanced economies in the coming years, driven by a wave of new construction and the development and deployment of SMRs in the United States, France and the United Kingdom. In the APS, global construction starts increase substantially in the period to 2030, from 60 GW over the past seven years to triple that amount in the next six years, by another 140 GW from 2031-2035 and another 110 GW in 2036-2040 (Figure 2.8).

Figure 2.8 **Nuclear power construction starts by national origin of technology in the Announced Pledges Scenario, 2017-2040**



Notes: SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

Large-scale reactor construction starts increase most in the advanced economies, resulting in more than half of the nuclear market share in the 2030s. Together, European and US technologies make up around 45% of global construction starts for large-scale reactors in the 2030s, compared with less than 5% in 2017-2024 (Figure 2.8). In the United States, for nuclear energy to play its role in energy security and climate, a return to building is needed, including starting construction of over 25 GW over 2024-2030 and another 30 GW of construction starts in the 2030s, capturing around 20% of the global nuclear market by 2040. Europe sees a surge in nuclear construction after 2030 too, driven by France's plans to build multiple European pressurised reactors (EPRs), with Europe gaining a 25% share of the market during that period in the APS. Other advanced economies, such as Korea and Japan, see an increase in nuclear construction after 2035.

Among the EMDE, China's capacity additions are expected to peak in the 2030s and then decline, resulting in a reduced global market share towards 2040, despite continued construction domestically and in other countries. Chinese technology accounts for just over one-fifth of global construction starts for large-scale reactors in 2036-2040, compared with almost half in 2017-2024. In other EMDE such as India and countries in the Middle East, including the United Arab Emirates and Saudi Arabia, new construction starts pick up in the early 2030s. These developments drive down the market share for Russian designs, though construction activities remain robust domestically and in several other countries.

The advanced economies are poised to dominate the SMR market, accounting for over 60% of installations from 2025 to 2040 in the APS. Several leading developers in these regions are driving SMR technology innovation, with plans to install reactors domestically and export to other countries. The United States is at the forefront of SMR development and is projected to hold more than one-third of the SMR market during this period, driving most of the growth in the advanced economies as a whole. Europe contributes another 15% of the global SMR market, led by companies in France and the United Kingdom installing capacity domestically, in other European countries and beyond. In China, SMR development by local companies is primarily focused on meeting domestic demand, though they export some capacity to other EMDE, capturing 25% of the global SMR market by 2040. The Russian Federation (hereafter, "Russia") also represents a significant portion of the SMR market, both for domestic use and export. The remaining 10% comes from other markets, including Canada and India.

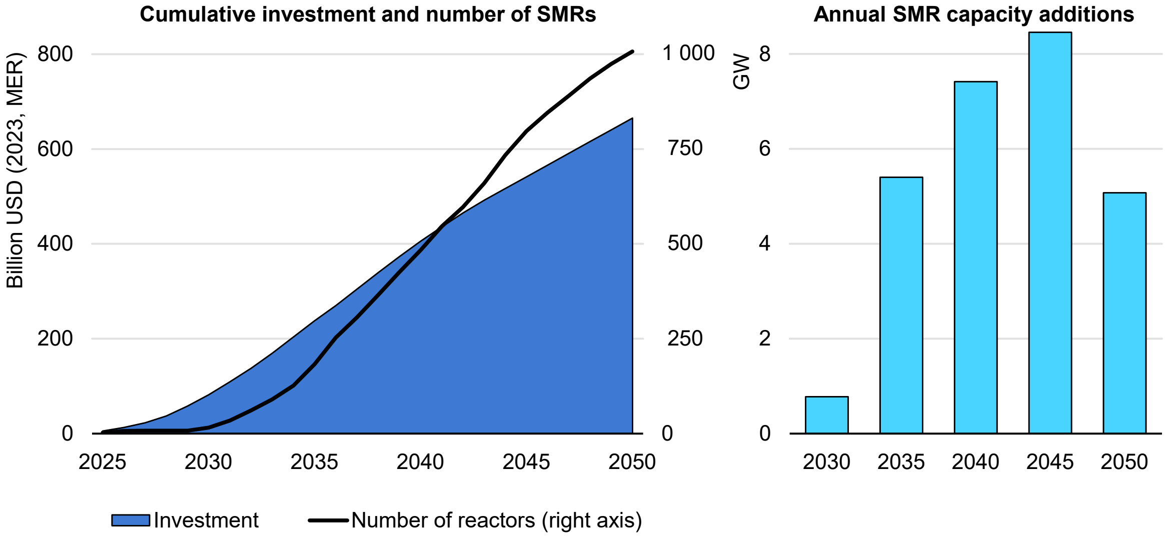
Prospects for SMRs

Successful SMR development could open up a huge market

Assuming SMRs follow a successful development path, the global market for the technology totals USD 670 billion over 2024-2050 in the APS, involving the construction of more than 1 000 reactors of varying size in over 30 countries with a combined capacity of 120 GW (Figure 2.9). SMR capacity additions reach 5 GW in 2035 and a high of nearly 9 GW in 2045. But this is far from assured. For the technology to succeed, sustained commitment and policy support from governments, timely design reviews by regulators, innovation by technology companies, and financing from public and private sources will be needed.

Creating the conditions that allow for a rapid scale-up in investment will be vital. In the APS, global investment in SMRs jumps from less than USD 5 billion today to USD 25 billion by 2030. Annual investment peaks at USD 35 billion around 2040. Thereafter, investment in SMRs, as in other low-emissions technologies, slows, as power systems in most major economies are either fully or mostly decarbonised.

Figure 2.9 Global SMR cumulative investment and capacity additions in the Announced Pledges Scenario, 2025-2050



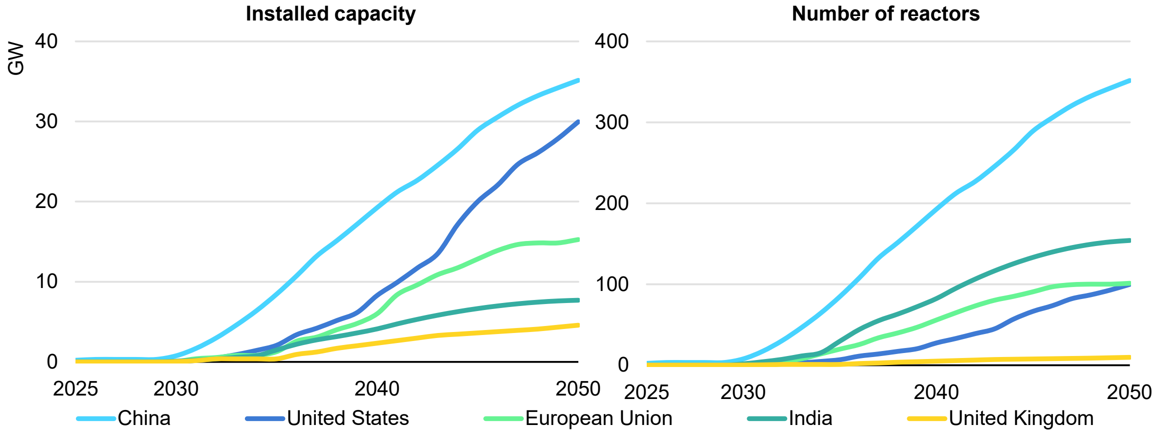
Notes: MER = market exchange rate; SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

As with any technology, achieving the first set of commercial-scale projects is a major milestone for SMRs. On current plans, a number of SMRs are expected to be installed and operating in several countries by around 2030. The first SMRs have already been put into operation in Russia and China. In Russia, several small floating reactors are in operation, primarily to power mining operations in remote areas. In China, the first SMRs (a pair of high-temperature gas-cooled reactor pebble-bed module [HTR-PM] reactors), began operating in 2023 as a demonstration of the technology and the ACP100 is expected to be in operation in 2026. In advanced economies, the first SMRs are scheduled to be completed around 2030, with projects moving ahead in the United States and Canada in particular.

Several countries are planning to deploy SMRs, led by the United States and China

Moving quickly from the first few projects to a larger number in more markets will hinge on supportive government policies and the successful deployment of the initial commercial projects. In the APS, the leading markets for SMRs are expected to be (in order of total capacity by 2050): China, the United States, the European Union, India and the United Kingdom (Figure 2.10). Together, these markets account for almost 80% of global SMR capacity by 2050. Overall, capacity is split roughly equally between the advanced economies and EMDE (including China), though there are almost twice as many projects in the latter (of a smaller average size).

Figure 2.10 SMR installed capacity and number of reactors in selected regions in the Announced Pledges Scenario, 2025-2050



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Note: SMR = small modular reactor.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

China is projected to be the leading market for SMRs to 2050 in the APS, with several SMRs starting to operate from the late 2020s and total installed capacity reaching around 35 GW by 2050. The country's first SMR, a high-temperature gas-cooled generation IV design (HTR-PM), was brought online successfully in 2023 and more units of the same design are planned, alongside several more large-scale reactors. Two other designs, the ACP100 and NHR200, are also under development in China. The three SMR designs have several applications, ranging from district heating and industrial heat to electricity supply.

The United States is today a global leader in SMR innovation, with the federal government supporting the development of various designs. Several companies are active in developing the technology and, as discussed above, some major technology companies are planning or considering investing directly in SMRs (see Chapter 1). The first projects are due to come online in the early 2030s and, in the APS, total installed capacity increases rapidly to 30 GW by 2050. SMRs account for almost half of all the nuclear capacity added in the United States over that period. Although the installed capacity in 2050 is close to that in China, the number of units is only about one-third due to the larger average size of US designs.

The development of SMRs in the European Union (EU) is supported by the European SMR Industrial Alliance, which aims to drive deployment across member states from the 2030s. EU countries with plans or interests to develop SMRs include France (up to 4 GW by 2050), the Czech Republic (up to 3 GW by 2050), Finland (considering 10-20 SMRs for heat and electricity), as well as Sweden, Slovakia, Poland, Hungary, the Netherlands and Romania. In total, EU SMR capacity climbs to about 15 GW in 2050 in the APS.

India is also looking to develop and deploy SMRs by the early 2030s. Smaller SMRs, with capacities of around 20 MW, have been identified as an important means to decarbonise power used in the industry sector, notably iron and steel, and for replacing coal-fired power. Total installed capacity reaches 8 GW in 2050 in the APS. Given their smaller size, that capacity is just one-quarter as much as in China, though the number of SMRs is nearly half.

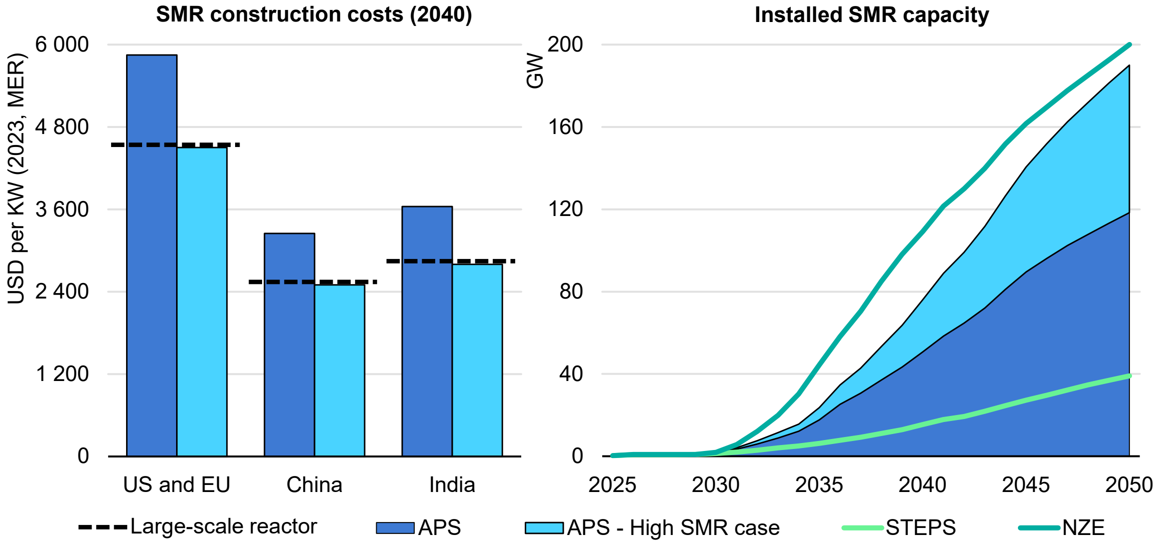
The United Kingdom has set a goal of achieving 24 GW of nuclear capacity by 2050, through a mix of large- and small-scale reactors. The government has provided financial support to Rolls-Royce to develop an SMR with a capacity of 470 MW, with the aim of bringing a first unit into operation in the country by the early 2030s. Canada is also supporting the deployment of SMRs, as set out in its long-term SMR Action Plan. A number of other markets, including countries in the Middle East, Southeast Asia and Africa, are also looking to develop SMRs. They account for around 15% of the nuclear capacity added by 2050 in each of these regions in the APS. Other international initiatives are promoting the uptake of SMRs and other advanced nuclear designs, including a World Economic Forum framework to help stakeholders co-ordinate key actions needed to accelerate deployment worldwide.

Faster cost reductions could unlock additional SMR deployment

The costs of building SMRs are highly uncertain and could turn out to be significantly higher or lower than projected in our scenarios. A higher-cost case is represented in the STEPS, where deployment is limited to 40 GW by 2050. In order to explore the potential for the faster take-up of SMRs, we have prepared a High SMR Case, based on the APS, in which SMR construction costs are assumed to fall to the same level as that of large-scale reactors by 2040. This equates to USD 2 500/kW in China and USD 4 500/kW in the United States and Europe – a reduction of around 25% relative to the levels projected in the APS. These costs are nonetheless higher than the targets that have been set by the leading private SMR developers.

In the High SMR Case, global capacity reaches around 190 GW in 2050 – 60% more than in the APS (Figure 2.11). This would raise total nuclear capacity by 60 GW, as more than two-thirds of the additional SMR capacity displaces large-scale reactors. In this case, installed SMR capacity rises almost as fast as in the NZE Scenario. Cumulative global investment in SMRs over 2024-2050 in the High SMR Case totals over USD 900 billion – USD 250 billion, or 36%, more than in the APS – making up more than one-third of total nuclear investment. Annual investment peaks at USD 45 billion in the late 2030s.

Figure 2.11 SMR construction costs in major markets and global installed capacity by scenario and case



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Notes: MER = market exchange rate; SMR = small modular reactor; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.
Source: IEA analysis based on IEA (2024), World Energy Outlook 2024.

The impact of lower SMR costs on their deployment could be particularly pronounced in the United States, where there is already strong interest in their deployment to meet rising electricity demand, in particular from data centres (see Chapter 1). In the High SMR Case, SMR capacity reaches nearly 60 GW in 2050, accounting for 60% of all US nuclear capacity additions over that period (compared with 45% in the APS). As a result, total nuclear capacity reaches 175 GW – 30 GW more than in the APS. The share of nuclear energy in total US electricity generation nonetheless declines compared with today. SMR capacity in the United States exceeds that of China in 2050 in the High SMR Case.

Cheaper SMRs also boost their deployment in China, in particular exploiting more opportunities to reuse the sites of coal-fired power stations, though the primary focus remains on large-scale reactors. In the High SMR Case, SMR capacity in 2050 reaches 50 GW – 15 GW, or 40%, more than in the APS – accounting for 20% of total nuclear capacity. Similarly in the European Union, installed SMR capacity reaches almost 30 GW – double that in the APS – accounting for almost one-third of all the nuclear capacity added over that period. Total EU nuclear capacity is around 10 GW, or 7%, higher than in the APS, with cumulative investment in SMRs rising by close to 50%. In EMDE other than China, 40 GW of SMR capacity is installed by 2050 in the High SMR Case – 15 GW more than in the APS – with cumulative capital spending on SMR rising by 40%.

The faster deployment of SMRs as depicted in the High SMR Case would complement the rapid growth of variable renewables and reduce the need to expand large-scale nuclear capacity and other sources of firm dispatchable power. Lower SMR costs could open up the possibility to run these plants more flexibly, while remaining economically viable. More SMRs would also reduce reliance on scarce hydropower and bioenergy resources, and temper demand for the critical materials needed to make wind turbines, solar PV panels and batteries. While the High SMR Case would represent a major success for the technology, even higher cost-effective deployment could be unlocked where electricity demand grows more than projected, or other factors present higher challenges for other low-emissions sources, including grid constraints.

Supply chains and workforce requirements

The next era of nuclear energy calls for efficient and diversified supply chains

The prospects for the nuclear industry worldwide depend critically on the resilience of its supply chains. Resilient supply chains are able to respond quickly to operational disruptions through flexible contingency planning and forecasting at all segments of the chain. Government policies need to avoid “stop and go” cycles, which are detrimental to all industries that need visibility on future projects to commit to major supply chain investments. The supply chain must be thought out well in advance by finding the best balance between global and local supply chains for each of its segments.

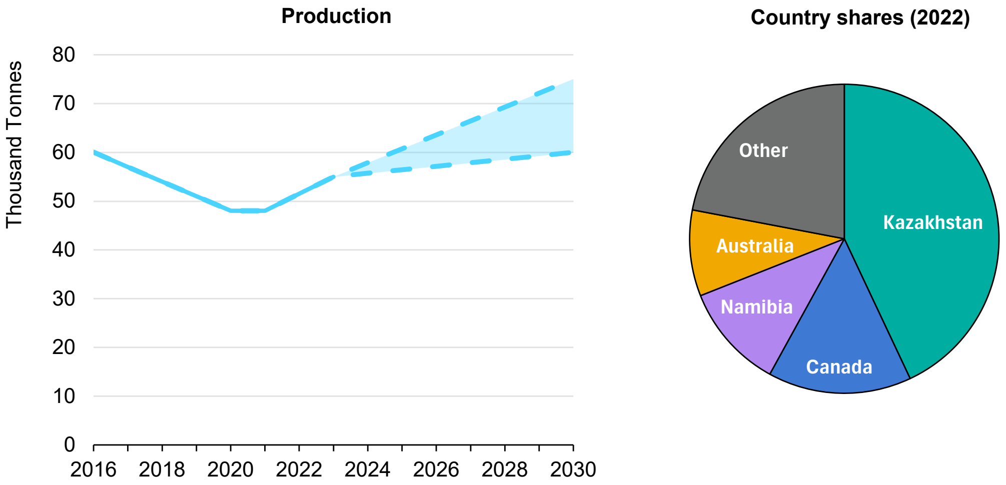
Local supply chains benefit from knowledge of local culture, industry codes and standards, and have clear advantages in certain market segments. Yet there are significant benefits to using global supply chains: they increase the number of suppliers, and foreign suppliers can be economically attractive if they have access to more cost-effective sources of energy, raw materials or labour. Using foreign suppliers is sometimes necessary: for example, global capacity for forging large ingots (greater than 500 tonnes) used in manufacturing major reactor components is currently sufficient to meet demand for 30 large reactors per year, but this capacity is located in only a handful of countries, mainly in Asia (including China, Japan and Korea), Russia, Europe (France, Italy) and South Africa.

The adoption of new technologies is key to increasing the reliability and competitiveness of supply chains. These include modular construction, additive manufacturing, and advanced manufacturing processes such as new welding technologies and digital innovations. For example, digital twins are a major source of innovation, enabling, among others, continuous online monitoring by receiving data from sensors or carrying out simulations. Supply chain efficiency, for example, is one of the ways in which new digital technologies can improve processes in nuclear power plants. Operators typically prepare for a wide range of eventualities by holding large amounts of stock of various components, much of which is never used. New digital technologies can facilitate the calculation of the probability of using a component, helping to optimise procurement.

Geopolitical instability in recent years has contributed to the growing interest in nuclear energy as a means of ensuring energy security. Yet that instability has also led countries with nuclear industries, including the United States and members of the European Union, to seek to diversify their supplies. The price of natural uranium has risen over the past five years, reaching over USD 100 per pound (lb) in early 2024 (compared with under USD 30/lb in 2019, when it was a period of low prices) before falling back under USD 80/lb at the end of the year. Uranium production peaked at more than 60 000 tonnes in 2016, falling back initially in the face of a deterioration in market conditions and then the Covid-19 pandemic to a low of less than 50 000 tonnes in 2020-2021. That led to some mines being idled. Output is expected to have recovered since then, reaching around 55 000 tonnes in 2023 (Figure 2.12). Four countries account for more than three-quarters of global uranium production from mines in 2022: Kazakhstan (43%), Canada (15%), Namibia (11%) and Australia (9%).

Current uranium market projections indicate that the current output of mines in operation should be sufficient to meet the world's uranium requirements for several years. However, as global nuclear capacity increases, uranium requirements will rise. According to the International Atomic Energy Agency (IAEA), uranium demand is expected to rise, ranging from 61 000 tonnes to 77 000 tonnes by 2030 depending on the scenario, while scenarios from other expert bodies could indicate greater needs. Historically, the gap between production and requirements has been filled by secondary resources, mainly stockpiles held by utilities and governments. But these resources are diminishing to fill the supply gap and are expected to continue to do so in the near term. Consequently, investment is needed now to transform existing resources into refined uranium, especially for member countries of the Organisation for Economic Cooperation and Development (OECD), where production meets only a quarter of uranium requirements. Governments and mining companies need to bring idled mines back into service and develop new mines. Opening up new deposits will require careful planning and sustainable market conditions, as the development of new uranium mines typically takes an average of 10 to 15 years from discovery to operation, and potentially even longer in recent times.

Figure 2.12 Global uranium production from mines, 2016-2030



Source: IEA analysis based on IAEA (2024), Nuclear Technology Review 2024 (left chart) and WNA (2024), Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2023-2040 (right chart).

The conversion and enrichment of uranium is another important supply chain consideration. For conversion, there are currently five plants in operation worldwide in Canada, China, the United States, France and Russia, with a combined licensed capacity of 62 000 tonnes, compared with a total output of 42 000 tonnes in 2022. Actual conversion output is then generally below nameplate capacity, although it is difficult to draw an industry-wide picture given that historically significant secondary supplies are replacing primary conversion output in the portfolios of many suppliers. While there is no immediate need for new capacity, it is expected that requirements will increase, and that consideration will have to be given to replacing ageing facilities with larger ones.

The prospects for enrichment are of greater attention given geopolitical factors and the heavy geographic and market concentration of the sector, particularly for countries such as the United States that import a large proportion of enriched uranium. More than 99% of enrichment capacity today is held by just four companies: China National Nuclear Corporation (CNNC) (15%), Russia's Rosatom (40%), Urenco (a British-German-Dutch consortium, 33%) and France's Orano (12%). Some suppliers are planning to extend their enrichment capacities. For example, Orano plans to increase its enrichment capacity in France by about 30% and to build a new enrichment facility in the United States (see below), while CNNC could see a 70% increase in its capacity by 2030.

Several countries have introduced policy measures to promote greater diversity of nuclear fuels supply and several projects are in development. In the United States, the government has issued a request for proposals to strengthen the domestic nuclear fuel supply chain by purchasing low-enriched uranium from domestic sources with public support of USD 2.7 billion. Orano's planned new uranium enrichment plant in Tennessee is expected to start operation in the early 2030s. In France, construction of Orano's Georges Besse 2 plant extension has begun. It will add four new modules to increase production capacity to around 11 million separative work units (SWU) by 2030. The United Kingdom also announced funding of GBP 196 million (USD 245 billion) for Urenco to build a uranium enrichment facility, which is expected to be in operation by 2031. The fuel will be used domestically and exported. Urenco has also announced a plan to add multiple new centrifuge cascades to expand its enrichment capacity in its plant in the Netherlands. The first new cascades are planned to come online by 2027. Japan recently restarted enrichment activities after adopting new regulatory standards and plans to increase its enrichment capacity to 1 500 tonne-SWU per year, covering one-third of the country's nuclear fuel needs.

The next generation of nuclear technologies can require new supply chains for new types of fuel. Some advanced reactor designs will require fuel based on high-assay low-enriched uranium (HALEU). Some countries are increasing their production capacity to ensure sufficient supply. For example, the US Department of Energy has created a HALEU consortium and co-funded a demonstration production facility at Piketon, Ohio. Production of another type of HALEU fuel, the tristructural isotropic particle fuel (TRISO), which is used in high-temperature gas-cooled reactors, is also starting up. As with all nuclear fuels, appropriate attention needs to be paid to minimise the risk of proliferation.

Planning for workforce challenges in advance is necessary to avoid bottlenecks

The total number of people employed in the global nuclear energy industry is estimated to be around 1.1 million people, with around 400 000 workers employed at the operational stages and more than 600 000 employed at the construction of new nuclear reactors. Especially in advanced economies, the lack of qualified personnel in the nuclear sector is becoming a challenge as a large proportion of the existing workforce retires in the coming years. This can be a major bottleneck for the nuclear expansion plans if it is not properly addressed. It is therefore essential to conduct workforce assessments at national and regional levels to enable a better vision of skills at risk and to plan for and train the skilled labour for the future of nuclear energy industry accordingly.

In France, for example, more than 40 000 workers are employed in nuclear power generation. Along the extended nuclear supply chain, whether in reactor design, construction, operation, the fuel cycle, or research and development, nuclear energy in France is the source of more than 200 000 jobs, representing around 7% of industrial employment. For its entire programme, including the operation of its fleet and its EPR2 and SMR new construction programmes, the French nuclear industry plans to hire around 10 000 people each year in the next ten years.

Ensuring the safe operation of nuclear reactors is paramount

Safety is essential for nuclear energy and it must play a key role to protect people and the environment in any circumstance. Safety in nuclear installations aim to prevent accidents and to mitigate the risks and consequences in the event of an accident. Safety systems are thus needed for both nuclear installations and the whole fuel cycle, from uranium extraction to waste management. These systems need to be associated with a safety culture that all nuclear power plant personnel must integrate and master. Public trust is thus gained not only through confidence and transparency of nuclear operation, but also with the competence and the independence of the regulator, which are just as essential.

Nuclear power plants are equipped with several emergency cooling systems, which are both redundant and independent of each other. Safety features also include redundancy of power supply systems, resistance to earthquakes systems, strong containment, etc. Safety levels are generally independent of the age of the reactors as safety is intended to be improved over time. For example, in every light water nuclear reactor, hydrogen is formed by the radiolytic decomposition of water. This must be remedied to avoid any risk of explosion in the presence of oxygen. Many reactors in the world are now equipped with passive autocatalytic hydrogen recombiners in their containment, instead of external recombiners that had to be connected and powered.

Safety improvements are not only the result of lessons learned from incidents and accidents, particularly those of Three Mile Island in 1979, Chernobyl in 1986 and Fukushima Daiichi in 2011, but also of technological innovations and the wide sharing of feedback among nuclear operators. Safety is a priority for which each national regulator requires operators to comply with the measures it has set. It is essential that standards are properly defined so that they are understood and applied. Safety and nuclear operation go hand in hand: the more robust the safety systems and the safety culture, the better the operation of nuclear reactors.

The IAEA defines general rules that countries are invited to follow as models. It also organises site visits to help member states improve the safety of their nuclear power plants by comparing practices with IAEA safety standards and making recommendations for progress. In addition to those, most national regulators impose requirements. The industry self-polices its own safety and performance, by continuously sharing operating experience and by peer reviews. The World Association of Nuclear Operators (WANO) sets peer review missions to all individual nuclear power plants every three years and issues a ranking.

Decommissioning and waste are key considerations

Decommissioning is a key consideration, given the need to manage radioactive materials safely. As of end of 2023, 210 nuclear reactors worldwide had been definitively shut down, 23 of which were fully decommissioned. More than two-thirds of the shut-down reactors, whether decommissioned or in the process of being decommissioned, are concentrated in five countries: the United States, the United Kingdom, Germany, Japan and France. The relatively limited experience worldwide in carrying out decommissioning projects, though it has grown in recent years, makes it hard to estimate the likely cost of decommissioning plants in the future.

For a nuclear power plant built today, the cost of decommissioning is assumed in our analysis to be around 15% of the total lifetime investment (in real terms). Where funds are collected during the period of plant operation, these costs represent a very small percentage of electricity rates, of the order of 1%. Most countries impose legal requirements on utilities to put in place adequate funding for decommissioning activities, with regulators holding responsibility for approving the funding mechanism and the amount of decommissioning costs to be set aside.

The safe disposal of spent fuel and other radioactive waste is essential to the public acceptance of nuclear energy programmes. Several countries have recently taken action to build or expand the existing capacity of deep geological repositories for the permanent disposal of waste:

- In Sweden, the SFR repository, which is situated 60 metres below the bottom of the Baltic Sea and began operations in 1988, is set to triple its volume in the coming decade: SKB, the private company that operates the facility, received approval from the Sweden's Radiation Safety Authority in 2024 to begin excavation work to extend the existing final repository for low- and intermediate-level waste.
- In France, ANDRA, the French national agency for radioactive waste management, submitted an application in 2023 for authorisation to build a geological disposal facility in Northeast France as part of the Cigéo project.
- In Finland, Posiva, the radioactive waste management company, applied in 2022 to the Ministry of Economic Affairs and Employment for an operating licence for the final disposal facility currently under construction at Olkiluoto.
- In Canada, the Nuclear Waste Management Organization selected in 2024 Wabigoon Lake Ojibway Nation and the Township of Ignace as the host communities for Canada's proposed deep geological repository.
- In Switzerland, Nagra, the national radioactive waste disposal co-operative, has applied to the Swiss Federal Office of Energy for a general permit for the construction of a deep geological repository for radioactive waste and a used nuclear fuel encapsulation plant.

3. Financing nuclear projects

Highlights

- **Nuclear energy investments are mainly financed by governments through state-owned utilities.** Even where the private sector takes the lead, as in the United States and Finland, governments still play a major role in enabling projects through supportive regulatory frameworks and tariff structures.
- **Nuclear projects are hard to finance due to their scale, capital intensity, long construction lead times and technical complexity.** Cost overruns and delays, which have plagued some recent projects, are major sources of risk for investors.
- **Government involvement is crucial to facilitate the involvement of commercial banks in financing nuclear power projects,** by ensuring predictable cash flows and taking on the construction risk. This enables nuclear projects to benefit from quasi-sovereign risk profiles, and a lower cost of capital.
- **Cash flow predictability is key for debt financing.** Financial institutions lend based on reliable future cash flow expectations. In markets with volatile electricity prices de-risking instruments such as long-term power purchase agreements, contracts for difference and regulated asset base models are indispensable.
- **The capital structure of investments vary significantly between new large reactor builds and lifetime extensions**. High risks associated with new nuclear projects, notably during the construction phase, mean banks are less likely to finance early stages. Lifetime extensions are easier to finance, because they involve already operating assets.
- **The smaller scale of SMRs makes them potentially more attractive to commercial investors, opening a door to broader private sector participation in nuclear energy.** The payback period of an investment in an SMR could be half the typical 20- to 30-year period for conventional projects, thanks to shorter pre-project and construction periods.
- **MDBs, despite the high demand for their resources across other sectors, could facilitate the financing of nuclear by supporting market designs and regulatory frameworks.** The typical investment needs of a single nuclear project exceed the annual energy lending of the eight largest MDBs combined, limiting the scope for them to finance new projects.
- **Green bonds and other green debt instruments can open up new sources of finance for nuclear energy projects.** Green bond issuances for nuclear energy have provided over USD 5 billion in financing to date, mainly for lifetime extensions and refinancing of projects entering their operating phase.

Distinctive factors in nuclear financing

The cash flow profile of nuclear plants requires a tailored approach to financing

Financing nuclear power projects is very different from financing almost all other types of energy assets. Nuclear power plants rank among the most expensive infrastructure projects undertaken. In terms of cost, they are comparable only to the biggest forms of transport infrastructure, such as major bridges, tunnels or long-distance railway lines. Yet the financing profile of a nuclear power plant differs from other megaprojects of comparable cost. The risk and spending profile typically involves a long, complex and extremely capital-intensive design and construction phase which can last up to 20 years, followed by a long economic lifetime of low fuel costs, relatively low operating costs and a high capacity factor. Other large infrastructure projects, which are typically able to start generating stable returns earlier, can largely be financed by the private sector or public-private partnerships, while nuclear requires much heavier public backing.

The financial risks associated with the very long construction phase and the fact that positive cash flows are achieved only 20 to 30 years after the start of the project generally make financing the construction of a nuclear power plant unattractive for traditional commercial investors. Investment committees of commercial banks will typically consider an investment horizon of about five years (unless clear refinancing or securitisation options are available), while managers of large assets with a longer horizon are rarely equipped to manage risks at the early design and construction phases.

The distinctive cash flow profile of nuclear projects also implies a limited role for project finance, which is commonly used for other infrastructure developments. Project finance is more suitable for smaller and shorter-term projects where the cash flow required to repay debt arrives more quickly. In the case of a new nuclear power plant, the risks implied by the duration and overall price tag of the plant are too high for this approach, necessitating firm government backing as well as guarantees of stable offtake and guaranteed cash flows after the plant is built.

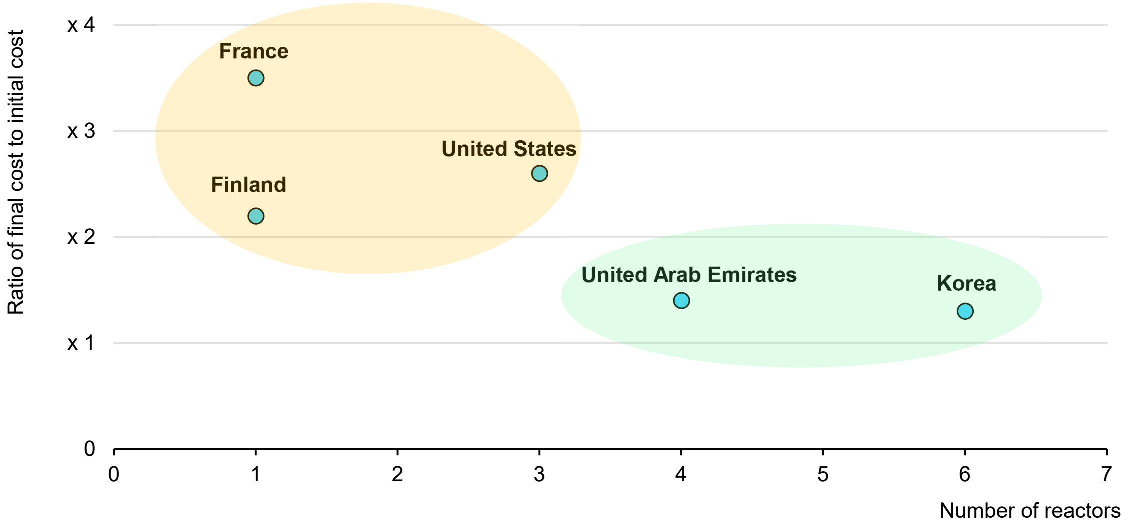
Since positive cash flows, even if guaranteed, start a long time after construction begins, uncertainty about the future value of money can also constitute a barrier for investors, especially if offtake agreements are not designed to be completely inflation-proof. Future competition with other electricity generation technologies and the impact of changes in the generation mix on wholesale electricity prices and the merit order of generating assets is another source of uncertainty and, therefore, financial risk. Renewables, with zero marginal costs, and, in some countries, cheap natural gas can depress wholesale prices, cutting revenues and profit margins for nuclear power plants. Risks associated with future revenue streams can undermine investors' confidence in their ability to generate sufficient cash flow from nuclear plants, even in countries with market structures that favour nuclear energy by factoring into the pricing mechanism its flexibility, dispatchability and low-carbon attributes.

Construction risk remains a major hurdle to financing

Cost overruns and delays in completing the construction of new plants are among the most critical risks associated with nuclear energy projects. The primary reason for these risks is the sheer complexity and scale of such projects. Compared with other forms of energy generation, nuclear projects involve particularly stringent regulatory scrutiny, safety standards and technological requirements. The often controversial nature of nuclear projects can also give rise to additional political and regulatory risks.

Without a strong industrial base, first-of-a-kind projects are prone to cost overruns and delays, mainly due to unexpected problems arising at the design and construction phases. Well-publicised cases of such problems, such as the delays in commissioning of the first-of-a-kind reactors in Finland, France, and the United States, have led to financial institutions becoming cautious about providing funds to new nuclear projects. Recent cost overruns at projects in other countries based on more standardised reactor designs that have been built in series have been less marked (Figure 3.1).

Figure 3.1 Final cost compared to initial cost of recently built nuclear reactors in selected countries and number of nuclear reactor projects started over the last 15 years



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Note: The projects considered for this analysis are Flamanville 3 for France, Olkiluoto 3 for Finland, Saeul 1&2 for Korea, Barakah 1-4 for the United Arab Emirates, and Vogtle 3&4 for the United States.
Source: IEA analysis based on publicly available data.

Limiting cost overruns and delays requires a multifaceted approach. Adopting well-established reactor designs and then building them in series can greatly help with reducing the risk of rising costs. For example, the French nuclear power programme during the 1960s and 1980s consisted mainly of three designs – 900 megawatt (MW), 1 300 MW and 1 450 MW units. Each design was largely standardised, being reproduced 34 times for the 900 MW type and 20 times for the 1 300 MW type. Standardisation allows for a streamlined construction process, reducing the time and cost associated with building each reactor, and lowering costs over time through learning. It also facilitates easier training for operators and maintenance personnel, as they need to be familiar with only a limited number of reactor types. Building up and maintaining a strong and skilled nuclear industrial base and supply chain is also needed to better manage construction risks (see Chapter 2). The recent success of the People's Republic of China (hereafter, "China") in achieving a rapid expansion of its nuclear power fleet and completing projects in just five years on average can largely be explained by its reliance on a small number of reactor designs built in series and the establishment of a strong nuclear supply chain, with a well-trained workforce.

Both standardisation of designs and developing a strong supply chain require long-term planning within the framework of industrial and energy policy. Nevertheless, implementing effective risk management or risk transfer mechanisms, such as government support in the form of loan guarantees or risk-sharing mechanisms, are still needed to mitigate risks and attract financing.

Special treatment of backfitting and accident risk is often required

Meeting stringent regulations covering all aspects of nuclear energy and the ability to meet regulatory requirements is one of their most critical fundamentals. However, these stringent regulations and potential for high costs to meet regulatory requirements also imply a significant degree of project risk. An important component of this risk stems from the concept of "backfit requirements", which mandate operators or nuclear facilities to upgrade or retrofit their facilities with new equipment in response to new safety standards or technological advances. Regulatory mechanisms typically require nuclear power plants to remain at the forefront of safety management, reducing both the risk of accidents and the extent of any damage in the event of an accident occurring. But such backfit requirements can impose substantial financial and operational burdens and create uncertainty about the long-term economic viability of a plant.

Regulatory bodies recognise the need to balance the costs and benefits of backfitting, but are sometimes obliged to mandate them when a new concern about safety comes to light. Therefore, the focus should be on how to manage the risk associated with backfits in a way that does not deter new investment. Some countries have implemented effective risk management or risk transfer mechanisms to share these additional costs between the public and private sectors.

Costs associated with the back end of the fuel cycle are another unique cost component of nuclear energy. This includes reprocessing spent fuel, the final disposal of high-level waste and the decommissioning of nuclear power plants. The allocation of these costs varies by country. In some countries such as Japan, they fall predominantly on private companies, raising costs and creating additional risks for plant operators (Table 3.1).

Table 3.1 Responsibility for back-end nuclear costs and funding mechanisms in selected countries

Country	Back-end costs responsibility	Funding mechanisms
Japan	Reprocessing spent fuel, disposal of high-level radioactive waste, and decommissioning: Operators based on the relevant acts	Nuclear operators are private companies in Japan and they are responsible for decommissioning of nuclear power plants. Under the Promotion of Spent Fuel Reprocessing and Decommissioning Act, the operators have to pay fees to a government-authorised organisation for necessary works on reprocessing spent fuel, decommissioning management and other relevant activities in each plant (except for Fukushima Daiichi NPS). Additionally, under the Designated Radioactive Waste Final Disposal Act, the operators also have to pay fees to another government-authorised organisation for necessary works on high-level radioactive waste management
United States	Disposal of spent fuel and high-level radioactive waste: Operators pay a fee levied on nuclear power sales to the federal government, which is responsible for waste management Decommissioning: Operators	The establishment of decommissioning provisions by the operators are regulated by the Nuclear Regulatory Commission Under the 1982 Nuclear Waste Policy Act, the operators have to pay fees which are deposited in the publicly managed Nuclear Waste Fund
United Kingdom	Disposal of spent fuel and high-level radioactive waste: Operators primarily pay the cost to government based on the Waste Transfer Price. Government is responsible for any future cost overrun. Decommissioning: Operators	Based on the Energy Act 2008, operating companies need to make prudent provision for the full costs of decommissioning their installations and their full share of the costs of safely and securely managing and disposing of their waste based on the Funded Decommissioning Programme
France	Reprocessing spent fuel: Operator (SOE) Disposal of high-level radioactive waste: Operator (SOE) Decommissioning: Operator (SOE)	Nuclear operators are owned by the French government, which gives them comprehensive responsibilities regarding their future liabilities for decommissioning and waste management

Note: SOE = state-owned enterprise.
Source: NEA (2021), Ensuring the Adequacy of Funding for Decommissioning and Radioactive Waste Management.

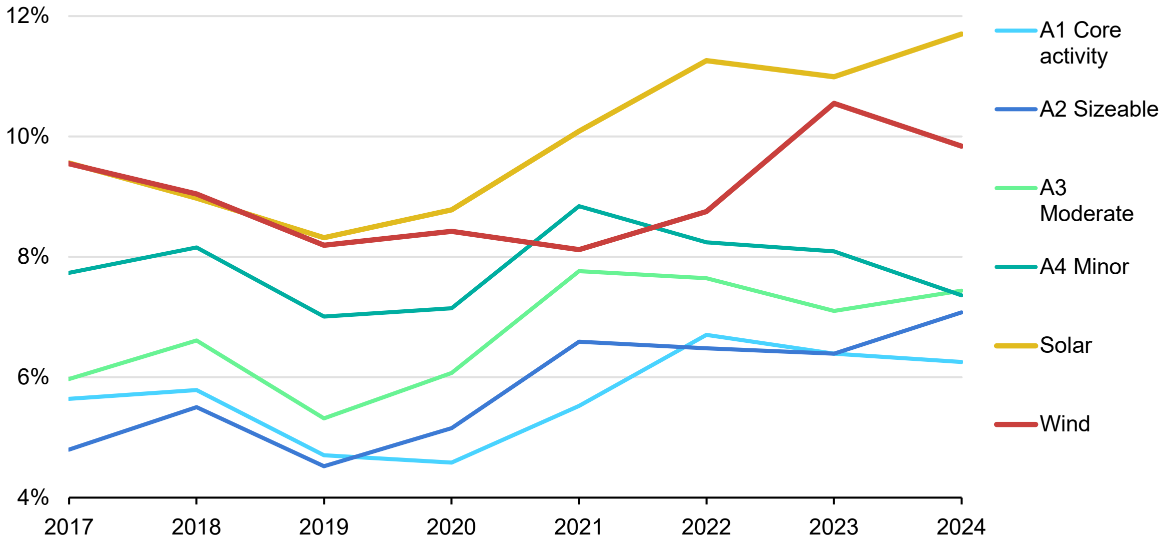
Risks associated with accidents also need to be managed in a way that does not deter investment. The aim should be to establish a system that enables businesses to operate effectively while ensuring the provision of adequate compensation to those affected by an accident. In some countries, legislation governing accident liability places unlimited responsibility on nuclear operators for damages resulting from a nuclear accident. This is the case in Japan, under the Act on Compensation for Nuclear Damage, except where the accident was caused by an exceptional event as defined in the act. This law requires that nuclear operators fully compensate for damages without a cap, regardless of the accident's scale. This model of unlimited liability reflects the gravity of nuclear accidents and the potential for widespread harm, but it also represents a substantial financial tail risk for operators. This model contrasts with practices in some other jurisdictions, where liability caps exist to protect nuclear operators from significant financial exposure. For instance, in the United States, the Price-Anderson Act provides a framework that limits the total liability of nuclear operators in the event of an accident, with additional compensation sourced from an insurance policy paid for by all the operators of reactors in the country.

The cost of capital is of particular importance for the financial viability of nuclear investments

Financing costs are particularly important for nuclear power plants, due to their highly capital-intensive nature, so the capacity of the industry to obtain finance at competitive rates is crucial to the competitiveness of the technology and its attractiveness to investors. The ownership structure of companies in the nuclear industry has an enormous impact on the cost of capital. SOEs, which often own and operate nuclear plants, typically enjoy a competitive advantage in this respect, as they can leverage some form of sovereign backing to obtain large amounts of financing at relatively competitive rates (usually close to those of sovereign entities).

Because of the dominance of state-owned utilities, the weighted average cost of capital (WACC) of energy companies with a high share of interests in the nuclear sector tend to be lower than those of solar and wind companies (Figure 3.2). While the WACC of a company does not necessarily reflect the cost of financing a specific project, and risk premiums may need to be added in some cases, especially during the construction phase, it does provide a useful indication of the cost of financing in the nuclear industry. In practice, however, the total cost of financing a nuclear project is strongly affected by construction risks and the impact of market design on electricity prices and revenue streams. For large plants, reducing the cost of capital will go only so far in keeping the overall project costs down; even a low WACC will result in a higher share of financing cost in the total cost of generation than for renewables (where positive cash flows are obtained much sooner).

Figure 3.2 Global average WACC for nuclear, solar and wind companies



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Notes: Nominal post-tax WACCs, based on a sample of 98 energy companies. The companies are categorised by Bloomberg from A1 to A4 according to the estimated share of their value derived from the production of nuclear energy (A1 = Nuclear is part of the core activity – A4= Nuclear is a minor contributor to the company's value chain).

Source: IEA analysis based on data from Bloomberg terminal.

Who invests in nuclear? How is it financed?

The enormous scale of a large-scale nuclear power plant, requiring initial investment that can be in excess of USD 10 billion, means that most projects struggle to get off the ground without some form of government involvement, either in the form of direct ownership, lending, or other forms of financial support or guarantees. This is particularly the case for first-of-a-kind projects, in new countries, for new advanced large-scale reactor designs and for small modular reactors (SMRs). But deploying more nuclear capacity in the coming decades will happen only if the industry is able to unlock large amounts of commercial capital, given the scale of the investment requirement and the constraints and competing priorities for public budgets.

Box 3.1 Understanding how projects are financed and by whom

The *capital structure* of an investment refers to how debt and equity are used to finance spending on energy assets and companies. The debt and equity shares consider the capital structure of both corporate finance and project finance transactions.

Investors refers to the entities making investment decisions, which can be SOEs or private companies (corporates). A company is considered state-owned if more than 50.1% of its shares are held by a public entity, usually the national government.

Financiers refers to the entities providing capital for an investment, evaluating the role of commercial and public sources of finance.

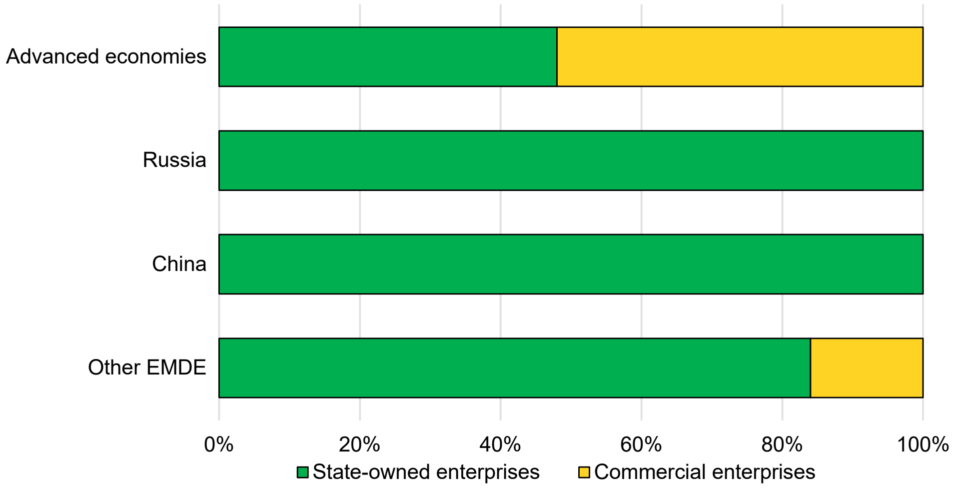
Commercial finance includes equity investments (including cash and savings) made by private enterprises, alongside debt from commercial banks and other financial institutions. It also includes some finance from public financial institutions, such as state-owned banks, sovereign wealth funds and pension funds, even though this may include a degree of state-directed lending, especially in emerging market and developing economies (EMDE) with highly interventionist industrial policies.

Public finance includes public equity stakes in private corporations and SOEs, state subsidies and tax incentives, and finance from some state-owned financial institutions, such as export credit agencies.

State-owned enterprises dominate the nuclear industry today

The global nuclear industry remains dominated by state-owned utilities, or SOEs. In EMDE, virtually all the utilities that operate nuclear plants are state-owned, while the share in the advanced economies is around half (Figure 3.3). Within advanced economies, the share varies considerably, with SOEs accounting for the bulk of capacity in Europe and Korea, while private companies typically operate plants in the United States. Since the 1990s, several utilities with nuclear assets have been privatised or subjected to greater market competition.

Figure 3.3 Share of investment in nuclear energy by type of company and region, 2023



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Source: IEA analysis based on data from Capital IQ and IJ Global (Accessed in January 2025)

The prominent role of SOEs in the nuclear industry historically can be explained by several factors, including strict safety regulations, high investment costs and the long-term nature of such investments, security-related objectives, and export potential. In many countries, state ownership is also a legacy of the traditional structure of the electricity sector. Safety regulation of the operation of nuclear plants and waste management is a core responsibility of governments, and SOEs, under government oversight, are often trusted more than private companies to meet these high regulatory standards. SOEs are better able to absorb the high upfront costs and risks associated with nuclear projects, requiring large amounts of capital, specialised expertise and long timelines often close to 100 years including decommissioning. These projects are difficult for private companies to finance and sustain due to long payback periods. SOEs, however, with government support and policy backing, can better absorb these costs and risks.

Table 3.2 Comparison of project owner type in nuclear power projects

	Government/SOEs	Private companies
Characteristics	A few countries, including some emerging economies, have established nuclear power frameworks based on government or SOE ownership.	Some advanced economies, such as the US and Japan, operate nuclear power systems under a private company-led market structure.
Safety regulation	Government or SOE ownership should ensure alignment with strict government safety regulations and facilitates stable operations.	To achieve a high level of compliance with safety regulations and other societal expectations, enforcement provisions are typically accompanied by a strong dialogue between the project owner and the government.

	Government/SOEs	Private companies
Long-term commitment for operation and decommissioning	Government or SOE ownership guarantees long-term commitment to project operations, as well as the management of waste and decommissioning.	To manage the unusually long-term responsibilities of nuclear projects, governments establish mechanisms (e.g. long-term funding schemes) to ensure future accountability.
Financial Implications	Governments or SOEs generally have higher creditworthiness compared with the private sector, enabling nuclear projects to access financing more easily and at a relatively lower cost of capital. Uncertainty in cash flow (e.g. decreases in cash inflow and increases in cash outflow) can often be absorbed by the government.	Multiple hurdles exist in managing nuclear power projects within the private sector and in deciding on the appropriate sharing of risk and reward between governments and owners. Owners require both systemic and individual support from the government or energy systems to minimise the risk of future cash flow fluctuations. Addressing funding procurement needs, particularly for new construction, requires owners to have high creditworthiness or government-backed credit enhancement.

SOEs often play a pivotal role in the development of nuclear projects overseas. This approach can foster international collaboration and partnerships, and support economic growth in both the country of origin and that hosting the project. Backed by state resources, these entities can provide comprehensive solutions – including financing, construction, maintenance and waste management – that may not be as readily available through private sector companies. The leading exporters of nuclear technologies are the Russian Federation (hereafter, “Russia”), France, the United States, Japan and Korea. Russia’s exports have dropped since the invasion of Ukraine due to sanctions, but it remains the leading overseas nuclear developer.

New reactors are generally financed by a mix of debt and equity, while lifetime extensions are debt-financed

The capital structure of nuclear energy investments varies significantly between new large reactor builds and lifetime extensions. New large reactors are typically financed with around 50% equity, while lifetime extensions rely more heavily on debt, accounting for 70% of overall financing. The relatively lower debt ratios for new-build reactors can be attributed to high upfront costs and risks, especially during the construction phase. Delays and cost overruns can play havoc with overall cost estimates, with financing costs capitalised and compounding over time. Consequently, banks are less likely to participate in the early stages of nuclear projects, making debt more prominent for capital expenditures, refinancing and maintenance.

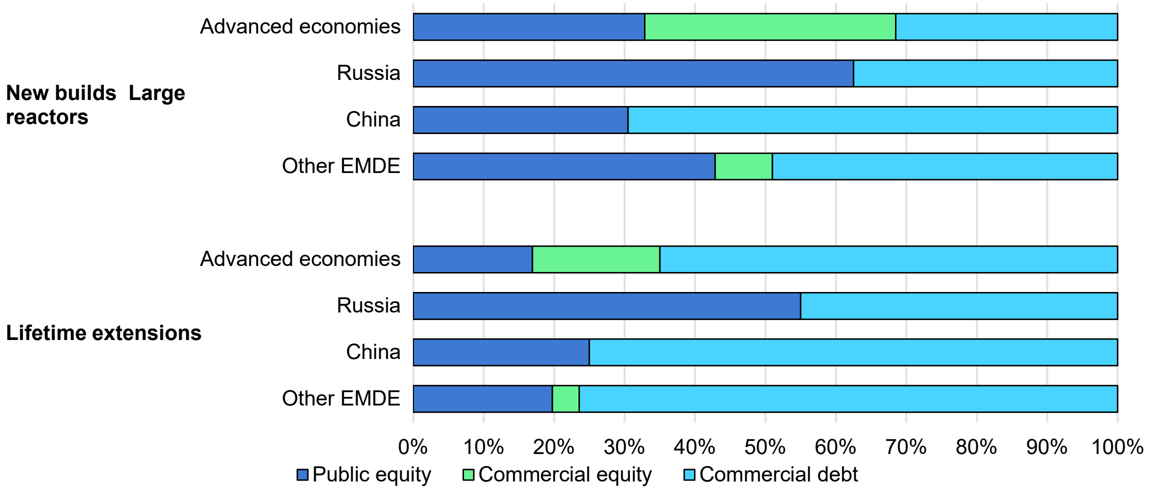
Government involvement in a project generally facilitates securing lower-cost debt financing, as lenders perceive loans as effectively backed by the state. Indeed, if there is publicly funded equity or junior debt, the credit risk assumed by private senior debt tranches is similar to sovereign credit risk, which is generally relatively low if the country has a good credit rating. Political and regulatory risks can deter private investors (see above), but the state can mitigate this by investing state funds, preferably as equity, to reassure private investors and absorb potential losses, thereby encouraging investment. Government involvement can be direct, when a project is publicly funded, owned by a state utility or when the government holds a majority stake. For example, the French government is considering an interest-free loan to Electricité de France (EDF) to finance the construction of the next set of reactors. Alternatively, it can be indirect, through financial assistance provided via guarantees.

There are also significant regional differences in capital structure. In advanced economies, debt generally constitutes a smaller portion of financing for new-build reactors, averaging around 30%, reflecting banks' cautious approach to financing construction. In China, the share of debt for both new builds and lifetime extensions is relatively high, at around 70%, partly due to the role of state-owned banks and a low internally funded capital expenditure ratio. In Russia, equity accounts for about 60% of financing for both new builds and lifetime extensions, indicating more restricted access to debt markets. In other EMDE, debt typically makes up around 50% of financing for new builds, which is common for energy investments generally: debt accounts for approximately 46% of total investment in the global energy sector. The share of debt and equity nonetheless varies significantly from one country to another, with Türkiye relying heavily on equity for its new reactors, while Egypt and the United Arab Emirates depend largely on debt. Russia and other former Soviet Union countries rely heavily on debt for lifetime extensions, generally up to 80%.

Public equity and commercial debt are the main sources of finance

Given the prominence of SOEs, public finance in the form of equity plays a major role in financing nuclear projects, accounting for around 25% of total financing in the advanced economies and China, 60% in Russia and 40% in other EMDE (Figure 3.4). Governments often directly invest in these enterprises or offer low-cost loans, enabling SOEs to secure large amounts of capital at low interest rates. Governments also frequently provide direct funding, subsidies, or tax incentives to cover early-stage nuclear development costs, such as research and development, feasibility studies, and initial infrastructure development. Commercial equity accounts for a significant share of total financing only in the advanced economies.

Figure 3.4 **Sources of finance for investment in new-build large-scale reactors and lifetime extensions by country/region, in 2023**



Note: Finance from state-owned banks is categorised as commercial.
Source: IEA analysis based on data from Capital IQ and IJ Global Databases (accessed in January 2025).

Commercial finance also plays a large part. SOEs are often, especially in advanced economies, publicly listed companies whose shares are partially owned by the private sector. Their debt is in large part provided by commercial or state-owned banks that have a commercial mandate. But for commercial banks to take part in financing, government involvement is always crucial, as nuclear projects are often difficult to justify purely on a commercial basis. Countries that export nuclear technology often rely on export credit agencies to provide financing to foreign buyers. This support can take the form of low-interest loans, loan guarantees and insurance.

The relatively heavy reliance on equity financing for new-build reactors in the advanced economies tends to result in a higher cost of capital. Debt financing, if it can be accessed more widely and at more favourable terms, would, in principle, lower the overall cost of capital, facilitating more investment and promoting faster development of the sector. As markets mature, the ability to tap into commercial debt financing will be essential for driving the growth of nuclear energy, particularly as new technologies emerge, international markets develop and de-risking mechanisms come into play. That will be harder during the construction phase of projects than during the operating phase due to the higher risks; lenders usually demand higher interest rates or additional guarantees to mitigate these risks. Once a plant has started operating, it is generally easier to raise significant amounts of debt as it provides a steady revenue stream, reducing risk. This stability allows the initial equity investors to take out their capital and fund the next project, thereby promoting continuous investment and growth in the nuclear energy sector.

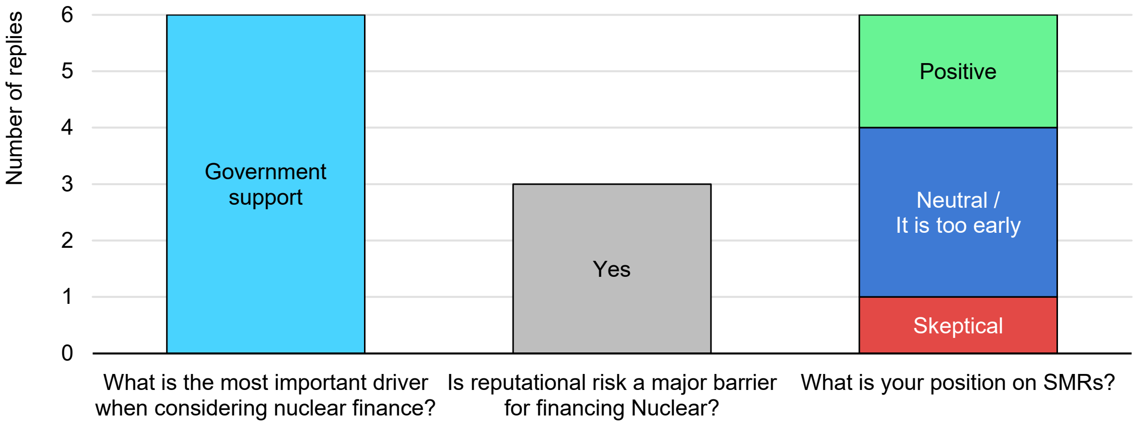
Private financial institutions hold a generally favourable view of nuclear financing

Historically, there has been a gap between expectations for private financial institutions to participate in nuclear finance and the limited extent to which these expectations have been realised. To gain a better understanding of private financial institutions' current attitudes and requirements regarding nuclear finance, the International Energy Agency (IEA) has conducted structured interviews with six private financial institutions, with the results presented here on an anonymised basis. The specific aim was to determine whether the finance sector holds a generally positive or negative stance on nuclear finance and identify the main factors affecting decisions on nuclear finance and what would be needed for institutions to expand financing.

The interviews revealed a neutral to generally positive stance towards nuclear finance institutions. Respondents fell into three main categories: already active in nuclear financing; open to considering participation in financing nuclear, but not active in the field; and not currently active in the field but preparing for the future consideration of the participation. No institution had a negative view of nuclear finance. Some are in the process of publishing guidance and/or have developed internal policies related to nuclear finance.

All participants highlighted government support as a crucial factor in their attitudes towards financing nuclear projects, and three institutions explicitly identified reputational risk as a disincentive. Regarding SMRs, financial institutions have yet to clearly define their stance. While two of the respondents expressed a relatively positive view, three institutions indicated that it is still too early to establish a clear lending position on SMR projects.

Figure 3.5 Views from financial institutions on nuclear financing



IEA. CC BY 4.0.

Source: IEA (2024), survey of six financial institutions.

The survey identified three main factors in determining decisions on nuclear financing:

- **Risk of cost overruns and project delays:** All respondents cited this risk, highlighting specific recent cases and the frequency with which cost overruns and delays have occurred. Many identified the combination of these risks, the large amounts of funding required for new builds and extended loan periods as the primary barriers to consideration being given to nuclear finance. Importantly, several institutions expressed the view that the private sector does not have the capacity to manage the risks related to cost overruns and project delays by itself, underscoring the need for a robust national strategy and government framework supporting nuclear energy projects. Several financial institutions also noted that, due to the inherent project risks associated with national laws, regulations and policy frameworks, it is hard to establish global lending strategies or policies, and the projects should be assessed based on the regional contexts.
- **Track record and technology concerns:** A track record of project implementation was widely cited as a crucial factor in assessing nuclear projects. This includes both the reliability of the technology and the robustness of the national policy framework. Some respondents highlighted that projects employing first-of-a-kind technologies, including SMRs, or new financial instruments are harder to evaluate and require thorough due diligence.
- **Reputational risk:** Concerns over reputational risk emerged as a significant factor influencing financial institutions' stances. Reputational risk is more complex to assess and manage than financial risk, being strongly linked to the public acceptance of nuclear energy, which varies considerably across countries. This risk was mentioned mainly by institutions with an extensive customer base in the destination country for nuclear finance. While recognition of the role of nuclear power in energy policy and climate change mitigation can help mitigate reputational risks, these concerns remain particularly strong among institutions engaged with broad stakeholders.

Some banks also cited political risk as a key factor, particularly in relation to the policy change and force majeure. In addition, some financial institutions highlighted their concern for future projects requiring very large amounts of lending. Based on their view, even though a framework for financing is acceptable, it may be difficult for financing to be obtained if it doesn't have enough financial institutions to share and break down the large amount of lending requirement.

To broaden nuclear financing, all interviewed financial institutions emphasised the need for strong government involvement in guaranteeing cash inflows and addressing risks at the construction phase. While current discussions around nuclear energy's positioning as a clean energy source are seen as beneficial, most respondents stated that these measures alone would not sufficiently mitigate the inherent risks of nuclear finance.

The results of our interviews point to the need for two broad strategies for addressing nuclear finance risks – *complementary* and *horizontal risk sharing*.

- **Complementary risk sharing** involves managing risk to ensure that projects are bankable, particularly for major long-term risks that private institutions alone cannot manage, by incorporating a strong commitment by governments or other public bodies entities to take them on in part or full.
- **Horizontal risk sharing** seeks to distribute risk across multiple institutions, preventing the concentration of financial exposure within a single or few financers. This approach also aims to create a virtuous circle that increases the pool of finance by involving more potential financiers, lowering barriers to entry and attracting more participants. To facilitate growth in the number of institutions capable of providing nuclear finance, support for capacity building from international organisations and leading banks, including assistance in developing national nuclear policies and using risk-assessment methodologies, can be instrumental.

Unlocking more finance for nuclear energy

Business models to de-risk nuclear investments can vary depending on country profile and preference

As described above, establishing a favourable financing environment for investment in nuclear projects hinges, in part, on ensuring stable cash flows once the projects begin operating, as this enables debt to be serviced and dividends to be paid. This requires a combination of pricing/revenue guarantee mechanisms to ensure stable and adequate cash inflows, and a robust de-risking mechanism that reduces or transfers the risk of unexpected cash outflows. Financial risks associated with cost overruns, delays and regulatory uncertainties at the construction stage also need to be mitigated.

On the **cash inflow** side, several recent nuclear projects exemplify how pricing guarantee mechanisms can provide stability. Long-term power purchase agreements (PPAs) with fixed prices are a common approach to reducing risks related to fluctuations in wholesale market prices. The Barakah project in the United Arab Emirates, for instance, operates under a PPA between the project operator and the Emirates Water and Electricity Corporation (EWEC), ensuring stable revenue. Similarly, Türkiye's Akkuyu project benefits from an intergovernmental agreement between Türkiye and Russia. Under this arrangement, Türkiye commits to purchasing a substantial portion of the plant’s electricity output under a PPA at a fixed price for the first 15 years. The Olkiluoto 3 project in Finland uses the "Mankala principle" – a co-operative financing model whereby several shareholders co-own the project and purchase electricity at cost under long-term PPAs. Olkiluoto 3 is owned by over 60 stakeholders, including industrial consumers who benefit from long-term, cost-based PPAs, thereby enhancing financial stability.

Table 3.3 Business models adopted for selected recent nuclear projects

Project	Cash inflow	Cash outflow
Barakah (UAE)	Long-term PPA Fixed-price agreement with EWEC	Costs are primarily borne by the construction consortium and risk is mitigated through Korean Export-Import Bank (KEXIM) and government-backed loans
Akkuyu (Türkiye)	Intergovernmental agreement guarantees fixed-price PPA for 15 years Government commitment to purchase a significant portion of the output	Equity provider bears the main construction risk, supported by Russian Export credit agencies (ECAs) and intergovernmental collaboration
Hinkley Point C (UK)	Contract for difference provides guaranteed strike price for electricity	Equity investors EDF and China General Nuclear Power Corp. (CGN) bear the risk
Olkiluoto 3 (Finland)	Mankala principle ensures cost-based PPA with over 60 stakeholders Financial stability achieved through shareholder commitment to purchase electricity at cost	Risk of cost overruns and delays managed through co-operative financing model Shareholders absorb financial risks proportionate to their ownership
Sizewell C (UK)	Regulated asset base model allows operators to start recovering investments during the construction phase	Shifts some risk to government, reducing the burden on developers

The contract for difference (CfD) model is another approach to guaranteeing revenues. Project developers and operators are guaranteed a fixed price for the electricity they generate, known as the strike price. Should wholesale electricity prices drop below this threshold, the government compensates the developer for the difference; if the market price exceeds the strike price, the project developers must refund the surplus to the government. A notable example of CfD is the Hinkley Point C project under construction in the United Kingdom (UK).

The regulated asset base (RAB) model, which was established in other infrastructure sectors, is increasingly being used for nuclear projects. It combines a revenue guarantee and de-risking mechanism as part of the national regulatory framework. The UK parliament passed the Nuclear Energy (Financing) Bill in 2022, providing the legal basis for applying a new financing framework to new nuclear power plants, which includes the use of the RAB model. The planned Sizewell C project is expected to be financed using this model. The RAB model's revenue guarantee mechanism is expected to work in a similar way to that of the CfD model, but is linked to a de-risking mechanism. It enables operators to start recovering their investment from the government during the construction phase.

On the **cash outflow** side, ECAs can play an important role in effectively managing or transferring risks related to cost overruns, delays and regulatory changes during the construction phase. ECAs are government-backed institutions that provide loans, guarantees and insurance to companies involved in international projects. In nuclear finance, ECAs can offer credit insurance and guarantees, thus lowering risks for private investors and lenders and making long-term, low-cost financing more accessible. For instance, the Barakah nuclear project in the United Arab Emirates was supported by financial backing from KEXIM and government loans. Similarly, Türkiye's Akkuyu nuclear project benefited from an intergovernmental agreement and substantial support from Russian ECAs, enabling Rosatom to take on a significant portion of the financial and operational risk.

ECAs often work in collaboration with multilateral development banks (MDBs) to provide not only financial support but also added credibility and security to projects in emerging markets. This is particularly beneficial in regions with nascent financial systems or less-developed energy markets. The involvement of ECAs can ensure that financing remains stable even when market conditions fluctuate, or local regulatory frameworks are in flux.

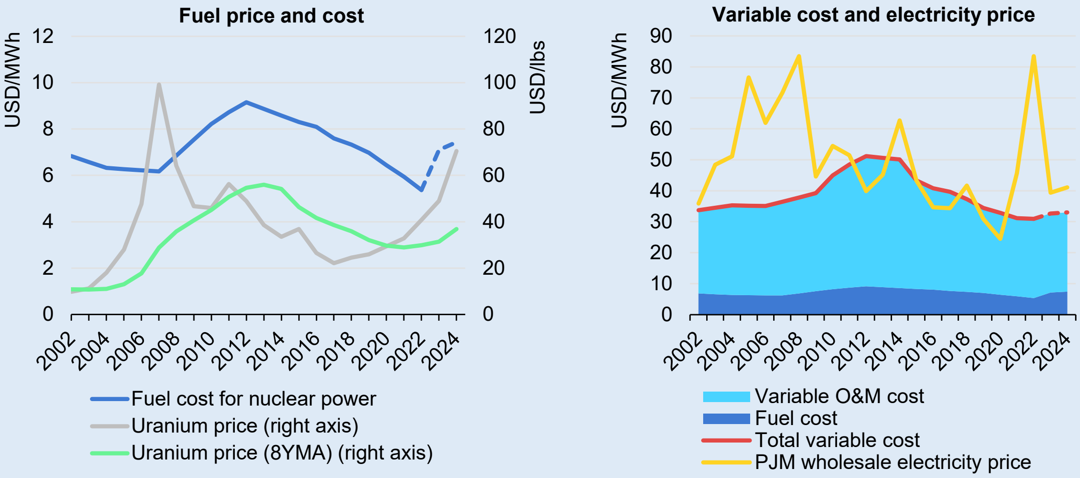
These initiatives especially on the cash inflow side need a government commitment and energy consumers' support for that commitment. For consumers, the expected benefits of such support are improved energy security and predictable costs in the event of disruptions. The government's support for nuclear energy aligns with consumer expectations of security and affordability, but it is essential to regularly assess options and communicate to consumers. Ongoing support, coupled with proper monitoring, is crucial to fostering an expansion phase of nuclear energy where the government, consumers, operators, and the private finance sector can all share in the benefits, as outlined in the next section.

Box 3.2 Electricity pricing and nuclear fuel costs

In liberalised wholesale markets, receiving sufficiently high electricity prices is important for long-term revenue and cost recovery. This is especially the case since nuclear power plants are capital-intensive assets with high fixed costs, which need to be recovered. This highlights the importance of appropriate power market design and relevant schemes that reduce the longer-term electricity price risk for nuclear energy.

By contrast, the variable costs of nuclear energy are relatively low. Short-term increases in spot prices for natural uranium do not have much impact on the variable costs of nuclear power generation, because uranium supplies are generally based on long-term contracts that protect fuel consumers from short-term increases in wholesale uranium prices. Variable operation and maintenance costs make up a larger portion of the total variable costs of nuclear than for most other dispatchable generating technologies. Higher fuel costs can, nonetheless, undermine the profitability of nuclear power plants in the medium to long term as new long-term contracts are negotiated.

Figure 3.6 Average international uranium and nuclear fuel price and variable cost of nuclear power generation and wholesale electricity price in the United States



Notes: MWh = megawatt-hour; lb = pound; 8YMA = 8-year moving average; O&M = operation and maintenance. PJM Interconnection is a regional transmission organisation serving markets in Northeastern states. 2023 and 2024 values for fuel cost and US variable costs are estimates (variable costs assume O&M costs remain unchanged from 2022).

Source: IEA analysis based on data from Nuclear Energy Institute (2023), Nuclear costs in Context; and Federal Reserve Bank of St. Louis, FRED.

Boosting private financing will be critical

Securing more private finance for nuclear projects will be critical to the future of the industry in many parts of the world, given constraints on public funds. That will require a more favourable financing environment, which depends – above all – on the nuclear industry delivering projects on time and to budget. Governments would benefit from this and could well become more supportive of further nuclear construction as a result, as a burgeoning nuclear power generation sector would also enhance energy security and affordability and contribute to national economic growth and industrial competitiveness. These benefits to governments would also make positive influences for energy consumers. Moreover, with a track record of receiving cash flow on schedule, nuclear operators would improve their financial creditworthiness and expand borrowing capacity.

Based on the track record of recent nuclear projects, it is unlikely that the need for strong government support and involvement in new projects will change in the short term. However, a more proactive government stance, combined with improvements in operators' financial performance, could encourage financial institutions to increase their lending for the sector. With leading players becoming more active, it may become easier to spread risk horizontally by broadening the financial base of projects.

The pathway to increasing financing for new nuclear projects over the next two and half decades consists of two phases. In the first, governments need to designate the next 10 to 15 years as a period for intensive nuclear power plant construction. During this phase, operators will need to focus on ensuring projects are completed on time, while governments actively support these efforts through mechanisms such as RAB, CfD and direct involvement in financing. Priority will need to be given to new builds and the development of SMR technology. Governments will need to work with private sector partners on establishing complementary risk-sharing mechanisms, such as the use of ECAs. Towards the end of this period, attention should be given to broadening the scope of horizontal risk-sharing mechanisms.

Following the concentrated construction phase, there is a transition to a broader phase of nuclear expansion after 2035-2040, involving a bigger role for SMRs. This would depend on leveraging the trust and confidence in the industry achieved by delivering the initial projects on time and on budget. The second phase sees an acceleration of participation by private financial institutions. While complementary government support is still needed, the growing number and diversity of participants would pave the way for the support from the capital market or milestone-based short-term financing and refinancing.

The scaling up of nuclear capacity during this second phase could be accompanied by a growing reliance on commercial debt. This could take various forms (Table 3.4). Bank loans are approved on a case-by-case basis in response to demand, rather than being allocated by someone in charge of capital allocation like bonds or equities by institutional investors. That means that nuclear projects are evaluated individually, and their unique risks and benefits are considered independently of other energy projects.

Table 3.4 Debt financing options for nuclear projects

Financing option	Provider	Pros	Cons
Corporate finance (loans/bonds)	Private lenders/ investors	Large companies or companies with explicit or implicit support from the government can benefit from lower cost of capital, leveraging their creditworthiness Flexibility of the use of proceeds (if the loan is for general corporate purposes)	If a company already has a large amount of debt, securing additional financing may be hard, regardless of the nuclear project risk The loan period for typical corporate finance is shorter than the project period for nuclear energy, making it vulnerable to changes of credit status during the project period Lending capacity depends on the company's size and creditworthiness
Corporate finance (green/ transition loans/bonds)	Private lenders/ investors	Access to a broader investor base interested in sustainable finance Possible benefits from a green premium (greenium)	Unlikely to be a major source of funding that can meet all capital needs during the construction phase Government support for the project will be necessary
Project finance	Private lenders/ investors	Limits sponsors' liability to the project, protecting other assets Can attract investment through isolated risk structure (special purpose vehicles) Long-term finance is possible	Early and highly predictable cash inflow is required, requiring several conditions to be met, including clear and strong government support The number of entities capable of providing project finance is limited compared with corporate finance Structuring is complex and time-consuming
Government guarantee	Government	Lowers perceived risk for project operator and other financiers, and reduces the cost of capital, attracting private sector interest and making projects more bankable	Taxpayer exposure to potential project failures or cost overruns The difficulty of expanding the scheme and the problem of increasing government contingent expenditure
Export credit financing	ECA	Similar to a government guarantee, it lowers project risk and improves bankability	Relies on diplomatic relations Increases government contingent expenditure
MDB loans	MDBs	Concessional terms specific to MDB loans especially in developing countries Provides credibility and may attract additional investors	MDB funding is limited and requires compliance with stringent guidelines Long approval processes and subject to political influence

Box 3.3 Demystifying “risk-taking” by financial institutions: The importance of cash flow predictability for debt providers

While there is external pressure on financial institutions to actively take the risk of nuclear finance, within the industry, strong government commitment is seen as essential for such expansion. One reason for this divide is the over-expectation for the term "risk-taking", which is often interpreted as an appetite for engaging in high-risk ventures. Some view the finance industry’s stances on nuclear finance as lacking a willingness to take risks or a recognition of the importance of nuclear energy. However, for private lenders, “risk-taking” requires a systemic approach beyond mere willingness.

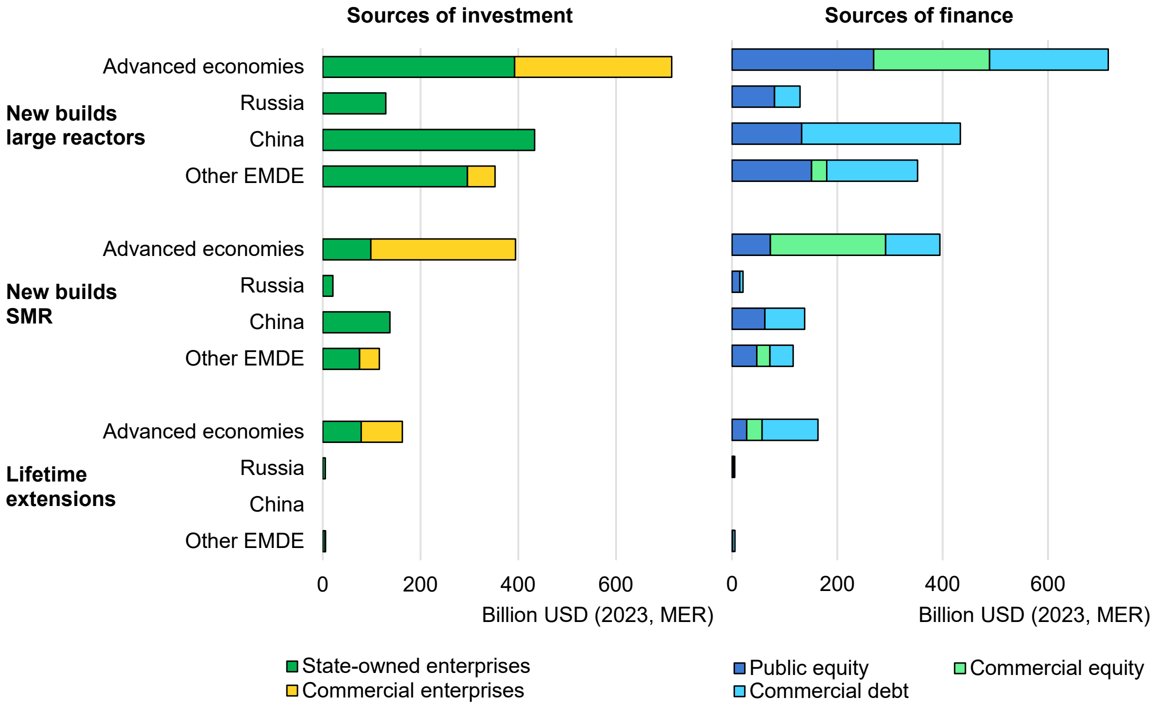
Funds for projects or business generally fall into two categories: equity investment and debt financing. The main difference for the financier is that, in the case of debt financing, a stronger business performance than expected does not directly increase the lender’s earnings. Loan agreements are documented with a preset interest rate and specific conditions prior to execution, and interest and principal repayments proceed according to the agreement regardless of how the business performs. This is a notable difference from equity, where investors hold a share of the ownership of the business and so can benefit from its upside potential.

However, while debt providers are generally safer than equity investors, they remain exposed to the downside risk, and if the business goes bankrupt, they may not recover their loans. Given that interest margins (the difference between a lender’s interest rate for borrowers and a base rate for lenders to procure their funds) are usually very small, the impact is considerable. Given debt providers’ asymmetric incentive structure, no upside benefits but bearing downside risks, financial institutions’ lending decisions are guided by whether there is likely to be sufficient cash flow to cover repayments, even in adverse scenarios – a principle known as “lending to cash flow.” In essence, the “risk-taking” function of financial institutions involves assuming the risks of business that demonstrate a sufficiently low probability of interruptions in principal and interest repayments. In the case of an energy investment, financial institutions without the benefit of upside returns do not lend based on their expectations for the technology itself or the importance of national energy policy, but rather on cash flow predictability.

Greater reliance on equity financing could push up the cost of capital in the near term

Changes in the mix of equity and debt could have a significant impact on the cost of financing nuclear projects in the coming decades. In the Announced Pledges Scenario (APS), the financing of nuclear power generation changes significantly, with equity financing rising faster than debt over the period 2024-2037. That reflects the fact that several countries launch their nuclear programmes, requiring a larger part of the financing to come from equity to cover for the high risk and long lead times of initial projects. This could push up the overall cost of capital, as equity is more expensive than debt. Debt also rises, as government-backed projects are viewed positively by commercial banks. As the level of investment in nuclear starts to fall back by the middle of the 2030s, the capital structure of nuclear investment worldwide moves back towards that seen over the last 15 years.

Figure 3.7 Cumulative investments in nuclear energy by source and type of finance and country/region in the Announced Pledges Scenario, 2024-2050



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Note: For new builds – large reactors, the sources of finance are assumed to remain constant at historical average levels in Russia, China and other EMDE. For lifetime extensions, the sources and types of finance are assumed to remain constant.

Source: IEA analysis based on S&P Capital IQ and IJ Global databases (accessed in January 2025).

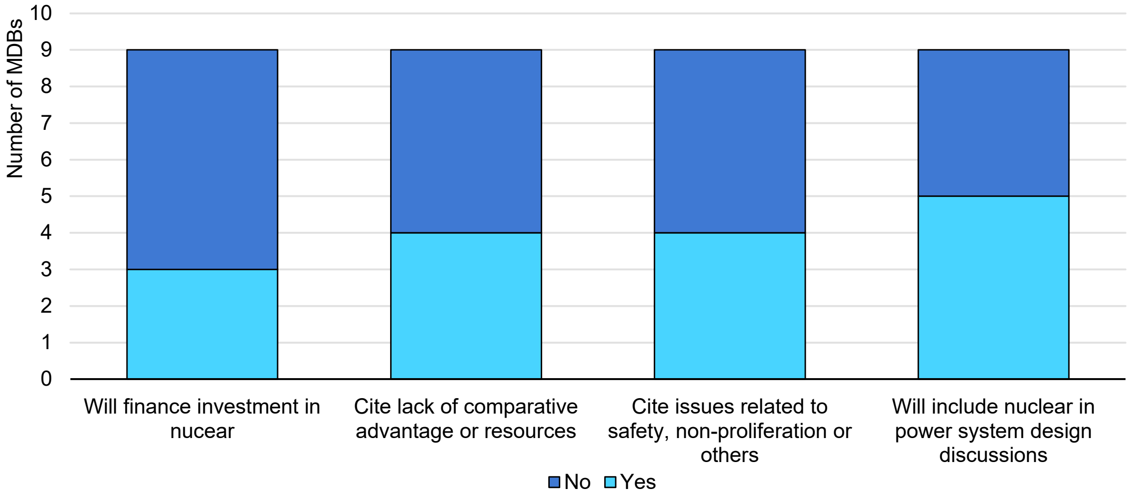
SOEs continue to play a major role in financing nuclear projects over 2024-2037 in that scenario, reflecting mainly the growth in investment in EMDE. Total cumulative investment by SOEs worldwide reaches USD 1 trillion over that period. More investment comes from advanced economies in the period 2038-2050, increasing the shares of commercial equity and debt. In the latter period, commercial finance increases slightly faster as more debt financing takes place in advanced economies, where the role of SOE is not as large.

This analysis underscores the importance of government-backed and SOE-led investments to drive nuclear energy in the early stages and the potential for more balanced public-private financing in the latter years. Size also matters. The massive scale of investments in large reactors requires the establishment of large consortia, to enable individual investors to limit their exposure. This is different from investments in most utilities, which usually hold a diversified mix of generating assets.

MDBs could help with financing nuclear energy, but only on a small scale

MDBs could also play a role in financing new nuclear projects, especially SMRs, in EMDE. They have the capacity to offer very long-term funding packages, sometimes exceeding 40 years, and have global reach. Up to now, most MDBs have avoided financing nuclear projects, and only a few million dollars were allocated to the sector over the past five years. Few MDBs explicitly exclude nuclear financing in their policies, but the majority have decided not to invest in specific projects due to limited expertise or comparative advantage in the sector or because they prioritised other development goals (Figure 3.8).

Figure 3.8 Position of multilateral development banks on financing nuclear energy



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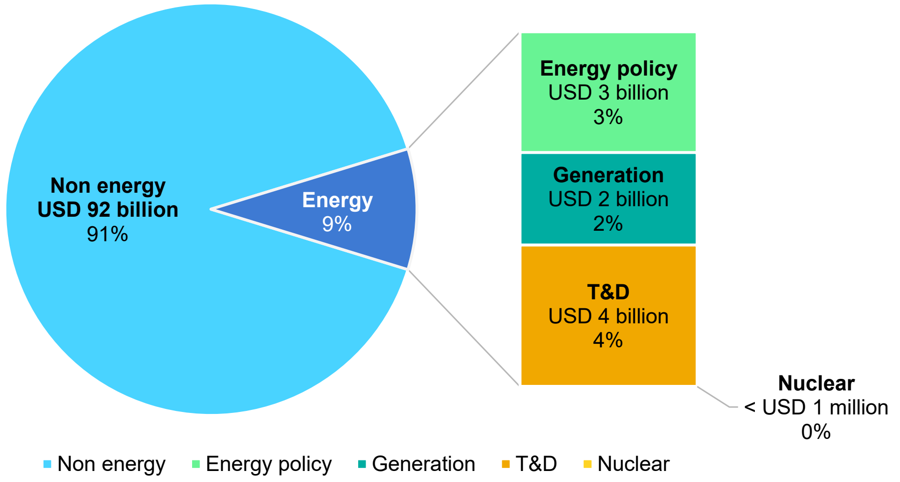
Note: MDBs include African Development Bank, Asian Development Bank, Inter-American Development Bank, Asian Infrastructure Investment Bank, Council of Europe Development Bank, European Bank for Reconstruction and Development, European Investment Bank, Islamic Development Bank, World Bank Group.

Source: IEA analysis based on MDB public policy or strategy framework documents.

Whatever the MDBs' stance on investing in nuclear projects, it unlikely that they would be able to contribute to financing them on a large scale in the absence of a massive expansion of their overall funding capacity. MDBs must direct their funds to a number of priority areas, including education, health, sanitation and energy, and while they have recently increased financing for climate change mitigation and adaptation, their balance sheets remain too limited to support significant nuclear investments. The combined annual disbursements of eight of the largest MDBs currently total around USD 100 billion across all areas of intervention, with around USD 9 billion, or 9%, allocated to the energy sector. Of this, about half is spent on electricity transmission and distribution, while power generation receives approximately USD 2 billion per year. This compares with global investment in nuclear energy alone of around USD 100 billion in 2030 in both the APS and Net Zero Emissions by 2050 (NZE) Scenario, i.e. equal to all the disbursements of MDBs today.

Figure 3.9 Average annual disbursements by MDBs by sector, 2019-2022



Notes: T&D = transmission and distribution. MDBs in this analysis include African Development Bank, Asian Development Bank, Inter-American Development Bank, Asian Infrastructure Investment Bank, Council of Europe Development Bank, European Bank for Reconstruction and Development, Islamic Development Bank and World Bank Group. Data from the European Investment Bank is combined with other European funds in the database and is therefore not included in this chart.

Source: IEA analysis based on total reported disbursements from the OECD CRS database.

Despite their financial constraints, MDBs could help catalyse nuclear energy developments through various financing instruments. For example, MDBs often provide technical assistance for electricity market design and contribute to key infrastructure necessary for nuclear energy in their client countries. In addition, they could fund and conduct feasibility studies, advise on electricity procurement mechanisms, offer templates for contractual arrangements such as PPAs, and support the establishment of regulatory frameworks and safeguards. As they have already done in some cases, they could also help countries access new pools of funding, for instance through the issuance of sovereign sustainable debt, such as sovereign green bonds. In the case of emerging nuclear technologies such as SMRs, MDBs can also help smoothing out the “first mover” risk, for instance by guaranteeing parts of the revenue streams for the initial plants to help bring them to market.

Green bonds and transition finance instruments are expanding

Operators of nuclear power plants in Europe and some other regions have recently been increasingly tapping into the debt capital market to finance their activities, in response to the introduction of supportive policies. In the European Union, the Complementary Climate Delegated Act to Accelerate Decarbonisation, which was adopted in 2022, incorporated nuclear energy (and fossil gas) into the EU taxonomy for sustainable activities. Under the act, nuclear energy-related activities are categorised as "transitional activities to facilitate the transition away from more harmful energy sources e.g. coal and towards a mostly renewables-based future" (Article 10 [2]). Specific nuclear-related activities that qualify for policy support include the following:

- pre-commercial stages of advanced technologies to produce energy from nuclear processes with minimal waste from the fuel cycle
- construction and safe operation of new nuclear power plants, for the generation of electricity or heat, including for hydrogen production, using best-available technologies (for which the construction permit has been issued by 2045)
- electricity generation from nuclear energy in existing installations (modification of existing nuclear installations for the purposes of extension, authorised by member states' competent authorities by 2040 in accordance with applicable national law, of the service time of safe operation of nuclear installations that produce electricity or heat from nuclear energy).

The screening criteria cover two main areas: greenhouse gas (GHG) emissions and activities that "Do No Significant Harm" (DNSH). For GHG emissions, nuclear energy projects must maintain life-cycle emissions below 100 grammes of carbon dioxide equivalent per kilowatt-hour. The DNSH criteria focus on safety, regulatory compliance, and effective management of radioactive waste and decommissioning.

This categorisation has bolstered the issuance of green bonds – the bond instrument where the proceeds or an equivalent amount will be applied to finance or refinance, in part or in full, new and/or existing eligible Green Projects – by nuclear operators in the European Union. A notable example is EDF, which has issued several green bonds to fund nuclear power-related activities.

The use of green bonds for nuclear financing is growing in other regions too (Table 3.5). Two Canadian nuclear power players – Bruce Power and Ontario Power Generation – and Constellation in the United States have recently issued green bonds. In Japan, two utility companies have issued bonds categorised as "transition bonds", reflecting the nation's strategic focus on nuclear energy within its broader green transformation agenda.[7] The main use of the proceeds of these bonds is the maintenance and lifetime extensions of existing reactors, rather than new construction, with the tenors in most of the bonds being shorter than the construction period for new projects.

Table 3.5 Green and transition bond issuances for nuclear energy

Type	Name	Country	Issue date	Currency	Amount (USD million)	Tenor (years)
Green	Bruce Power	Canada	Nov 2021	CAD	370	6.9
			Mar 2023	CAD	222	4.8
			Mar 2023	CAD	222	9.8
			Mar 2024	CAD	444	7.3
Green	Ontario Power Generation	Canada	July 2022	CAD	222	10
Green	EDF	France	Nov 2023	EUR	1 087	3.5
			Jun 2024	EUR	1 087	7.0
			Sep 2024	EUR	543	5.3
			Sep 2024	EUR	707	8.0
			Sep 2024	EUR	543	11
Green	Constellation	US	Mar 2024	USD	900	30
Transition	Kyushu Electric Power	Japan	Jun 2024	JPY	71	5
			Jun 2024	JPY	134	10
Transition	Kansai Electric Power	Japan	July 2024	JPY	201	5
			July 2024	JPY	100	10

These developments represent a tailwind for private sector financing in the nuclear industry and a positive shift in market sentiment toward nuclear financing. However, market-driven financing mechanisms cannot function on their own and cannot entirely replace fundamental government support. The inherent cash flow risk of a project cannot be changed by the form of financing and therefore, a project with concern of cash flow characteristics cannot become bankable simply by changing the procurement method. The success of these financing instruments in the long run depends on robust public-private partnerships.

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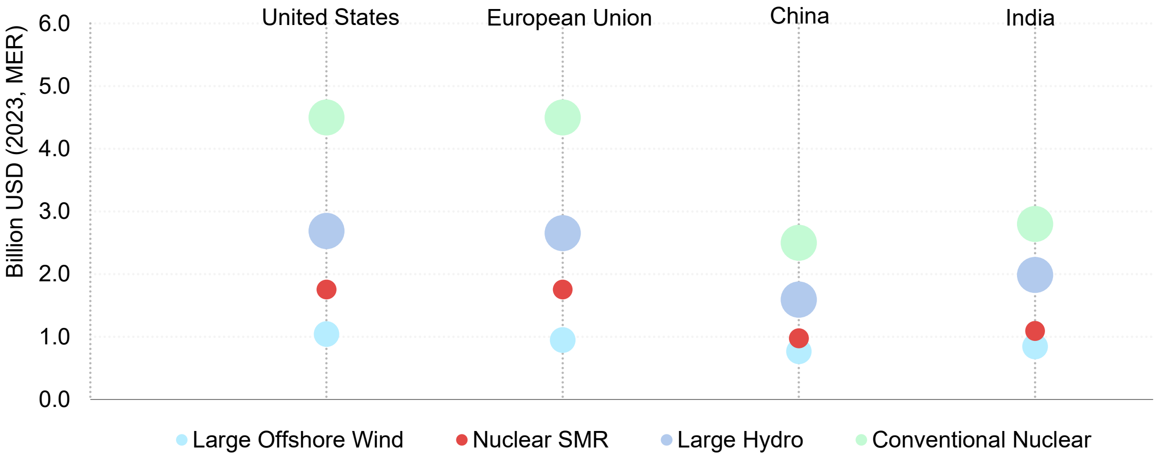
[7] Japan's Basic Policy for the Realisation of Green Transformation, published in February 2023, outlines an investment roadmap aimed at achieving carbon neutrality by 2050. This comprehensive plan covers 22 industrial sectors and includes the introduction of carbon pricing. Transition roadmaps developed with input from both public and private stakeholders provide detailed guidance for investors, explicitly recognising nuclear power as a key component of the strategy.

SMRs could open the door to greater private sector participation

The smaller scale of SMRs makes them potentially more attractive to commercial investors, opening a door to broader private sector participation in nuclear energy. Recent investments in conventional nuclear plants involve an upfront investment that have exceeded USD 10 billion in certain markets, but would be reduced substantially if projects are delivered on time, while most SMRs under development are expected to cost no more than USD 2 billion – less than a typical large-scale hydropower project and a far more manageable sum for private finance institutions (Figure 3.10).

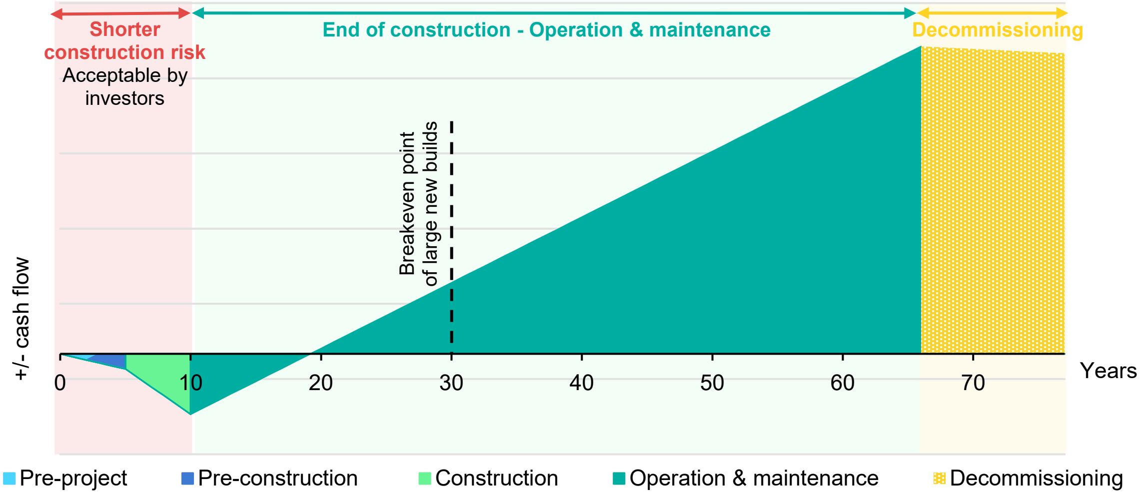
Figure 3.10 Indicative capital expenditure per project for selected technologies by country/region, 2040



Note: Capacity assumptions differ per technology: Large offshore wind – 500 MW; SMR – 300 MW; Large hydro – 1 000 MW; Conventional nuclear – 1 000 MW.

The smaller scale of SMR projects has the potential to reduce the necessity of engaging multiple financial institutions for horizontal risk sharing. However, if such collaboration is required, the smaller size can also make it more manageable, thereby streamlining the overall financing process. If SMRs are able to build a track record of successful projects, they could attract investment more readily than conventional nuclear projects. Assuming SMRs reach cost parity per megawatt with conventional nuclear energy through standardisation of designs, the payback period of an investment in an SMR could be shortened by as much as ten years compared with the typical 20- to 30-year period for conventional projects thanks to shorter pre-project and construction periods and lower financing costs (Figure 3.11). By shortening the payback period and generating net cash inflows sooner, SMRs could free up capital for new projects, building momentum in the market. To establish this virtuous cycle, it is crucial for the initial projects to progress steadily and become operational as quickly as possible.

Figure 3.11 Indicative cumulative cash flow profile of an SMR power plant assuming cost parity with a conventional large-scale nuclear plant



Note: Cost parity is on a per-megawatt basis.

The shorter construction period, standardised designs and earlier cash flow prospects associated with SMRs present an opportunity for developers to seek refinancing of their initial investments during the construction phase, prior to the realisation of revenue streams. This approach can release early-stage capital, enabling its redeployment towards the expedited development of additional SMRs. While a similar approach could also be used for large new builds, it is uncertain at which stage of the lengthy construction phase the investment would become attractive to private investors.

Abbreviations and acronyms

AEOI	Atomic Energy Organization of Iran
AI	artificial intelligence
APS	Announced Pledges Scenario
AWS	Amazon Web Services
CAD	Canadian dollars
CCGT	combined-cycle gas turbine;
CCS	carbon capture and storage
CCUS	carbon capture, storage and utilisation
CEFR	China Experimental Fast Reactor
CfD	contract for difference
CGN	China General Nuclear Group
CHP	combined heat and power
CNNC	China National Nuclear Corporation
CNY	Yuan renminbi
CO_2	carbon dioxide
CTT	Clean Transition Tariff
DNSH	Do No Significant Harm
DOE	Department of Energy
ECA	export credit agency
EDF	Electricité de France
EMDE	emerging market and developing economies
EPR	European pressurised reactor
ESBWR	Economic Simplified Boiling Water Reactor
EU	European Union
EV	electric vehicle
EWEC	Emirates Water and Electricity Corporation
GBN	Great British Nuclear
GHG	greenhouse gas
GX	Green Transformation
HALEU	high-assay low-enriched uranium
HTR-PM	high-temperature gas-cooled reactor pebble-bed module
i-SMR	innovative small modular reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEPMP	Integration Energy and Power Master Plan
KEXIM	Korean Export-Import Bank
KHNP	Korea Hydro & Nuclear Power
KNPP-NB	Kozloduy Nuclear Power Plant New Build
LCOE	levelised cost of electricity
LFR	lead-cooled fast reactor
LWR	light water reactor

MDB	multilateral development bank
MER	market exchange rate
MoU	memorandum of understanding
NDC	nationally determined contribution
NPP	nuclear power plant
NRA	Nuclear Regulation Authority
NZE Scenario	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPG	Ontario Power Generation
PEJ	Polskie Elektrownie Jądrowe
PPA	power purchase agreement
PV	photovoltaic
PWR	pressurised water reactor
R&D	research and development
RAB	regulated asset base
SDA	Standard Design Approval
SFR	sodium-cooled fast reactor
SMR	small modular reactor
SOE	state-owned enterprise
STEPS	Stated Policies Scenario
SWU	separative work units
TRISO	tristructural isotropic particle fuel
UAE	United Arab Emirates
UK	United Kingdom
US	United States
VALCOE	value-adjusted levelised cost of electricity
WACC	weighted average cost of capital
WANO	World Association of Nuclear Operators

Measures and Units

GJ	gigajoule
Gt	gigatonne
GW	gigawatt
kW	kilowatt
lb	pound
MW	megawatt
MWh	megawatt-hour
TWh	terawatt-hour

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Unless otherwise indicated, all material presented in figures and tables is derived from IEA data and analysis.

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