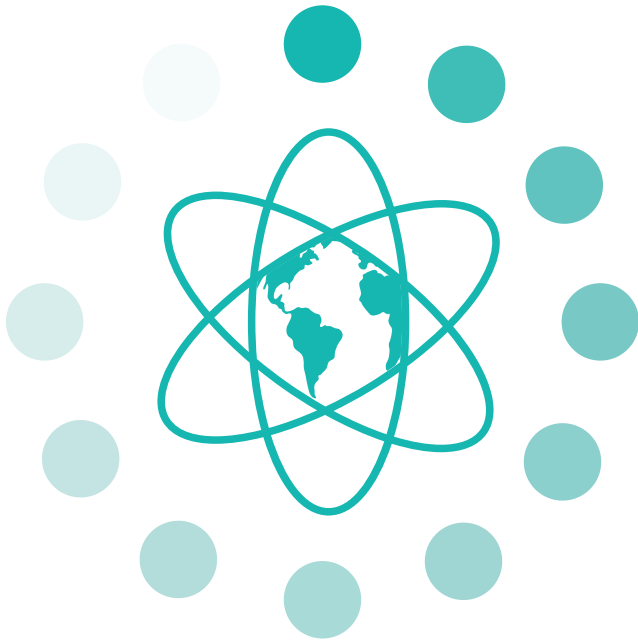
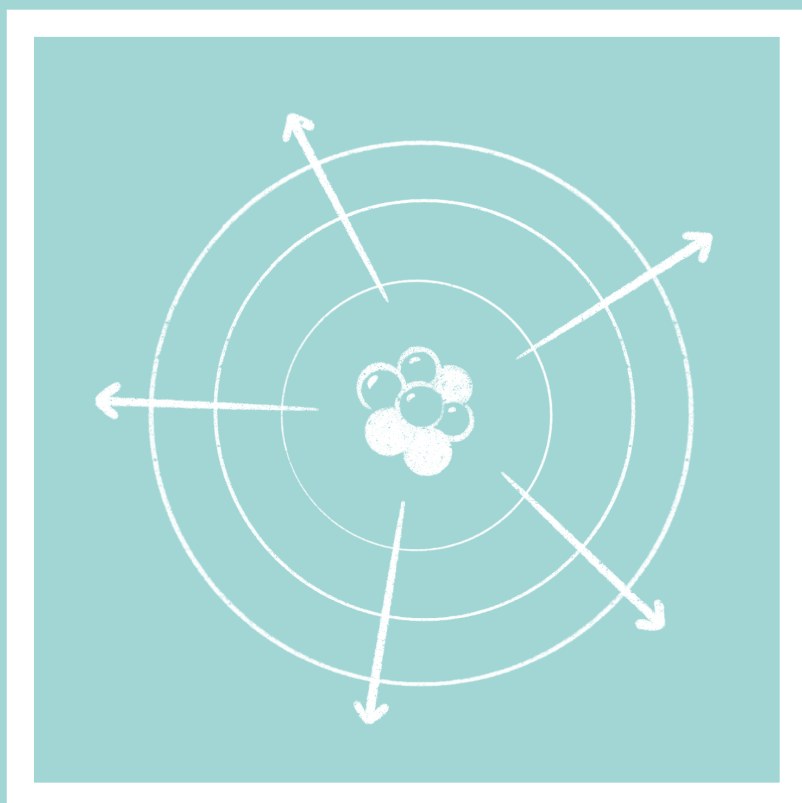




The global nuclear energy revival

2023 Review Study

Preface by the French Institute of International Relations (Ifri)



Preface

Given the abrupt shift in geopolitics, a comprehensive industrial strategy is crucial

Supply security, economic sovereignty, decarbonization...
As the myth of untroubled globalization fades from the collective memory and at a time when energy transitioning is increasingly painful, Europe appears ill-prepared to face these challenges. Europe has to rely on its existing assets, including nuclear energy, i.e. Europe's primary low-carbon energy source, as part of a credible industrial policy.

Marc-Antoine Eyl-Mazzega, Director of the Centre for Energy and Climate at the French Institute of International Relations (Ifri)

Climate neutrality is the new *raison d'être* of the European Project

In 2019 Ursula von der Leyen's European Commission drew up the European Green Deal that was implemented in 2020 and 2021. This policy initiative garnered an unprecedented amount of support from the European Parliament and the EU Member States and generated with it real economic, political and societal optimism and momentum, stretching well beyond the political bubble in Brussels. There was even the thought that the EU, having been buffeted first by Brexit and then by nationalistic leanings at the onset of the Covid-19 pandemic, was at long last emerging from that period stronger and re-invigorated, in particular thanks to the unprecedented scope of the EU economic relaunch plan and the decision to fast track the energy transition pathway.

The EU could even dream about being a geopolitical power. It would be energy independent and a leader in environmental issues that would impact the whole world.

The election of US President Biden at the end of 2020 combined with the Democrats' better-than-expected showing during the mid-term elections (winning Senate control) saw the US return to the forefront in terms of tackling climate change. Lastly, in 2021 during the COP26 event, China along with other major carbon emitters committed to reaching climate neutrality by 2060 (2070 for India).

Four years ago interest rates were low and energy prices were also generally subdued. The Euro currency was trading strongly and the EU 27 was running a trade surplus. Economic growth was making a comeback and Europe's citizens ultimately appeared to be the most effectively protected population both in terms of health and economic support. Against the backdrop of a European rebound, thoughts were even turning to a new geopolitical order in which the rich oil producing nations would falter and be quickly side-lined in favor of a totally new set of actors sitting outside the traditional trading and inter-dependence framework, which would instead be supplying metals, green hydrogen, and attractively priced renewable energy.

The EU could even dream about being a geopolitical power. It would be energy independent and a leader in environmental issues that would impact the whole world. Europe could be in a position to offer a third alternative to the

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nascent Sino-US duality. At that time China also became Germany's main trading partner. The Federal Republic's new traffic light coalition (SPD/FDP/Green) had set course for a geopolitical trinity comprising a US alliance, careful constructive ties with China and Russia, and European integration. In effect however, Berlin found itself dependent on cheaply priced Russian gas supplies and exports to China. The strategy was also to involve the whole of Europe, with policies designed to support the German transition model that itself was based on a combination of renewable energies, cheap natural gas for supply balancing purposes, carbon contracts, and large-scale hydrogen. Although hydrogen was to be heavily subsidized, this was only meant for the start-up phases, as it was widely assumed that electricity would be cheap and plentiful as renewable energy production ramped up. Furthermore, if it became clear that key elements would have to be imported, then this would be using German technology components. Equipped with more than 400 TWh of domestically produced nuclear energy that sat alongside its significant export capacity, France failed to focus on its nuclear and renewable energy profile, and paradoxically found itself sleepwalking its way towards deindustrialization, and this in spite of its ample supplies of cheap low-carbon electricity. During this period the nation's public debt ratio was climbing to 110% of GDP, with increasingly onerous servicing costs. Indeed, debt related repayments are now the number one drain on public finances, whereas defense spending, technology and economic modernization would logically be expected to be the major funding recipients.

The chapter of smooth globalization that had opened with China's accession to the WTO has closed once and for all.

The 'Made in China 2025' strategy, electricity supply security, issues surrounding metals and rare earth metals, the outlook for energy-intensive industries, the challenges of innovation, as well as low-carbon technology value chains are all key issues that failed to take center-stage at national or European public policy level. At that time the geopolitical backdrop was still significantly tilted towards the remnants of the war against terrorism in the 2000s and 2010s (Afghanistan, Libya, Iraq, the Sahel region), the challenges of immigration for example, as well as to the contagion-type tensions bubbling up on Europe's periphery, albeit without fully realizing their ability to propagate (such as Mali, the Donbas region, Syria).

Low cost was the key consideration in the energy sector and all parties were reliant on their neighbours for energy supply support during peak and winter periods. Lastly, we were still so focused on fostering generalized co-operation with China at national and or European level that we appeared to be incapable of including the notions of rivalry or conflict in our thoughts or relationship with this interlocutor. Short-term interests dominated a somewhat vague long-term strategy.

Era of untroubled globalization ends: balance of power dynamics dominate

Almost four years after the Green Deal launch, and almost two years after Russia's invasion of Ukraine, Europe has suffered several shocks and, in an increasingly fragmented world, is itself becoming peripheral, whilst other geographic centers are maintaining and even asserting their positions (China, USA, India), albeit with none of them securing absolute power. The international system that bears the hallmarks of the West is under siege and disintegrating. Authoritarian systems are in the ascendancy and operating via business transactions and multiple flexible alliances.

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Europe is now facing existential challenges.

Power-based relations are being increasingly honed and the existing rules are being cast aside. International governance has been weakened, but importantly still remains effective on certain issues (WTO fishing subsidies agreement, COP15 environmental protection agreement). The chapter of smooth globalization that had opened with China's accession to the WTO has closed once and for all. Europe is now facing existential challenges. While international trade is holding steady, albeit at a slower pace due to several sharp hikes in tariff barriers, it is above all investment flows that are steadily shifting course. Last but not least, the major powers are now engaged in intense rivalry over industrial policies, while mobilizing technologies, industries, market access, investment, finance, hydrocarbon resources and supplies, as well as raw materials for geopolitical and geo-economic ends, all in a bid to consolidate their own positions of power and/or to protect themselves from the power of others. Europe's nations carry little individual weight on the global stage and are now financially much weaker. The collective power of the EU, which is based above all on the rule of law and a common market with free and open competition, must shift up a gear and become stronger if it is to exist in the new geopolitical and geo-economic sparring arenas. Europe is aware of the situation and never before has there been so much shared analysis and effort in order to strengthen its strategic autonomy, which is essential for its future prosperity.

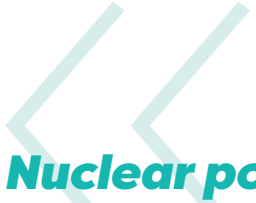
However, progress for a 27-member collective is bound to be protracted, not least given the extent to which the EU Member States have fallen behind.

Europe facing existential challenges

It is against these worsening conditions that Europeans must now fast-track their energy transition, the strategic objectives of which have not yet been formulated. Yet they should be: i.e. achieving a real and rapid reduction in emissions and environmental degradation; and in doing so, safeguarding the economic and social security of Europe's citizens, which means that decarbonization must not augment external dependencies, shutter factories, or place citizens in difficulty without support and solutions; and finally, acting strategically along well-established and well-ordered priorities with adequate short- and long-term resources, and in close coordination and agreement, so as to guarantee both the feasibility of the whole process and that the associated costs are managed and monitored.

Europeans are now facing a raft of existential challenges: strategic marginalization would mean being unable to exert a decisive influence on the course of the world, and suffering many geopolitical risks; fewer energy-intensive industries would augment dependencies and vulnerabilities, and weaken the economic, social and institutional environment; greater dependence on metals and refined metals would mean growing economic and geopolitical vulnerability; failure to master the equipment and building blocks of low-carbon technologies would translate into a trade deficit, a weak currency, a risk that the value chain comes under pressure, and probably a continued high level of dependence on hydrocarbons over the long term. In short, tax revenues would plummet, and imports would rise, as would both external and internal vulnerabilities,

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Nuclear power represents a huge challenge but also an historic opportunity, especially if the promise of small modular reactors materializes.

whereas instead we need to invest, protect, support, and rearm across the board, both in terms of depth and breadth. Yet, Europe has failed to master solar industry on a large scale, there are worrying signs that European domination of offshore wind power is faltering in the face of the overwhelming presence of Chinese equipment, hydrogen is far from being brought up to scale under the European flag, key links in the electric mobility value chains have not been mastered, and China has taken an overall lead, and all the more so with the transition to scale production. The loss of competence in nuclear power is concerning, and the advances made by the Russians and Chinese in fourth-generation nuclear power, and by the Americans in small nuclear reactors, are well documented. The USA and others are also devoting increasing resources to direct CO₂ capture and geoengineering technologies, CCUS, and fusion, while taking full advantage of their abundant hydrocarbon resources, which offer strategic economic and fiscal advantages.

Two key factors need full consideration. Firstly, China has acquired a significant, if not decisive, lead in many low-carbon and digital technologies, and secondly, the United States is deploying its Inflation Reduction Act and other

programs to try to catch up technologically and industrially and become self-sufficient. Europe now has some of the highest energy costs vis-à-vis the OECD countries, and is the big loser in the current polycrisis wave, which is only intensifying and looks set to persist. Europe is facing an environment of existential threats, one that calls for an unprecedented response in terms of mobilization and forward intent. We need to build on our strengths, which must be consolidated instead of being neglected. In the electricity and electrification sector, which is the backbone of decarbonization, nuclear power is unquestionably a key element, as are renewable energies.

Nuclear power represents an historic opportunity for Europe

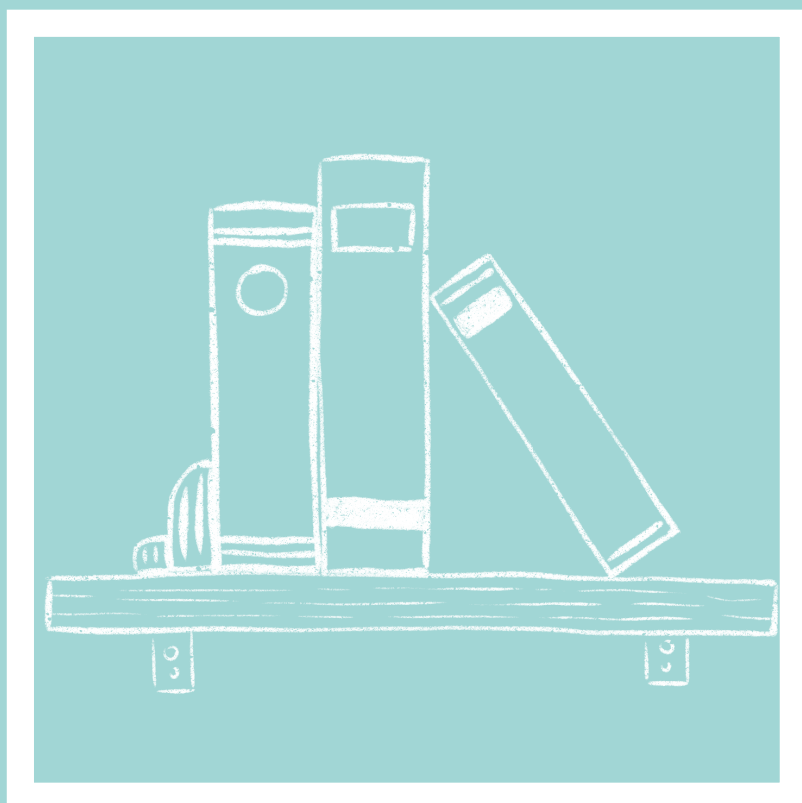
Europe can't allow itself to rush into an electricity system where the bulk of production capacity is intermittent, and where supply can no longer handle peak demand periods, unless we carve out a major role for long term gas (inevitably imported and a carbon emitting source), and secure massive investments in gas-fired power plants. Nor can Europe hope to achieve its renewable energy targets and guarantee its electrical and economic security by 2030 under the current set of circumstances, by pursuing policies that were formulated before this polycrisis era. These co-occurring crises are creating a new, game-changing environment that will further restrict Europe's ability to meet its targets. The IPCC's work shows that in the short term, if we are to have any hope of saving the planet from runaway warming, then we need to limit fugitive methane emissions, invest massively in wind and solar power, and reduce coal. In the long term, we need to include nuclear power, which represents a huge challenge but also an historic opportunity, especially if the promise of small modular reactors materializes.

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For France and the other European countries now mobilizing around the civil nuclear challenge, this means leading the charge for know-how and the appropriate industrial tools, securing a supportive standardized regulatory framework that enables financing for this type of highly capital-intensive equipment, and leading the way on electricity network grids and storage, and low-carbon hydrogen sources. While some in Europe are voicing their scepticism and opposition to this nuclear position, it is nonetheless a key lever if we are hoping to win the battle for electricity and electrification, and more generally, for low-carbon technologies, all of which are facing challenges and are individually unable to meet energy demands. Complementarity of low-carbon production tools should be sought in an optimized system to guarantee both energy and economic security, and we need to move away from the illusion of the all-nuclear versus the all-renewables scenario. This battle must now be waged on all electricity fronts right across Europe, without equivocation or exclusion, thus including renewable energies, hydroelectricity, networks, power electronics equipment, storage systems, metals, recycling... and civil nuclear power. This is essential for decarbonization, and for preserving France and Europe's already fragile industrial fabric, across the automotive, steel and petrochemicals sectors. In addition to the risk of

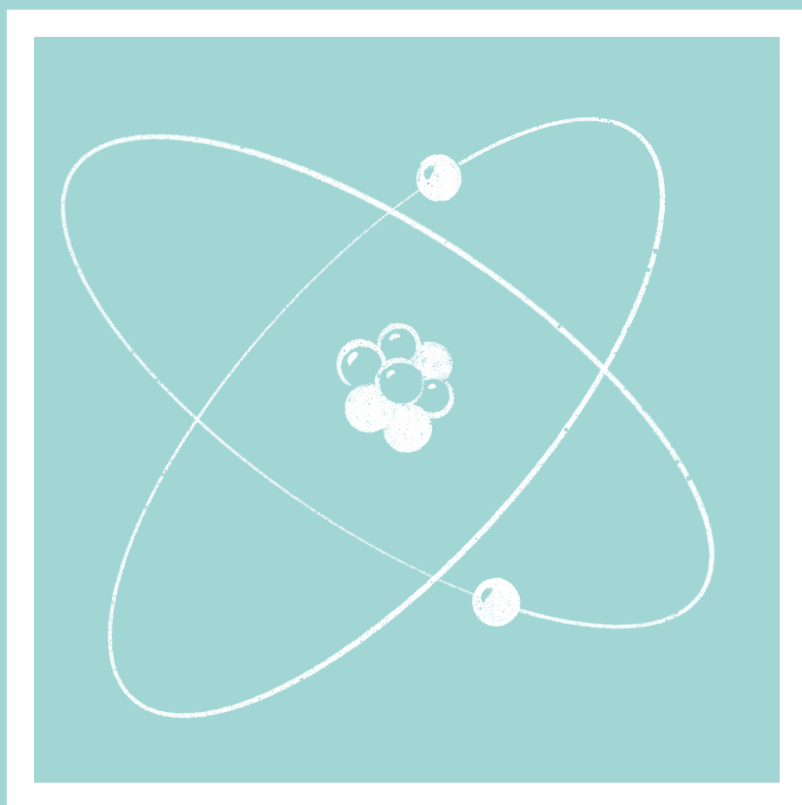
external fragmentation. Although Russian and Chinese competitors are now being squeezed out of European markets, the United States is waging an aggressive and effective campaign to position its technologies and fuels in Europe, and to harmonize regulations to facilitate the mass deployment of its modular reactors. South Korea is doing likewise, albeit to a lesser degree. Although Europe is already replacing its Russian hydrocarbon purchases with North American substitutes, along with hydrogen in the future, and is adding nuclear and CO2 storage and capture technologies, as well as ongoing arms purchases, Europe's economic security will be undermined, and inevitably so will European integration. Both France and Europe's strategic marginalization will accelerate. If Europeans do not do more to coordinate, structure and support their national nuclear industries together, just as all the major established and emerging powers have been doing in other sectors, particularly in terms of finance, then clearly European players will progressively relinquish control of the value chains. General energy supply security will progressively diminish. This also means overcoming the aftermath of Brexit and rebuilding bridges with the UK, a common-sense ally and partner with which European ties are fundamental. King Charles III's call to form a new entente cordiale must be seized. These are all issues that will need to be addressed responsibly by calm rational minds in the run-up to the European elections in June 2024, as will the next multi-year energy plan, to which this study makes a most useful contribution. Nuclear power represents a huge challenge but also an historic opportunity, especially if the promise of small modular reactors materializes.

Complementarity of low-carbon production tools should be sought in an optimized system.



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Editorial

Nuclear power is making comeback-and in a strong fashion,” announced the Director General of the International Energy Agency (IEA), Fatih Birol, at the COP27¹ event in November 2022. Amid the global climate and energy crises, he noted that “countries around the world are showing renewed interest in nuclear power, including countries that previously had sought to phase out the technology. Driving this change is not only the need for low-carbon energy, but secure and reliable energy. Nuclear power provides both.”

Although the war in Ukraine, and in particular the Zaporizhia nuclear facility, has put nuclear safety front and center at the international level, it seems that at the end of 2021 nuclear energy had already embarked on a ‘revival’ phase. As we shall see in this report, nuclear energy is benefiting from renewed public support in many countries. Furthermore, week after week nuclear projects are being announced across the globe whether they be restarting or extending the operations of existing reactors, constructing new reactors, or developing small modular reactors based on both current (SMR) and advanced (AMR) technologies.

Today, this revival is aspirational and in order to move it to a reality, both governments and the nuclear industry will have to meet a number of challenges. Firstly, they must demonstrate the capability for successful series production of the latest generation of nuclear reactors, both on time and on budget, and as part of scheduled industrial programs.

Secondly, they must show they can innovate in particular through small advanced reactors, to make access to nuclear power easier for new entrants and, going beyond electricity production, enable new decarbonized uses, such as urban district heating, industrial heating and low-carbon hydrogen production. Finally, they have to demonstrate that they can put financial schemes in place to raise the capital needed to finance new infrastructures, and at rates that guarantee the competitiveness of tomorrow's electric power system.

The purpose of this report, Sfen's new reference tool, is to regularly evaluate the progress being made by governments and the nuclear industry in various regions of the world. This document is intended to be updated annually, knowing that all the while the Sfen, through the daily publication of articles in the *Revue Générale Nucléaire* (RGN), continues its ongoing analysis of the international news throughout the year. The focus in this inaugural report will remain primarily on nuclear reactors, although many other topics are also calling for analysis and they will be explored in turn going forward, key among which is the question of the nuclear fuel cycle.

Valérie FAUDON,
Executive Director of the French Nuclear Society (SFEN)

¹ AIEA – “Nuclear is making a strong comeback,” IEA’s Birol Tells IAEA Director General Grossi at IAEA COP27 Event – November 2022



Synopsis for the decision-makers

1 Nuclear power plays a significant role in decarbonizing the global electricity mix.

By 2022, nuclear power was the second-largest source of low-carbon electricity in the world, and the largest in the European Union. Major institutions' decarbonization scenarios show that in addition to solar and wind energy, nuclear power will have to make a greater contribution, doubling or even tripling output by 2050. After delays hampered the initial suite of projects, the construction of third-generation reactors is now reaching maturity in countries such as China, which have embarked on industrial programs that include series production builds.

2 Several signs of a nuclear power revival are evident worldwide, and nations are witnessing increasing public support for nuclear power.

A global Ipsos study shows that in 2022 support for nuclear energy rose 7 percentage points overall. In Europe support rose by 11 points and in Germany it rose by 15 points. This means that governments can realistically launch their programs. Numerous decisions have been announced to extend the operation of existing reactors, even up to 80 years in the United States. Several countries, such as Belgium, have reversed initial decisions to shut down reactors. In May 2023, 15 European countries gathered

together as part of the 'Nuclear Alliance,' and announced a target of 150 GW of electricity capacity by 2050, which means the equivalent of between 30 to 45 new-build reactors. Lastly, and just as with the space industry, nuclear power is riding a wave of unprecedented innovation, with over 70 leading-edge small reactor concepts in design-stage worldwide.

3 On top of existing industrial capacity for new installations, fresh schemes will have to be put in place.

The war in Ukraine has revealed links that certain countries have with Russia in the fuel manufacturing chain. This is indeed the situation for Eastern Europe (Russian technology reactors) and the United States (uranium enrichment). It should also be noted that the cost of producing nuclear energy, with its high proportion of fixed costs, is highly sensitive to the cost of financing the installations. While Russia has traditionally offered, and the US is currently offering, bilateral aid, greater support for nuclear power is needed within multilateral institutional taxonomy frameworks and portfolios. Finally, and going further than electricity, countries have to accelerate their experimental use of nuclear energy for urban district heating (China), industrial heating (USA), and low-carbon hydrogen production (UK).



Introduction

Nuclear energy can help make the energy sector's journey away from unabated fossil fuels faster and more secure,"² stated the International Energy Agency (IEA)³ in mid-2022. While solar and wind power are both set to participate even more greatly in terms of global decarbonization, the agency points out that they will need to be supplemented by predictable and controllable low-carbon energies (hydro, nuclear, CCUS) with flexibility capacity (storage).

The main question for the future is if the contribution from this new wave of nuclear power will be able to meet expectations.

This report provides an overview of the current state of nuclear power worldwide, the most up to date information available on its revival, and the challenges facing governments and the industry if this renaissance is to succeed. The report is based exclusively on publicly available sources, including international organization databases (IAEA, OECD-NEA) and observations by the Sfen and French embassy-based nuclear advisors, using government sources.

Acknowledgements

The Sfen thanks Gaïc Le Gros, who headed up this project. Appreciation is also due to the embassy-based nuclear advisors for their invaluable proofreading and suggestions. We express our gratitude to Marc-Antoine Eyl-Mazzega of the Institut français des relations internationales (Ifri - French Institute of International Relations) for kindly agreeing to write the preface for this report, and we also extend our appreciation to our readers: we look forward to receiving your feedback as well as your suggestions for the 2024 edition. Please do not hesitate to contact us: sfen@sfen.org.

2. Nuclear energy can help make the energy sector's journey away from unabated fossil fuels faster and more secure , A new dawn for nuclear energy? - June 2022.

3. From the report: Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems - June 2022.

Lessons learned



Lessons learned

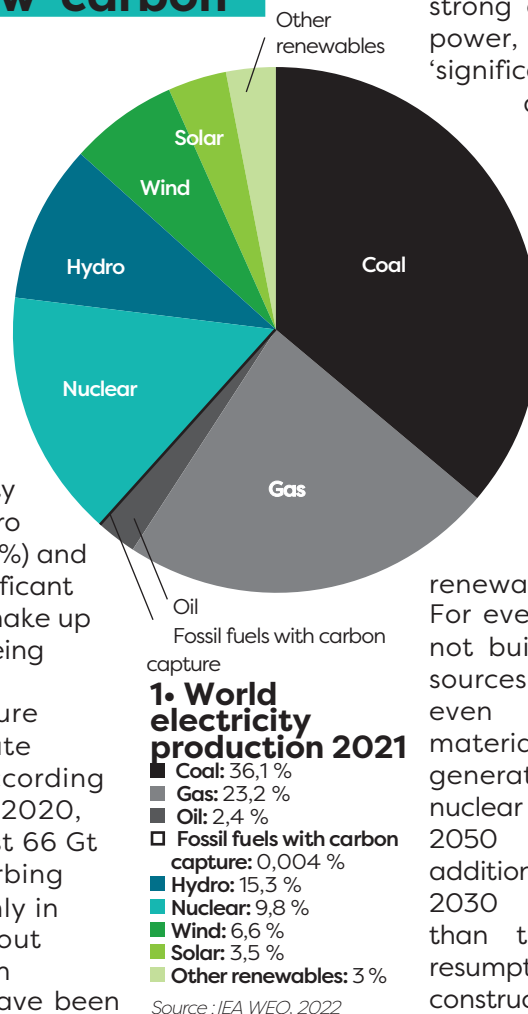
1 An important part of the global low-carbon mix

1.1 The world's second-largest source of low-carbon electricity

According to the International Energy Agency (IEA), in 2021 nuclear power, with more than 400 reactors operating in over 30 countries, was the world's second-largest source of low-carbon electricity. Nuclear accounted for 9.8% of electricity production, second behind hydro (15.3%), and ahead of wind (6.6%) and solar (3.5%). Coal and gas, significant greenhouse gas emitters, still make up more than 60% of electricity being generated (Figure 1). Nuclear power's past and future contribution to tackling climate change is well recognized. According to the IEA, between 1971 and 2020, nuclear power avoided almost 66 Gt of CO₂ emissions, thereby curbing the growth in emissions, mainly in industrialized countries. Without nuclear power, emissions from electricity generation would have been 40% higher in Europe and 25% higher in the United States. In Europe in 2022, nuclear power was the leading source of low-carbon electricity, ahead of wind power. Including the UK and Switzerland, Europe represents the world's leading nuclear power bloc, with 116 nuclear reactors operating in 15 countries.

1.2 Nuclear's expected contribution

The IEA's 2050 Net Zero Emissions (NZE) scenario predicts electricity production to rise by a factor of between 2.5 and 3, meaning that electricity would account for 50% of



final consumption in 2050 compared with 20% today. Against a backdrop of strong growth in both solar and wind power, nuclear power will play a 'significant role' in securing the

decarbonization pathway out to 2050. In the 2023 'NZE by 2050' scenario, nuclear power generation more than doubles from 2,700 TWh in 2022 to 6,000 TWh in 2050.

Without this contribution from nuclear power, the IEA indicates that achieving carbon neutrality would be both more difficult and more expensive and would mean exceeding technological limits for integrating intermittent

renewables in a real significant way. For every GW of nuclear power that is not built, 3.5 GW from other energy sources will need to be built involving even greater use of critical materials for both power generation and networks.⁷ Doubling nuclear capacity between now and 2050 corresponds to a net addition rate of 35 GW/year from 2030 onwards, which is higher than the current rate, despite the resumption of new reactor construction in recent years (58 reactors were under construction worldwide in mid-2023). Decisions need to be taken now.

In its 2018 Special Report on 1.5, the IPCC modelled 90 pathways consistent with limiting global warming to 1.5°C. Most of the scenarios included growth in nuclear power, with an average capacity of 1,160 GW by 2050, i.e., a tripling of production capacity.

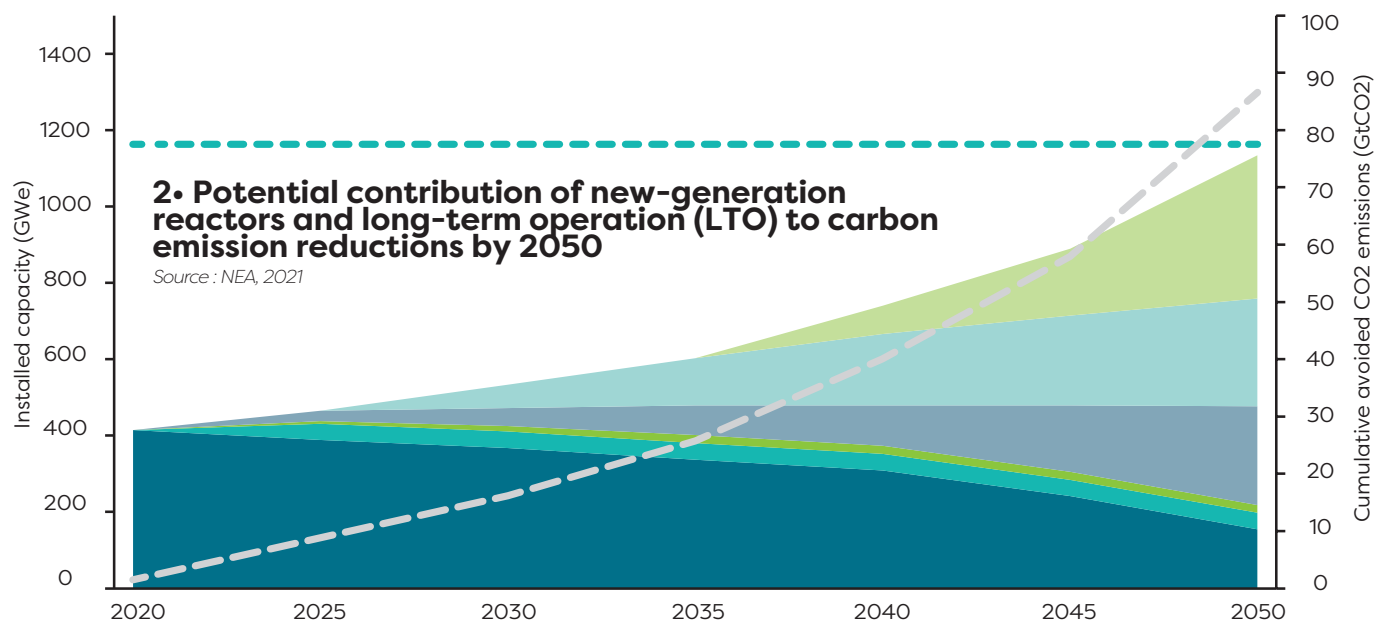
4. IEA – World Energy Outlook .

5. IEA – Ibid.

6. Eurostat.

7. IEA – Nuclear Power and Secure Energy Transitions – June 2022.

Lessons learned



— Cumulative emissions avoided
— IPCC scenarios at 1.5°C (average in 2050) = 1,160 GW of nuclear capacity

Current outlook

- Small modular reactors (market outlook in 2035)
- Large new-generation reactors (under construction)
- Long-term operations (planned)

Aims

- Small modular reactors (extrapolating market cost)
- Large new-generation reactors (planned)
- Long-term operations (to 80 years)

The OECD's Nuclear Energy Agency (NEA) study in 2022 (Figure 2) examined how this ambition could be achieved by combining capacity potential from the extension of existing reactors, the construction of new high, small, and medium-power reactors, as well as advanced reactors that can also lower emissions via other vectors such as hydrogen and heat. With this type of pathway, nuclear power contributes close to 90 Gt of avoided CO₂ between 2020 and 2050.

1.3. The construction of new-generation reactors is reaching maturity

In the 1980s both France and Sweden deployed ambitious industrial programs that demonstrated their prowess at series production and their ability to decarbonize their power systems in less than two decades..

The first EPR projects in Europe (Olkiluoto-3 in Finland and Flamanville-3 in France) and Westinghouse's AP1000s in the United States (Vogtle-3 and 4) however experienced major delays. These missed deadlines can be explained first and foremost by the decision to develop a new generation of reactors (the 'third generation')

with enhanced safety features. They are also the result of a loss in industrial competence, in so far as the West had not built any new reactors for many years.

However, several examples recently show that the rapid deployment of large, latest-generation reactors is indeed possible. The United Arab Emirates (UAE), in partnership with South Korea, built four nuclear reactors in Barakah between 2012 and 2023 with a total capacity of 5.6 GW, capable of independently supplying 25% of the country's electricity. China, with over 20 reactors having been commissioned in the last five years, has a fully comprehensive and operational industrial chain, as well as a planning process that guarantees its manufacturers' benefit from ongoing predictability and business. Its first domestic-technology Hualong-One design reactor was commissioned after sixty-six months of construction (Fuqing-5). Most recent project announcements now forecast sixty months. The manufacturer, CNNC has also announced a simplified design version, the Hualong-Two, with the aim of reducing construction time to 48 months.

Lessons learned

2 Signs of a nuclear revival

2.1. Public support returning for nuclear power

An Ipsos survey (Figure 3) of over 20,000 people in 30 countries carried out for EDF in September 2022, reported 46% of respondents were in support of nuclear power as a means of generating electricity.

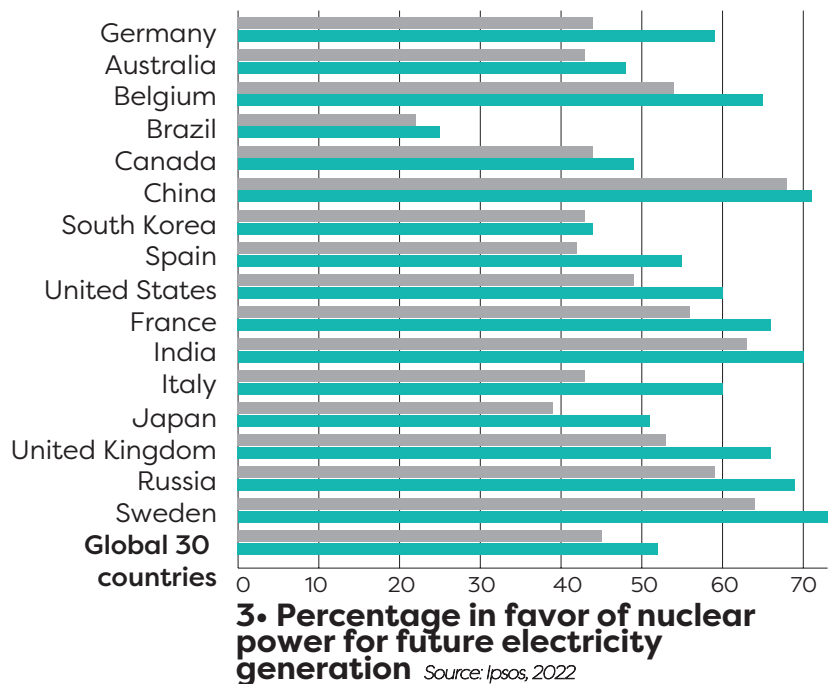
This represents a jump of 7 percentage points compared to 2021, and the increase was particularly marked across the European Continent, which has felt the brunt of the gas supply crisis and higher electricity prices. Support across Europe rose 11 percentage points on average, with traditionally anti-nuclear countries including Italy (+17), Germany (+15), and Spain (+13) showing the greatest percentage increases.

This renewed support is notable in so far as the respondents lack a full understanding of all aspects of nuclear power. While 66% of those surveyed ranked climate change and extreme weather events as the number one environmental problem, 57% still believed that nuclear power plants produce a lot, or a significant amount, of the CO₂ responsible for climate change.

2.2. Decisions in favor of long-term reactor operation

According to the OECD-NEA⁹, long-term reactor operation is both the quickest and most competitive way to generate electricity. Although safety authorities may require significant concomitant maintenance work (components replacement, new safety system installation), the initial construction costs will have already been largely amortized.

In the United States, where nuclear power accounts for more than half of low-carbon electricity, of the 93 units in operation, 78 already have



an operating license to run for up to 60 years, and 6 even have the authorization to run for up to 80 years. In Finland, two units have been licensed to operate for 70 years. In Switzerland, the 60-year threshold is not a legal limit and may even be exceeded. Japan has announced its intention to fast-track the restarting of its nuclear power plants. By September 2023, only 11 units out of 33 operable reactors had been restarted. Legislation has been adopted to extend the operating life of Japan's reactors to 60 years, in order to guarantee supply security and to meet climate targets.

Several countries that had been on course to close down their nuclear reactors have recently reversed their policy positions. In the USA, the Democratic governor of

Lessons learned

California¹⁰ reversed plans to close the Diablo Canyon nuclear power plant in 2022, and instead announced financial support for its long-term maintenance and operation. France, which in its annual energy program had scheduled the closure of 12 reactors by 2035, has also reversed its decision. EDF and the French Nuclear Safety Authority (ASN) are studying the possibility of operating reactors for up to 60 years, or perhaps even longer. In June 2023 the first 50-year operating license was granted to the Tricastin-1 power plant in southern France.

Belgium, which was in the process of shutting down its seven nuclear reactors by 2025, has overturned this plan and will instead extend the life of two units (Doel-4 and Tihange-3) by 10 years until 2035.

Germany, which is notably bucking this new trend proceeded to close its remaining operating reactors in April 2023, ignoring the recommendations of the International Energy Agency in the wake of the gas crisis, which was exacerbated by the invasion of Ukraine. In the summer of 2023, public debate on the question of restarting the closed power plants resumed at the initiative of the opposition CDU party, and then of the FDP, one of the government's ruling 'traffic light' coalition.

In France, EDF and the French Nuclear Safety Authority (ASN) have announced that they are studying the possibility of operating reactors for 60 years, or even longer.

2.3. Announcements of new build programs

In May 2023, 15 European Union countries¹¹ along with the United Kingdom, met within the Nuclear Alliance that France launched in February 2023, and set the ambitious target of developing a nuclear fleet of 150 GW in Europe by 2050, compared with 100 GW today. Their stated intention was “the construction of 30 to 45 new large reactors as well as the development of small modular reactors (SMR) in the EU.” France has announced its intention to launch the construction of six EPR reactors without delay, and to begin studies for the construction of eight additional units by 2050. It also plans to launch, around 2030, both the first Nuward-type flexible nuclear reactors designed for electricity and heat cogeneration and a prototype for an innovative AMR-type reactor as part of the France 2030 plan.

According to the IAEA, as of September 2023, 57 nuclear reactors are under construction worldwide, most of which are high pressure reactors. China alone accounts for more than a third of these reactors, as part of its domestic series construction program. Russia continues to deploy its export policy to new countries, and is reporting on the progress of its projects, in particular on its four units in each of Turkey and Egypt.

2023 has seen several governments make fresh policy announcements including Poland and the Netherlands, which, against all expectations, are relaunching new reactor construction projects. Several announcements feature small reactors, for instance the United States and Estonia (a first-time nuclear power adopter). Many nations have also announced high-pressure power reactors (e.g. Bulgaria).

¹⁰• California Governor – Governor Newsom Statement on Federal Funding for Diablo Canyon Extension – November 2022

¹¹• Belgium, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Hungary, Netherlands, Poland, Romania, Slovenia, Slovakia, Sweden, United Kingdom as invitee and Italy as observer.

Lessons learned

Canada is planning to build large reactors and small reactors more suited to isolated areas such as in Saskatchewan province. Ontario-based Bruce Power, Canada's only private sector nuclear generator announced plans to build 4.8 GW¹² of new nuclear capacity.

2.4. A global wave of innovation in the nuclear industry

Just as the space industry has been riding a wave of innovation for the past fifteen years, the nuclear industry is now enjoying similar momentum linked to the development of small modular reactors (SMRs), advanced technologies (AMRs), 'fourth-generation' fission reactors, and even fusion reactors. By 2022, the IAEA had counted over 70 different design concepts worldwide. Governments are supporting this new growth trend.

For example, the US Department of Energy's (DoE) annual budget for nuclear research and development amounts to roughly \$1.7 billion for 2021, 2022, and 2023, and is targeting support for approximately ten projects.

The Chinese authorities are also supporting several projects, across all technologies. For instance in 2021 they announced the commissioning of their first high-temperature reactor. In 2017 and in 2020 they launched the construction of two fast-neutron reactors, and in 2023 they granted an operating license for an experimental molten-salt reactor.

France, as part of the 'France 2030 Investment Plan' launched a call for projects for innovative reactors worth a total of €500 million. The number of respondents exceeded initial expectations, with nearly fifteen start-ups coming forward.

Just as the space industry has been riding a wave of innovation for the past fifteen years, the nuclear industry is now enjoying similar momentum.

In June 2023 the first two winners of Phase 1 of the project were announced: Naarea and Newcleo. Although the European agency Euratom is currently not very active in supporting fission reactor research, start-ups are nonetheless emerging in European countries, such as Thorizon in the Netherlands, and Seaborg in Denmark¹³, a country that does not currently operate any nuclear reactor units.

Finally, the Fusion Industry Association's (FIA)¹⁴ third annual report notes that 2022 proved to be a record year in the world of nuclear fusion¹⁵ with \$6.1 billion in investment funding. The investment base is progressively widening. The FIA report surveyed 43 private companies specializing in fusion, compared with just 27 the previous year.

12• Bruce Power – Ontario government supports long-term planning and consultation work to explore the expansion of clean nuclear at Bruce Power – September 2023.

13• RGN – Barge nucléaire : le Danois Seaborg s'allie avec des constructeurs – Avril 2023/ RGN – Nuclear barge: Denmark's Seaborg teams up with builders – April 2023.

14• Fusion Industry Association – Global Fusion Industry Report – 2023.

15• RGN – « Nouveau record d'investissement dans la fusion nucléaire en 2022 » – Août 2023/ RGN – "New record for investment in nuclear fusion in 2022" – August 2023.

Lessons learned

3 Fresh approaches

The main challenge for the nuclear industry going forward will be turning this revival into a reality. The West in particular must regain the level of industrial capacity appropriate for series production. Furthermore, the events of 2023 have highlighted the need for new approaches in at least three areas: fuel geopolitics, project financing, and new uses for nuclear power.

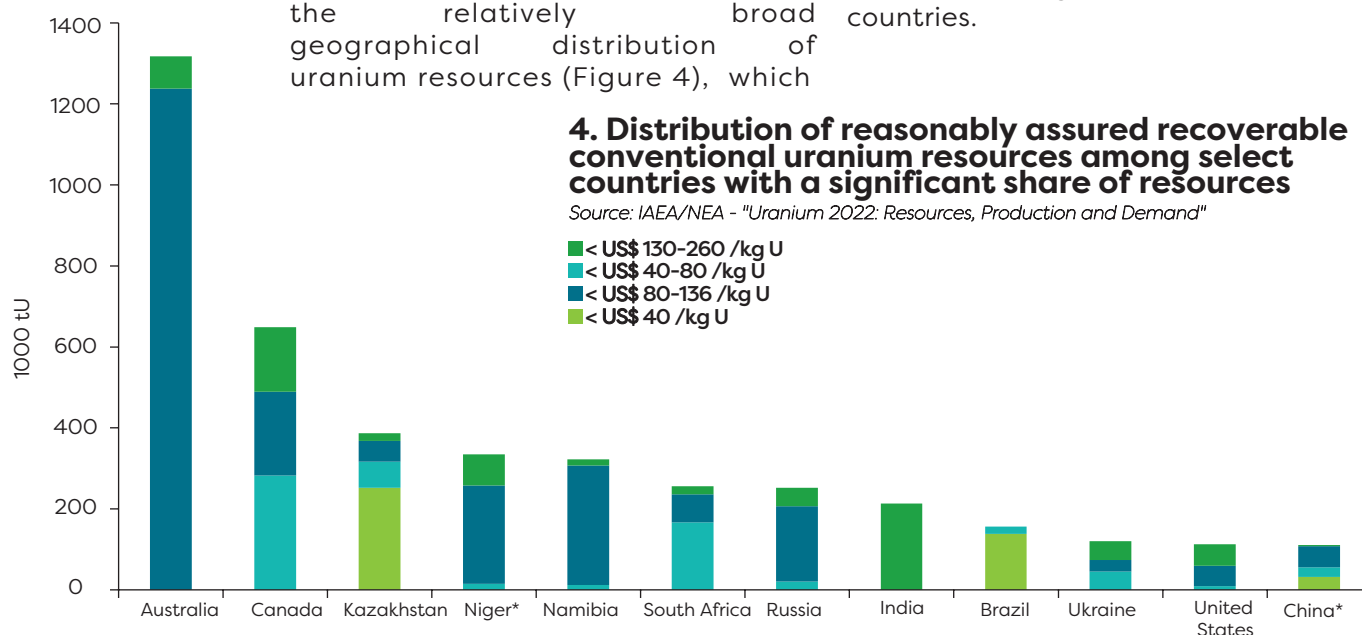
3.1. The geopolitics of fuel

Many countries, including France, have invested in nuclear power to protect their economies from fluctuations in world energy markets. One of the great advantages of nuclear is that only 5% of the cost of producing this form of electricity depends on the price of uranium. In 2022, France imported €115 billion worth of oil and gas. In contrast, the value of French power plant-related uranium imports amounted to less than €1 billion. Another advantage is the relatively broad geographical distribution of uranium resources (Figure 4), which

facilitates supply. Lastly, given uranium has such a high energy density, operators can manage large stockpiles, thus securing protection from sudden supply disruptions. France's stockpile corresponds to ten years' production.¹⁷

Since 2022, the crisis in Ukraine has shown that several countries are dealing with a number of dependencies across the entire fuel cycle. Although Russia accounted for only a small percentage of global uranium production, its market share in uranium chemical conversion and enrichment was significant, particularly vis-a-vis the United States. Russia also manufactures fuel assemblies for VVER power plants operating in Eastern Europe.

France has the facilities needed to convert and enrich its natural uranium stocks (with the exception of reprocessed uranium) as well as manufacture fuel for its own power plants. Various action plans are currently being launched in many countries.



* NEA Secretariat estimate or partial estimate.

16. Le chiffre du commerce extérieur - « Synthèse annuelle : les résultats annuels 2022 » 'Annual summary: annual results 2022'

17. Orano - Includes inventories of natural and depleted uranium

Lessons learned

Eastern European countries such as the Czech Republic and Bulgaria have announced new agreements with Westinghouse (U.S.) and Framatome (France). The United States has launched initiatives to stop importing enriched uranium from Russia and to break its dependence on Russia's Haleu (enriched uranium) monopoly. In France, Orano has announced the continuation of its project to extend the capacity of its Georges Besse-2 enrichment plant at Tricastin so as to offer its Western customers a non-Russian substitute. Orano's Board of Directors will have to approve the project by the end of 2023.

Finally, in April 2023, five G7 nations (Canada, France, Japan, United Kingdom, United States) gathered on the margins of the G7 Climate meeting and agreed to strengthen cooperation on nuclear fuel for current and future reactors. As far as global uranium supplies are concerned, the global recovery is not posing any constraints.

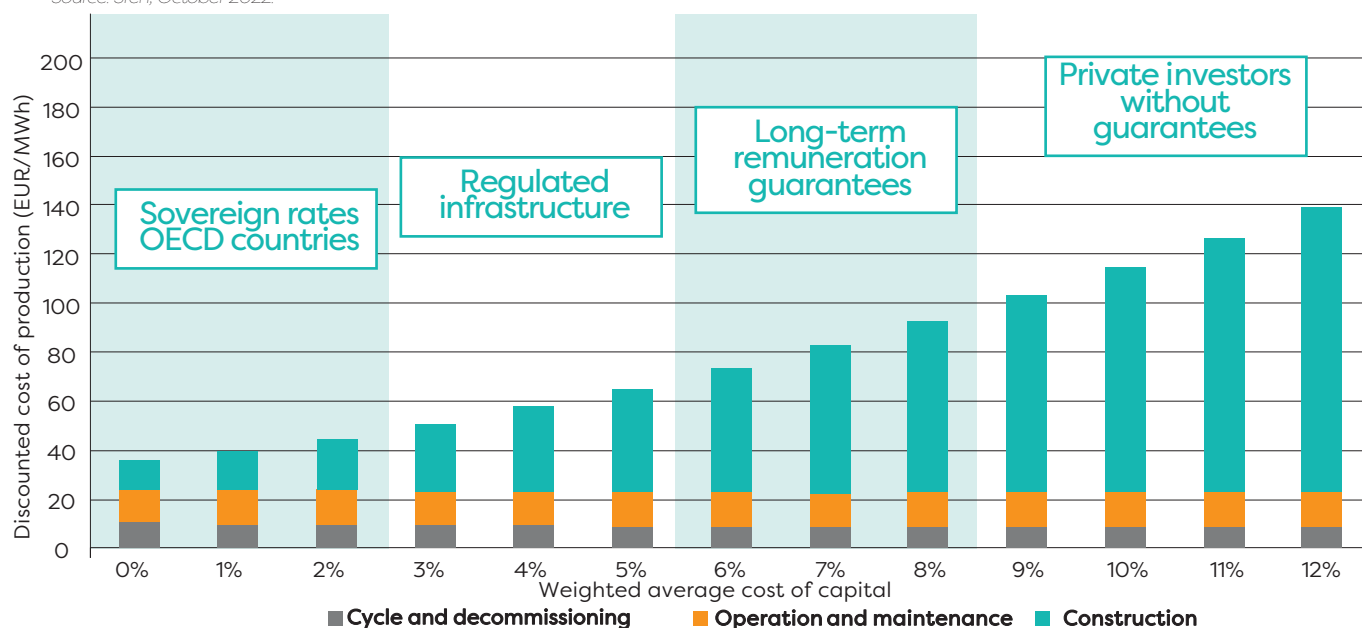
The latest World Nuclear Association (WNA)¹⁸ report indicates that the mining industry is in a position to supply reactors consistently over the long term, even under their most ambitious scenario (threefold increase in demand by 2040). Medium-term supply, however, requires mining facilities to come on stream quickly in order to compensate for the drop in production from 2030 onwards.

3.2. Financing issues

Beyond being capital-intensive, nuclear projects are also specific in terms of their size and duration. They require a substantial initial investment, with high financial costs throughout the construction period, and they do not provide a return on investment for five to ten years. The Sfen (Figure 5) shows¹⁹ that the cost of producing electricity is extremely sensitive to the project's expected internal rate of return.

5. Cost of electricity generation according to financing cost

Source: Sfen, October 2022



¹⁸ WNA - Nuclear Fuel Report 2023 - September 2023

¹⁹ Sfen - « Comment financer le renouvellement du parc nucléaire ? » - Octobre 2021/Sfen - Financing France's New Nuclear Build - October 2021

Lessons learned

For example, the cost per kilowatt-hour at Hinkley Point C (UK) doubles when the internal rate of return rises from 3% to 10% (a value close to the rate used by EDF for the project).

Russia has traditionally supported its export projects with bilateral financing solutions. With the Paks project in Hungary, for example, Russia offered Hungary an 'interstate loan' at 3% (sovereign rate). In recent months the US has also been developing bilateral financing offers, particularly in Poland and Ukraine, and in so doing supporting American technologies. At the COP27 event in Egypt in 2022, the US announced its Phoenix financing program, which aims to promote nuclear energy and SMRs in particular. The question of nuclear power's inclusion in the new taxonomies for clean investments has generated debate across the European Union. Although Europe's scientific body, the Joint Research Center (JRC), had validated nuclear power as meeting the taxonomy's clean investment criteria, it only classified nuclear as a transitional energy.

Discussions in Brussels are now focusing on the strategic status of nuclear power within the EU's Green Deal related Net-Zero Industry Act (NZIA) program, which is designed to support activities that will help achieve carbon neutrality by 2050. It should be noted that the United States has included nuclear power as a low-carbon energy source that can accordingly benefit from the Inflation Reduction Act (IRA).

3.3. New uses: electricity and more

While electricity is an essential vector for decarbonizing the economy, other vectors, such as low-carbon heat and hydrogen, will also be needed to replace fossil fuels in industry, construction, and transport. Numerous pilots and trials are underway around the world to enable nuclear power to contribute to decarbonization processes beyond those linked to electricity.

Cogeneration, i.e. the simultaneous production of low-carbon heat and electricity, is already a proven solution for supplying urban heating networks. According to the IAEA, 43 nuclear reactors worldwide are currently supplying urban heating networks, most of them in Eastern Europe and Russia. Closer to home, the Beznau power plant in Switzerland has been supplying heat to 20,000 people since 1983.²⁰ China is now stepping things up, and in late 2020²¹ launched a large-scale low-carbon heat supply service in the coastal city of Haiyang, using AP1000 reactors. This project is to accommodate a 23 km extension pipeline that will serve one million inhabitants, and will eliminate 1.65 Mt of annual CO₂ emissions by replacing the current suite of coal-fired power boilers.

In addition to electricity, other vectors, such as low-carbon heat and hydrogen, will be needed to replace fossil fuels in industry, construction, and transport.

20• IAEA – « Au-delà de la production d'électricité : l'électronucléaire au service des applications non électriques »/ IAEA – Beyond electrical power generation: nuclear power for non-electrical applications

21• WNN – China starts building long-distance nuclear heating pipeline – February 2023.

Lessons learned

New advanced nuclear technologies are also aiming to produce heat at the high temperatures (above 500°C) that are needed to decarbonize a number of industrial processes. China started up the first high-temperature reactor at the end of 2021, and US chemical company Dow Chemical has announced an agreement with X-energy to build four Xe-100 high-temperature reactor demonstrators, the first of which will be at its Seadrift industrial site in Texas.²²

Nuclear power can contribute to low-carbon hydrogen production targets by powering low and high-temperature electrolyzers, either on site or via the electricity transmission grid. In March 2023 in the United States, the first nuclear power plant, Nine Mile Point (Constellation)²³ in New York State, began producing low-carbon hydrogen as part of a federal program using an on-site low-temperature electrolyzer. In the UK, a consortium led by EDF received funding from the UK government in September 2023²⁴ to develop low-carbon hydrogen production for asphalt and cement production at the Heysham-2 power plant, using high-temperature electrolyzers coupled to reactors in cogeneration mode.



Nuclear power can contribute to low-carbon hydrogen production targets by powering low- and high-temperature electrolyzers.

Lastly, the use of nuclear energy to desalinate water is also a proven technology²⁵. In Japan, several desalination plants connected to nuclear reactors produce around 14,000 m³ of drinking water per day. The Madras nuclear power plant²⁶ in India is home to a desalination plant that produces 6.3 million litres of fresh water per day. By way of a hybrid thermal and reverse osmosis technology, the plant uses seawater and heat generated by the power plant.

22• Energy Intelligence – "United States: Dow's decarbonization ambitions via X-energy's SMR" – July 2023.

23• Office of Nuclear Energy – Nine Mile Point begins clean hydrogen production – March 2023.

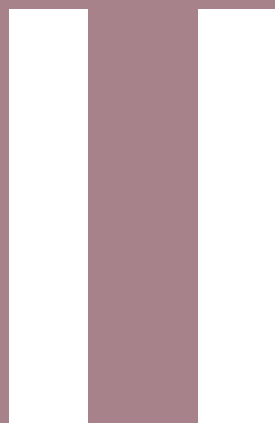
24• WNN – "More funding to progress UK nuclear-generated hydrogen project" – September 2023.

25• AIEA – Ibid.

26• The Hindu – "Hybrid desalination plant at Kalpakkam" – December 2012.

Geographical

Focus



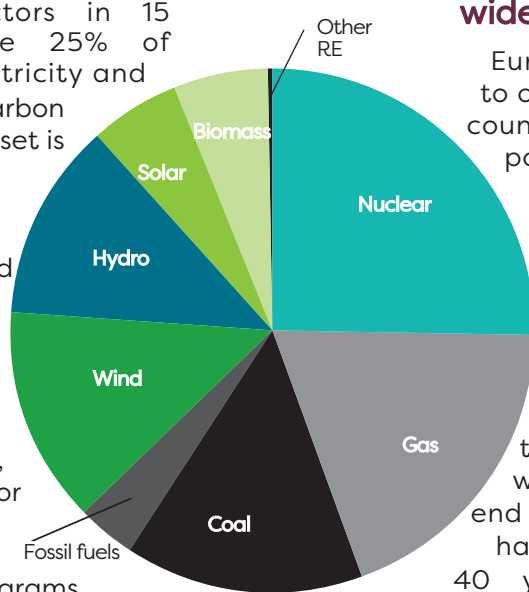
Geographical focus

Europe

1

Europe: a nuclear power relaunch

For Europe,²⁷ nuclear power is a low-carbon foundation stone. 116 nuclear reactors in 15 countries generate 25% of the continent's electricity and account for 50% of its low-carbon electricity production. This asset is a legacy of the Hydro period spanning the 1970s-1990s. Since then, new reactor construction has been limited to a handful of projects. However, the atom Wind is now making its comeback on the European stage, in two main ways. Firstly, long term reactor operation (LTO), i.e. operating a reactor unit for more than 40 years, is being generalized. Secondly, real new reactor construction programs are being planned. On 28 February 2023, fifteen European Union countries (Belgium, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Hungary, Italy, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden²⁸) created the 'Nuclear Alliance' in a bid to strengthen cooperation in this field.



6. Electricity mix in Europe 2021

■ Nuclear: 25.4
 ■ Gas: 19
 ■ Coal: 14.5
 ■ Fossil fuels (other): 3.6
 ■ Wind: 13.4
 ■ Hydro: 12
 ■ Biomass: 5.8
 ■ Solar: 5.6
 ■ Other RE: 0.2
 Source : Eurostat

1.1. Reactor operation beyond 40 years is becoming widespread

European nuclear reactors continue to operate beyond 40 years, even in countries that do not support nuclear power. Belgium is one such case; it has postponed its nuclear phase-out by 10 years by extending the operating life of two reactors (Doel-4 and Tihange-3) to 50 years. Finland has also announced that it will operate two reactors at Loviisa until 2050 meaning their ultimate operating lifespans will be 70 years. In France, by the end of 2023, 25 of its 56 reactors will have been operating for more than 40 years. While French operating authorizations are granted on a ten-yearly basis, i.e. for shorter periods than in Finland or in the United States, the French Nuclear Safety Authority (ASN) is already studying the feasibility of 60-year operating lifespans.

²⁷ The European Union, the United Kingdom and Switzerland.

²⁸ Italy and Belgium attended as observers.

1.2. Buoyant forecasts for new reactors

New reactor projects are multiplying in France, the UK, Hungary, the Czech Republic, Poland and Bulgaria, as well as in the Netherlands, Sweden, Finland, Slovenia and Slovakia.

Of these, three programs in particular stand out, namely in France, the UK, and Poland. In France, the aim is to build between six and fourteen EPR2s in order to maintain a significant nuclear power base. The UK is planning to start work on two EPRs at Sizewell in the east of the country, while two units are currently under construction at Hinkley Point C in the south-west. The UK authorities have set an ambitious target of reaching 24 GW of nuclear capacity by 2050, compared with 5.8 GW currently, and in spite of the fact that the country is facing into a shrinking nuclear fleet because the technological specificities of its current reactors mean they cannot operate for as long as pressurized water reactors.

Poland's challenge is to build the country's first reactors as part of a program involving 6 - 9 GW of nuclear power. Poland did not pursue the competitive route and instead selected the US firm Westinghouse in October 2022 for its first three units.

In March 2022, the Czech Republic launched a call for tenders to build a reactor at Dukovany. At the end of 2022, the Netherlands announced its intention to build two units by 2028. Hungary's project for two 1,200 MW Russian reactors (Paks2) received its construction permit at the end of August 2022. Bulgaria is also planning to build four units. Finally, Sweden launched an initiative in 2023 to end its old regulatory framework, which limited the number of reactors in the country to ten and excluded the possibility of opening new sites.

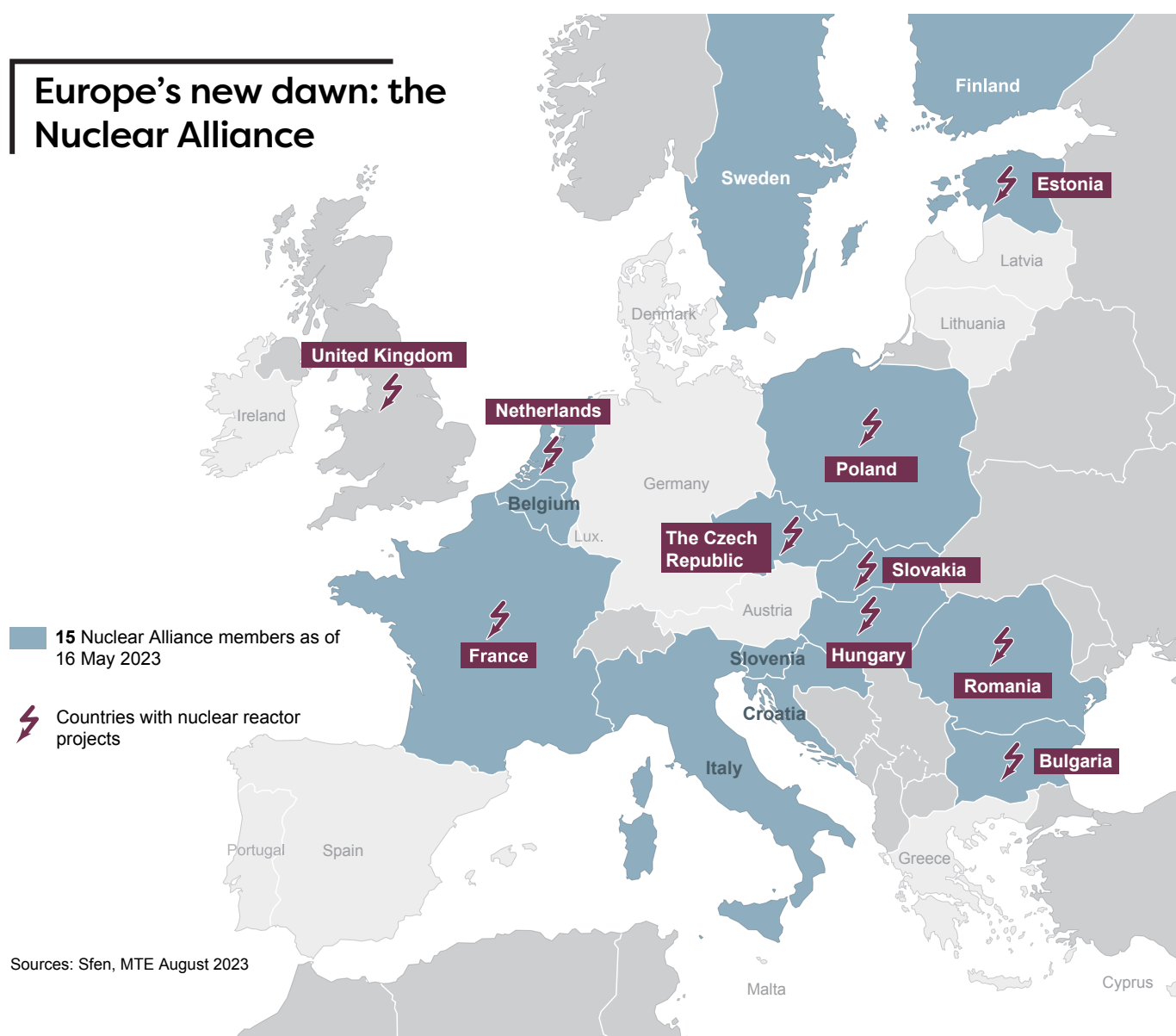
Furthermore, several other countries (Belgium, Estonia, Finland, Italy, Poland, the UK, etc.) are interested in small modular reactors (SMRs) and advanced reactors (AMRs), although it is too early to know which projects will come to fruition.

Key point: The Nuclear Alliance believes that nuclear power could provide the European Union with up to 150 GW of electrical capacity by 2050, compared with approximately 100 GW today.

Geographical focus

Europe

Europe's new dawn: the Nuclear Alliance

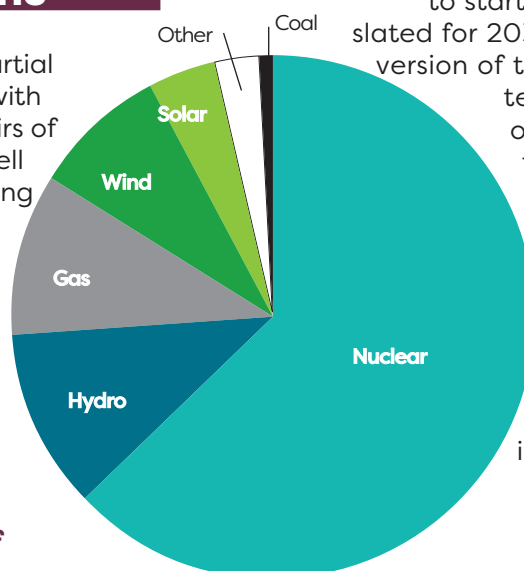


Geographical focus

France

2 France's four nuclear power programs

France is preparing for the partial renewal of its nuclear fleet with the construction of three pairs of EPR2 units (1,650 MW), as well as simultaneously encouraging the development of innovative reactors under the France 2030 investment plan. A total of €1 billion has been earmarked for disruptive technologies (AMR) and the Nuward SMR project. Sfen has identified close to fifteen new start-ups based in France.



option for eight additional units. Construction of the first unit is scheduled to start in 2028, with commissioning slated for 2035. The EPR2 is an optimized version of the earlier EPR, particularly in terms of construction. It draws on the experience learnt from the three EPR units in service in China (Taishan-1 and Taishan-2) and Finland (Olkiluoto-3), as well as from two units under construction in the UK at Hinkley Point C, and the Flamanville unit in France that is due to go into service in 2024. The sites selected for the EPR2 units are Penly, Gravelines and Bugey.

2.1. Long-term operation of reactors

Long-term operation, or LTO, refers to a period of operation beyond 40 years. The term is used especially in the United States, where a reactor is licensed for 40 years, and can be renewed in 20-year increments. In France, this 40-year concept carries less significance because the French Nuclear Safety Authority (ASN) authorizes reactors to operate in 10-year increments, with no time limit. To ensure that the established nuclear fleet, which accounts for between 60% and 70% of electricity production, continues to operate safely, EDF launched the 'Grand Carénage' (Great Refit) program in 2014. The Grand Carénage consists of refurbishing or replacing major components that are reaching the end of their technical lives, making the modifications needed to improve safety, and ensuring equipment continues to meet required standards beyond 40 years of operation. Grand Carénage inspections and works have been carried out on almost all the 900 MWe reactors, and are continuing on the 1300 MWe reactors.

7. 2022 Electricity mix

■ Nuclear: 63 %
 ■ Hydro: 11 %
 ■ Gas: 10 %
 ■ Coal: 0,6 %
 ■ Wind: 8,4 %
 ■ Solar: 4 %
 ■ Other: 3 %
 Source : RTE

2.3. The Nuward SMR

Nuward is a 340 MWe power plant comprising two 170 MWe pressurized water reactors. Unveiled in 2019, Nuward benefits from the expertise of the CEA (French Alternative Energies and Atomic Energy Commission), TechnicAtome, Naval Group, Framatome, and Tractebel. Since March 2023, Nuward's development has been in the hands of Nuward, itself a wholly owned subsidiary of EDF. Target markets for Nuward include the replacement of older coal, oil, and gas-fired power plants around the world, as well as providing new uses for nuclear power, also in France, including heat generation, desalination, and hydrogen production. The construction of an initial reference unit could be launched in France as early as 2030.

2.2. The EPR2 program

The EPR2 program involves the construction of six EPR2 reactors, with an

Key point: On 10 February 2022, French President Emmanuel Macron announced the construction of six EPR2 units and the launch of studies for an additional eight units.

Geographical focus

France

2.4. A plethora of innovative projects

The term "innovative reactors", or AMR (Advanced Modular Reactors), refers to a multitude of technologies that differ from the low water pressure reactors, which account for almost all the units currently in operation. These new innovative reactors can deliver major benefits in terms of nuclear materials management, safety, and competitiveness, including new uses such as urban or industrial heat

production, hydrogen, fresh water, etc. The France 2030 Plan's call for projects has led to the emergence of a large number of French, and even some transnational, players, which are presenting proposals for innovative reactors based on concepts explored in the past, but not at the time developed on an industrial scale, for lack of economic competitiveness vis-a-vis gas or coal.

A powerful nuclear industry

Sfen

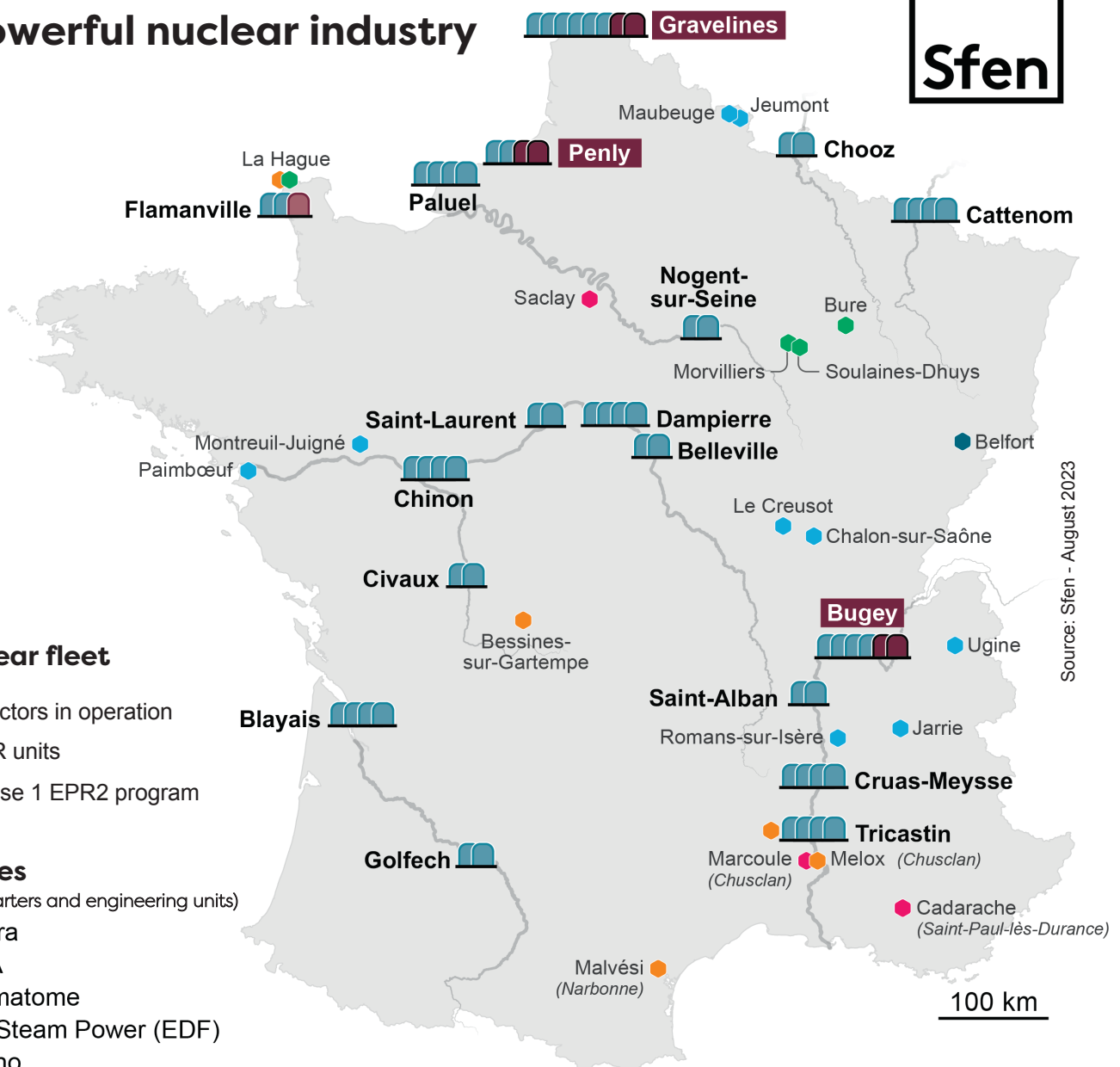
EDF nuclear fleet

-  Reactors in operation
-  EPR units
-  Phase 1 EPR2 program

Major sites

(excl. headquarters and engineering units)

-  Andra
-  CEA
-  Framatome
-  GE Steam Power (EDF)
-  Orano



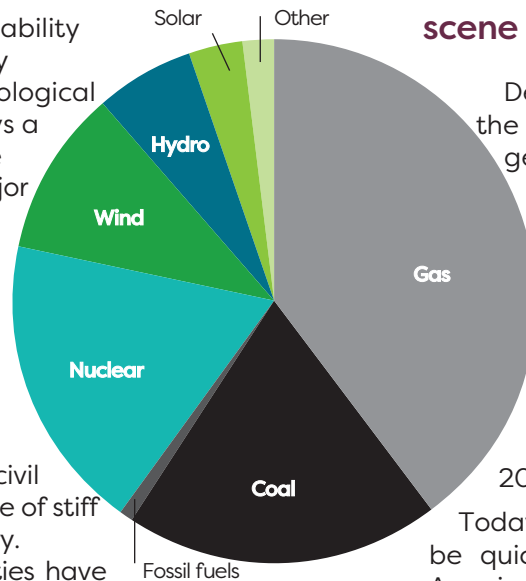
Source: Sfen - August 2023

Geographical focus

United States

3 United States: a superpower awakens

Complete nuclear capability continues to be a key component of technological sovereignty and plays a significant role in the geopolitical strategies of the major nations. Yet, 'America has lost its competitive global position as the world leader in nuclear energy to state-owned enterprises, notably Russia and China, [...],' stated the US Department of Energy (DoE) in April 2020.²⁹ This slippage is the result of underinvestment in the civil nuclear power industry in the face of stiff competition from the gas industry. To remedy this, federal authorities have rolled out an array of initiatives to revitalize the US industrial landscape as a whole, including public funding to support private sector R&D, closer cooperation between the private sector and national research laboratories, the development of a domestic fuel supply chain, reform of the nuclear regulatory framework, and tax-based incentives support for the current and future nuclear fleet. Furthermore, and on the back of this political will, the United States has made a real comeback on the export market with the



8. Electricity mix 2022

■ Gas: 39.8 %
 ■ Coal: 19.5 %
 ■ Fossil fuels (other): 0.9 %
 ■ Nuclear: 18.2 %
 ■ Wind: 10.2 %
 ■ Hydro: 6.2 %
 ■ Solar: 3.4 %
 ■ Other: 1.7 %
 Source : US EIA

Westinghouse third-generation reactor, the AP1000 (1,100 MW).

3.1. Back on the international scene

Despite several domestic setbacks, the outlook for Westinghouse's third-generation reactor seems brighter, as evidenced by the completion of the Vogtle project and a number of different countries showing serious interest in this reactor. As a reminder, in 2013, construction commenced for four AP1000 reactors, including two V.C. Summer units that were finally abandoned in 2017 when Westinghouse collapsed.

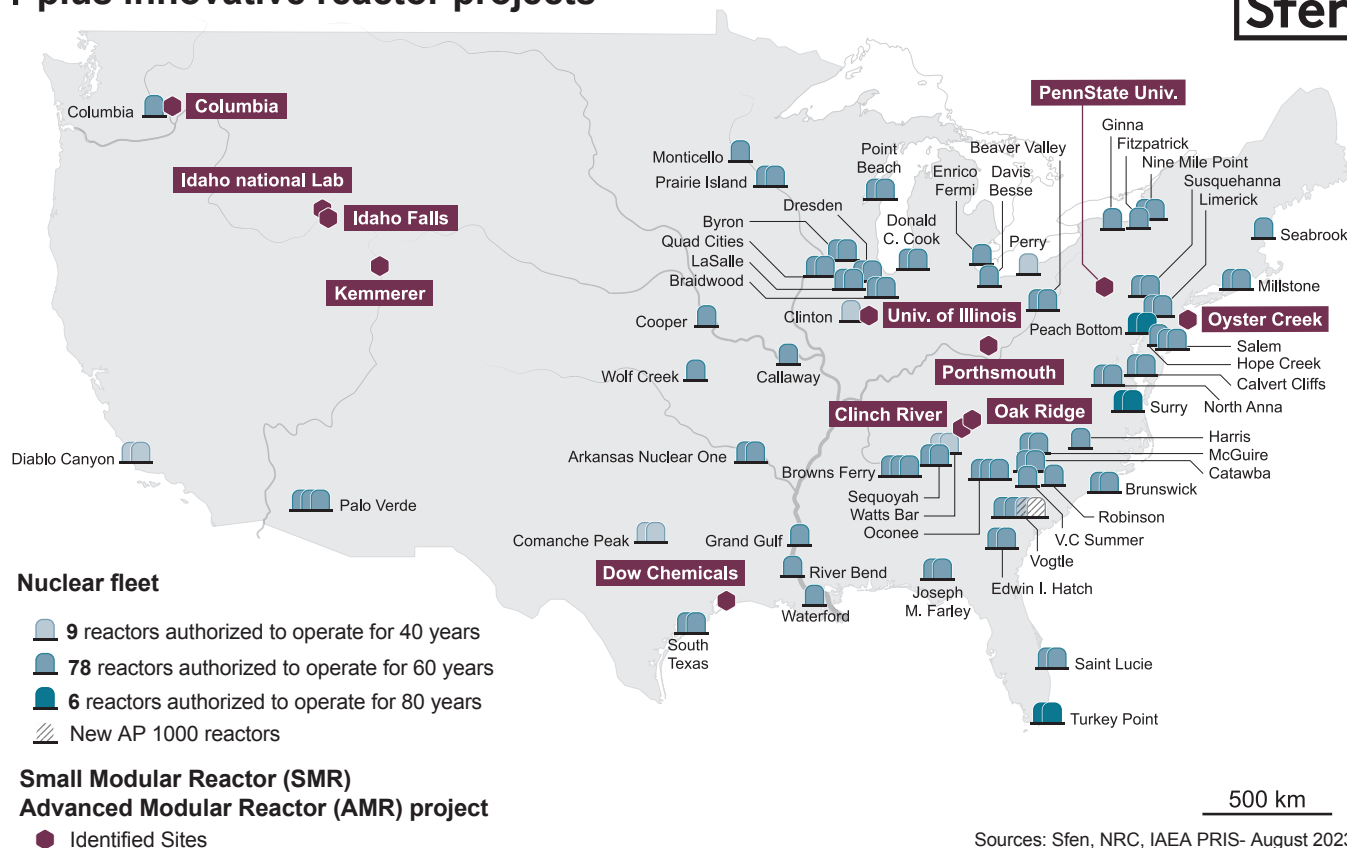
Today, those uncertain times seem to be quickly receding, with the first American AP1000 entering commercial operation on 31 July 2023, and with several countries (China, Poland, Ukraine, Bulgaria) showing serious interest in this reactor type. At the end of 2022, Poland selected the US manufacturer to supply its first three units. Ukraine and Bulgaria have also expressed an interest in procuring several units, and there are plans to build six more reactors in China, in addition to the four already in commercial operation since 2018. These projects have yet to materialize.

Key point: The Inflation Reduction Act includes several measures to maintain the nuclear fleet in operation, tax incentives to facilitate the deployment of innovative reactors, and \$700 million to support the development of a domestic enriched fuel (Haleu) supply chain.

29. Restoring America's Competitive Nuclear Advantage: US Department of Energy Report <https://www.energy.gov/articles/restoring-americas-competitive-nuclear-energy-advantage>

United States: long term operations plus innovative reactor projects

Sfen



3.2. A major boost for small modular reactors (SMR/AMR)

US nuclear policy combines financial support for struggling power plants, through the Infrastructure Law and the Inflation Reduction Act (IRA), along with support for a wide range of small modular reactor (SMRs) projects. SMR projects comprise a variety of technologies developed by both start-ups and major manufacturers. One of the aims of this policy is to innovate rapidly. As part of the 2021 Advanced Reactor Demonstration Program, the US Department of Energy awarded \$2 billion in funding to TerraPower for its sodium-cooled fast neutron reactor, and \$1.2 billion to X-energy for its high-temperature gas-cooled reactor.

Also of note, in January 2023, NuScale's reactor became the first SMR to be certified by the Nuclear Regulatory Commission (NRC). Similarly, GE-Hitachi, with its small boiling water reactor, signed North America's first commercial contract for an SMR at an existing construction site in Canada.

The first unit could be commissioned as early as 2028, with a further three units between 2034 and 2036.

3.3. Fuel supply: are weaknesses being fixed?

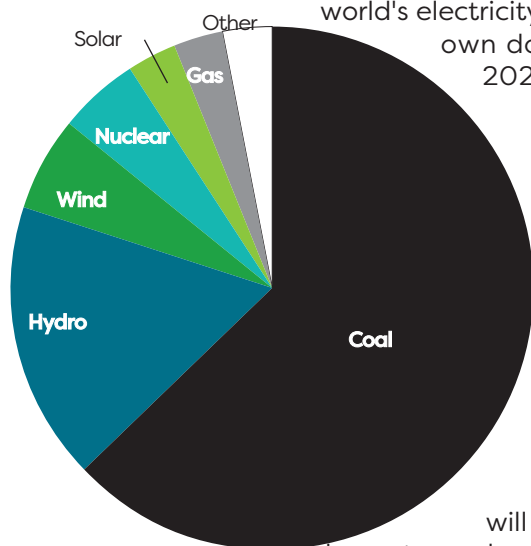
The United States is refocusing on its fuel supply sovereignty; part of its dependency relies on Russia with 24% of the US nuclear fleet drawing on Russian enriched uranium. Furthermore, access to the enriched fuel (Haleu) required for certain innovative projects is held solely by a subsidiary of the Russian giant Rosatom. Several actions have been announced to address these issues, including the creation of a Federal Strategic Uranium Reserve in 2022 as a contingency supply source, and the creation of a consortium to secure the supply of Haleu. A preliminary request for proposals for the construction of enrichment plants (Haleu plants) on U.S. soil was published in June 2023.

Geographical focus

China

4 China: the new giant

China is a giant that is focused on meeting its ever-increasing electricity needs. In 2010 the country consumed almost 4,000 TWh of electricity,³⁰ and by 2022 this had more than doubled to 8,400 TWh. Indeed by 2022, China was producing a third of the world's electricity! Coal largely meets its own domestic demand, and in 2022 accounted for almost 60% of the nation's electricity mix. Despite doubling capacity between 2015 and 2021 to more than 57 GW, nuclear power only accounts for 5% of China's electricity production. However, with over twenty reactors under construction, China will soon have the second largest nuclear fleet in the world, second only to the United States. Lastly, China is also making its mark in terms of R&D, and is without doubt one of the most enterprising nations.



9. Electricity mix 2020

■ Coal: 63 %
■ Gas: 3 %
■ Hydro: 17 %
■ Wind: 6 %
■ Nuclear: 5 %
■ Solar: 3 %
■ Other: 3 %

Source : IEA

4.1. 100% Chinese produced reactors currently being deployed

Since its first nuclear power plant was commissioned in 1991, China has acquired the expertise to develop reactors with 100% Chinese intellectual property and know-how. Spearheading its efforts are the dozen or so Hualong-One³¹ reactors currently under construction, the first of which was put into service in October 2020. In terms of export capabilities, two units are currently in service in Pakistan, and work is about to commence on a third. A reactor is also planned for Argentina. However, prospects abroad have dimmed since the exclusion of state-owned China General Nuclear (CGN) from several projects in Europe, notably in the UK.

Less well-known than the Hualong reactor (Dragon), is the slightly more powerful (1,400 MW) CAP1400 reactor aka Guohe-One, which is based on the US Westinghouse AP1000 design. Construction of the first two units began in 2019.

4.2. Innovative elements: SMR and advanced reactors

Chinese performance is not limited to purely construction prowess. Beijing has embarked on an innovation race and is

Key point: China is exploring a wide range of technologies. In particular, it has high-temperature reactors, and is building a pair of sodium-cooled fast-breeder reactors, as well as a molten-salt reactor.

³⁰ IEA
³¹ In reality, there are two versions of the Hualong-One, one developed by the CNNC and the other by the CGN.

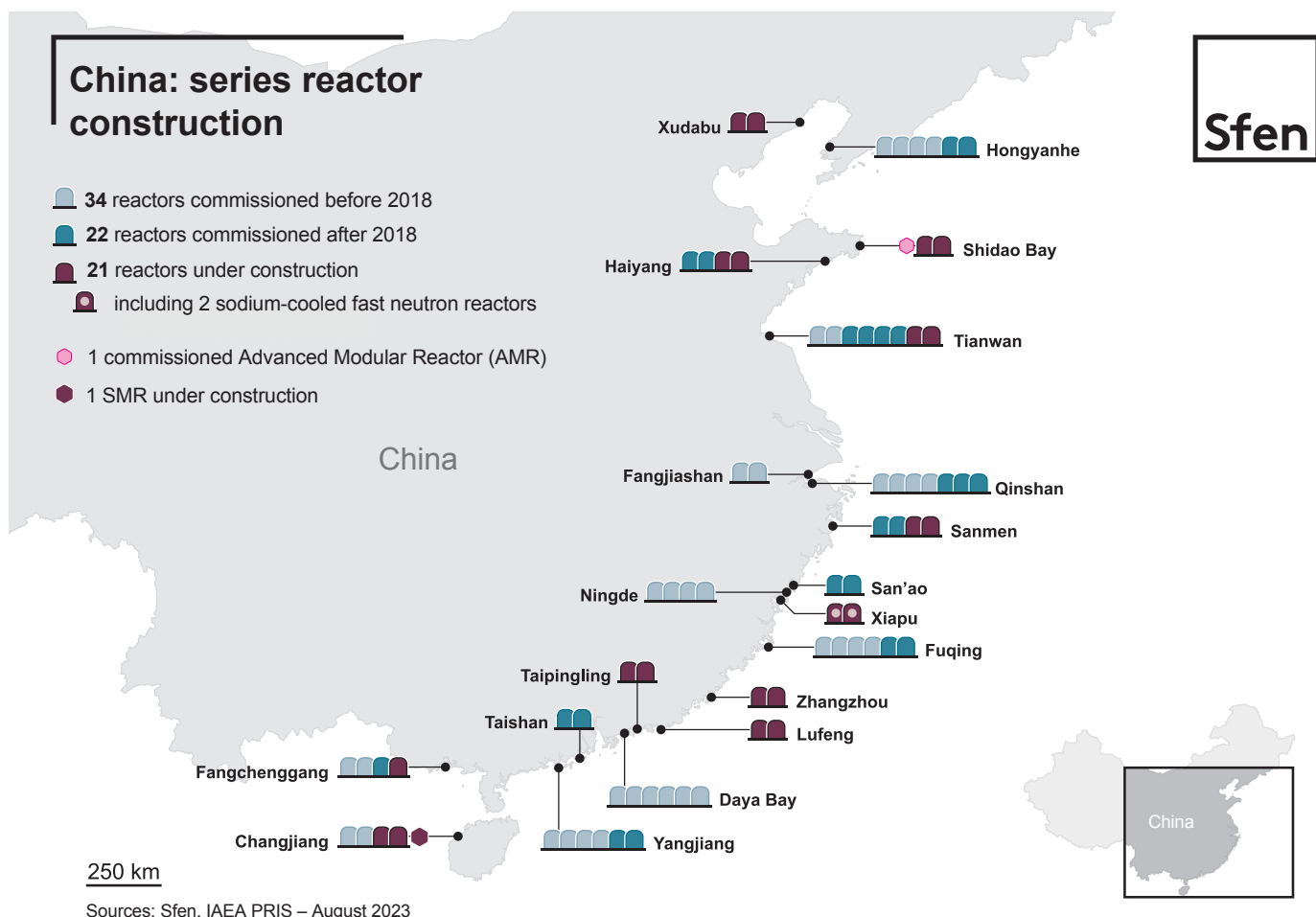
Geographical focus

China

Sfen

China: series reactor construction

-  34 reactors commissioned before 2018
-  22 reactors commissioned after 2018
-  21 reactors under construction
 -  including 2 sodium-cooled fast neutron reactors
-  1 commissioned Advanced Modular Reactor (AMR)
-  1 SMR under construction



exploring several reactor technologies, in particular sodium-cooled fast breeder reactors (RNR-Na) and high-temperature reactors (HTR). Fast breeder reactors (FBRs) are designed to extract maximum value from nuclear materials, while high temperature reactors (HTRs) are intended for new uses such as hydrogen or heat production. Beijing has been ramping up its fast-neutron reactor development, with the first small-scale prototype (20 MWe) commissioned in 2011, as well as two larger 600 MW units that have been under construction since 2017 and 2020.

Plans are also underway to connect a 1,200 MW reactor to the grid in 2035. On top of this China is making a name for itself in the field of HTRs, with the first HTR-PM, rated at approximately 200 MW, and commissioned in December 2021. The Tsinghua University Institute of Nuclear and New Technologies (Inet) has also launched the design of a 600 MW reactor. In June 2023, China once again made headlines by granting an operating license to the experimental 2 MWth molten-salt reactor (TMSR-LF1). Several countries are very interested in this technology because of its ability to accommodate a variety of fuels, including thorium.

Geographical focus

Russia

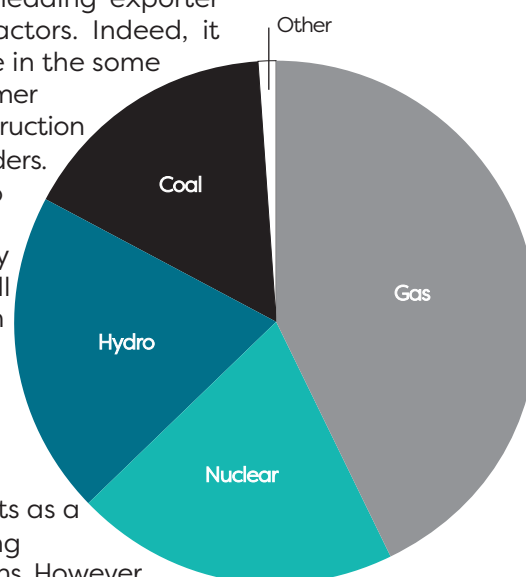
5 Russia, the world's leading exporter of nuclear reactors

Russia is not only a pioneer in the field of nuclear technology, it is also the leading exporter of nuclear reactors. Indeed, it can take pride in the some

23 reactors that by summer 2024 will be under construction outside its own land borders. Countries venturing into nuclear power for the first time are especially attracted by Russia's full package offering, which includes the reactor as well as the financing components. Russia's state machine actively supports this exporting activity in so far as it acts as a conduit for implementing its foreign policy ambitions. However, things have changed since the outbreak of the conflict with Ukraine. On top of imposing sanctions on Russia, several countries are looking for substitute suppliers of reactor units and fuel supplies.

5.1. Seller, financier, and more, Russia is attracting market newcomers

Russia's success in attracting market newcomers lies in particular in its ability to provide finance for these countries' projects.



10. Electricity mix 2020

■ Gas: 43 %
■ Coal: 16 %
■ Nuclear: 20 %
■ Hydro: 20 %
□ Other: 1 %
Source : IEA

Out of seven countries where Russia has secured construction projects (Bangladesh, Belarus,³² China, Egypt, Hungary, India, Turkey), four are building their very first reactor units. Two financing models are available, namely a substantial state loan model and a 'build-own-operate' (BOO) model. The state loan model was used in Bangladesh, where Russia financed 90% of the Rooppur project, and also in Hungary, where an inter-state loan of €10 billion was agreed for a project estimated at €12.5 billion.

Key point: Russia is the only country with a floating nuclear power station; a barge equipped with two small nuclear reactors. In operation since May 2020, the plant supplies electricity to the city of Pevek. In December 2020 Rosatom announced the construction of four new-generation floating power stations.

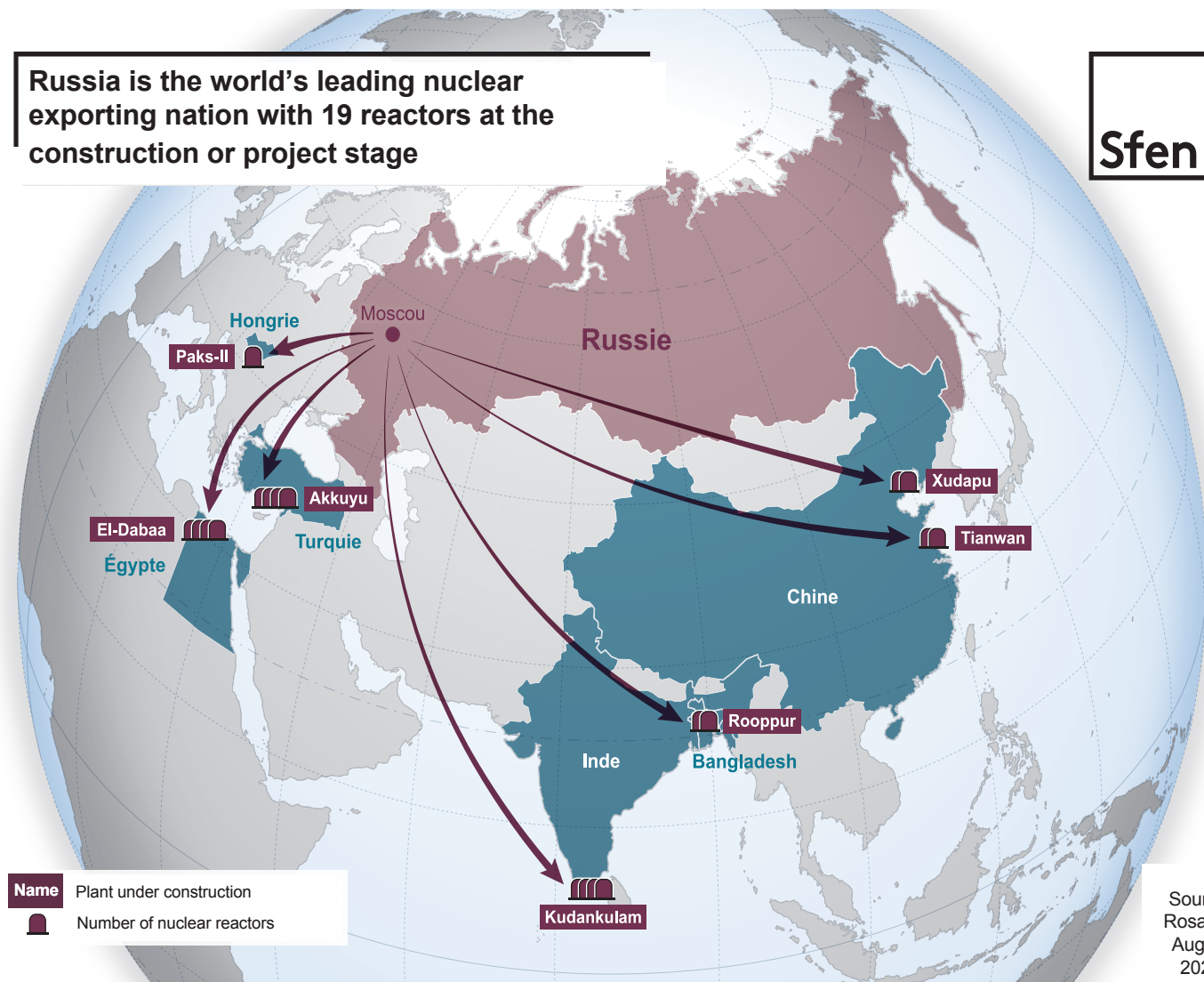
³² The Belarusian power plant was completed with the Unit 2's grid connection in May 2023

Geographical focus

Russia

Russia is the world's leading nuclear exporting nation with 19 reactors at the construction or project stage

Sfen



Turkey currently is the only country using the BOO model, where Rosatom (Russian state corporation) is building the Akkuyu plant and will repay itself via the ensuing electricity sales revenues due to its majority owner status. Commissioning of the first unit is scheduled for 2024.

5.2. A weakened leader?

Has Russia's nuclear industry been weakened by international sanctions imposed since the 24 February 2022 invasion of Ukraine? Although difficult to answer unequivocally, it would be reasonable to assume this to be the case. Firstly, fresh business opportunities appear to be dwindling and apart from the Paks-2 project in Hungary, Russia no longer has any projects in Europe, and more broadly, the United States is

making a real comeback on the export front, and will readily counter any efforts from the Kremlin.

Secondly, both Framatome (France) and Westinghouse (United States) are helping to diversify the market and develop an alternative sovereign European fuel solution, particularly in response to the needs of European VVER operators so that these units are operationally secure (continuity and safety), while also being able to wean themselves off their dependence on Russia. Lastly, although the economic impact of sanctions is difficult to assess, the future of Russia's financing capacity may be called into question.

Geographical focus

India

6 India: a global nuclear player in the making

While India's nuclear fleet of 23 reactors with capacity to generate 7.48 GW of power currently only contributes 3% (43TWh)

of overall domestic electricity production, the government's strategy as announced at the end of 2022 affirms the need to scale up the nation's nuclear reactor electricity capacity. India is going to have to meet what is forecasted to be a very sharp rise in electricity demand (+ 150% by 2040 as compared to 2019) while still aiming to meet its carbon neutral target date of 2070.

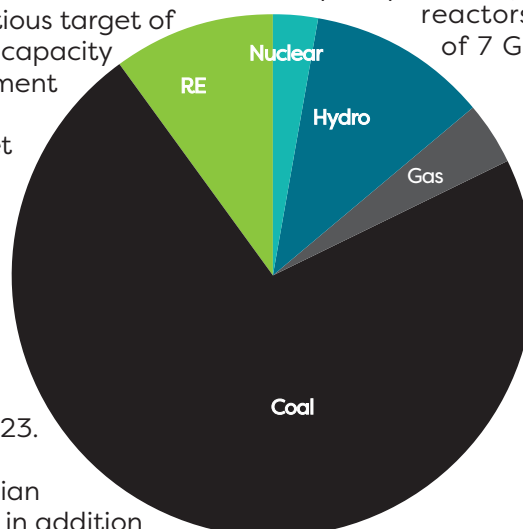
To meet the ambitious target of 22.48 GW of nuclear capacity by 2032, the government has commenced construction of a fleet of 700 MWe natural uranium reactors (IPWHR); India's reactor technology derives from 1960s Canadian models. The first unit in this series went into operation in June 2023. Construction is also ongoing for four Russian reactors (VVER1000), in addition to two units that are already in operation. India is also studying deployment scenarios for Indian and foreign technologies, (both small and large power units). India has considerable expertise in a wide range of areas within the nuclear field and is working on a number of different technologies (pressurized water, fast breeder reactors, fusion, high temperature, etc.).

These programs receive support from major research centres and an established industrial sector. India is a major contributor to all international nuclear forums and projects (the Iter project, the RJIH international consortium, etc.).

6.1. Ramping up the nuclear fleet

In terms of the number of reactors under construction, India's nuclear program is the second largest in the world, with ten reactors under construction (for a total capacity of 8 GW) and a further ten reactors (for a total capacity of 7 GW) already signed off and financed by the government.

In addition to these projects, negotiations are underway with foreign suppliers for 11 reactors.



11. 2020 Electricity mix

■ Coal: 72 %
■ Gas: 4 %
■ Hydro: 11 %
■ RE: 10 %
■ Nuclear: 3 %

Source: IEA

Geographical focus

India

The Jaitapur plant will be the most powerful in the world, with an installed capacity of almost 10 GWe. For this project, EDF is putting forward its EPR technology, engineering studies and equipment.

India's nuclear utility, NPCIL, will be responsible for construction, commissioning, and obtaining all necessary authorizations and certifications. To accelerate the pace of nuclear power development, India is seeking to attract new public and even private players to participate in and/or finance future projects. To this end, India's largest electric utility (NTPC) has set up a joint venture with NPCIL for new PHWR reactor projects.

However, India is also very aware of the potential of SMRs and advanced reactors (AMRs), with installed capacity expected to reach several tens of gigawatts by 2040. Applications for these new technologies include replacing existing thermal power plants and producing carbon-free (green) hydrogen. As part of the G20 forum, of which India assumed the presidency in December 2022, an international seminar was organized on the conditions for the large-scale deployment of SMRs, and included discussions on arrangements for future co-operation. India is seeking to optimize its established and experienced industrial sector, and to position itself as a supplier of equipment for projects abroad.

6.2. India prepares to inaugurate a fast-neutron reactor

As part of its long-term policy of closing the fuel cycle, India is pursuing the development of fast-neutron reactors. In addition to a small research reactor based on the French Rapsodie model, since 2004 the country has been building a 500MW sodium-cooled industrial demonstrator, which after multiple postponements is now scheduled for commissioning in 2024. On the basis of this demonstrator, India plans to build a fleet of six power reactors.

Key point: In July 2023, France and India announced a partnership focusing on small modular reactors (SMRs) and advanced reactors (AMRs).

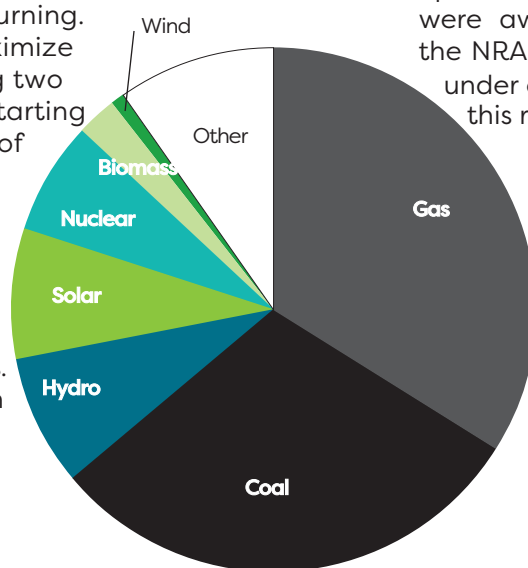
Geographical focus

Japan

7

Japan: nuclear revival well underway

More than ten years after the Fukushima Daiichi power plant nuclear accident in March 2011, Japanese governmental support for nuclear power is returning. The government's aim is to maximize nuclear power generation along two main axes. The first involves restarting the current nuclear fleet, much of which is still shut down, and subsequently extending its operating life over the long term. The second, which is still somewhat vague, involves a partial renewal of the nation's nuclear fleet via new reactor units. Japan's multi-annual energy plan (2021-2024) sets a goal of having 20%-22% nuclear power in the nation's electricity mix by 2030, compared with just 7% today.



and acceptance among locally elected representatives and the wider general public. In September 2023, of the 33 reactors that were fit to be operational, 11 had been restarted, 6 were awaiting restart after receiving the NRA's green light, and 8 were still under examination. In order to pursue this restart policy, and in light of the fact that reactor life had been capped at 60 years of operation, as of May 2023 the situation has been changed so that reactors can now be operated for 60 non-calendar-consecutive years. In other words, the decade of shutdown following the Fukushima accident will not count in a reactor's total operating period.

7.1. Restarting reactors step-by-step

Following the accident on 11 March 2011, all the archipelago's reactors were shut down, and 24 are now permanently closed. However, some are being restarted under the careful eye of the new safety authority, the NRA, which was set up in 2012. Operators are facing the twin challenges of meeting the NRA's standards as well as building confidence

12. Electricity mix 2021

■ Gas: 34 %
 ■ Coal: 30 %
 ■ Hydro: 8 %
 ■ Solar: 8 %
 ■ Nuclear: 7 %
 ■ Biomass: 2,5 %
 ■ Wind: 1 %
 □ Other: 9,5 %
 Source : IEA

7.2. Renewing the national nuclear fleet now a key issue

As regards renewing the nuclear fleet, in August 2022, Japan's Prime Minister made his first mention of the idea of building new reactors in light of the energy crisis. At the same time, Mitsubishi Heavy Industries presented a new-generation 1,200 MW reactor (SRZ-1200). Japanese manufacturers have also been involved in several small modular reactor (SMR) projects in partnership with the USA, including GE-Hitachi's small boiling water reactor (BWRX-300) and NuScale's pressurized water reactor.

Key point: In August 2022, the Japanese Prime Minister mentioned the idea of building new reactors for the first time since the Fukushima accident.

Geographical focus

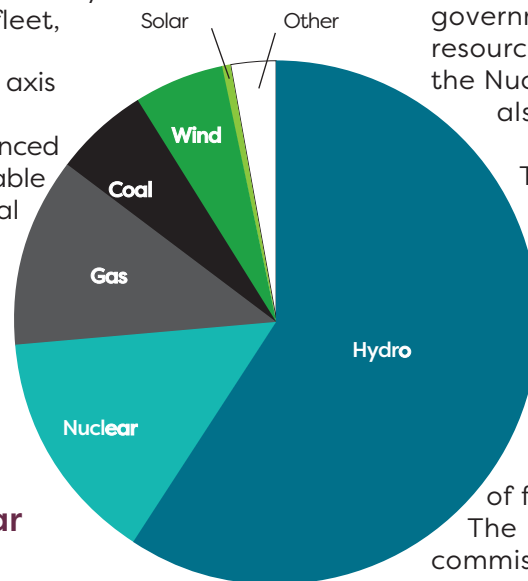
Canada

8 Canada's nuclear revival

Canada's nuclear policy articulates around two main axes, namely the extended operation of the country's established nuclear fleet, and the development of small modular reactors (SMRs). A third axis was added in July 2023, when Ontario's Energy Minister announced plans to build new reactors capable of delivering 4.8 GW of additional power. Eighteen of Canada's 19 reactors are located in this province, which, the authorities say, will have to respond to electricity demand that is "growing for the first time since 2005."

8.1. Operating the nuclear fleet for up to 60 years

The first priority is to keep Canada's 19 natural uranium reactors (Candu), which supply around 15% of the country's electricity, in operation by way of a refurbishment program that started in 2016. With this program, reactor units undergo an overhaul close to their thirtieth anniversary, enabling them to continue operating for a further 30 years.



13. Electricity mix 2021

■ Hydro: 59,2 %
■ Nuclear: 14,4 %
■ Gas: 11,8 %
■ Coal: 5,7 %
■ Wind: 5,5 %
■ Solar: 0,8 %
□ Other: 2,5 %
Source : IEA

8.2. Small power moves center stage

The second axis focuses on small modular reactors (SMRs) as part of the Canadian Small Modular Reactor Action Plan that was published in 2018. To boost SMR development, the government is allocating additional resources to its Ministry of Energy and the Nuclear Safety Authority, and is also supporting SMR development manufacturers (Moltex Energy, Terrestrial Energy, Westinghouse Canada). Lastly, at the end of 2022, the government decided to include SMRs as a clean energy technology eligible for a new investment tax credit equal to 30% of the capital cost. The province of Ontario has already selected a site for the construction of four 300 MW SMRs (GE-Hitachi). The first of these could be commissioned as early as 2028. The province of Saskatchewan, which so far has no nuclear reactors is also considering SMRs: in August 2023, the federal government approved C\$74 million (approx. US\$55 million) in funding for preliminary studies into this power alternative.

Key point: Ontario's Energy Minister has announced the intention to build four BWRX-300 SMRs, i.e. three more than previously planned, and that the operator Bruce Power will study the environmental impact of a project to add an extra 4.8 GW of electricity capacity to the Bruce Nuclear Station.

Geographical focus

South Korea

9 South Korea shifts its nuclear policy to include exports

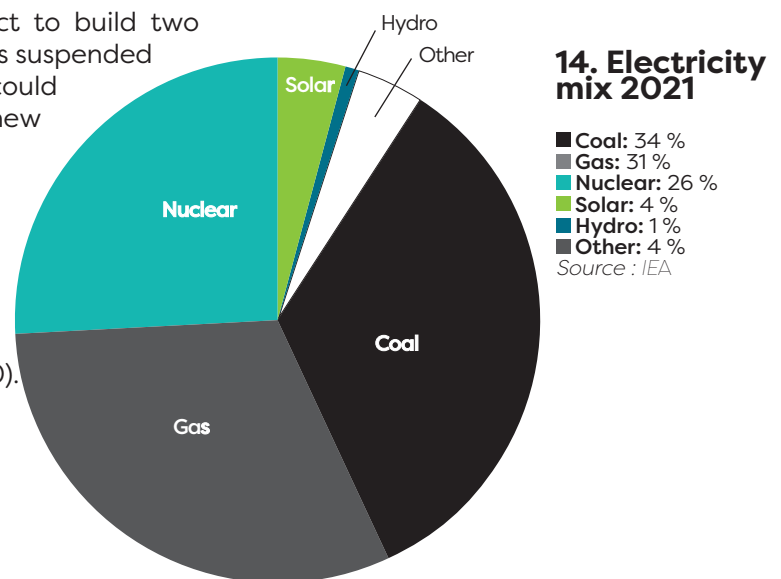
South Korea is determined to revive its nuclear power industry. The new government, elected on 09 March 2022, has overturned the previous government's policy of phasing out nuclear power and is now aiming for nuclear to account for a minimum of 30% of the country's electricity mix by 2030. The country also wants to make a real comeback to the export market with its Gen III+ 1,400 MW (APR1,400) reactor, as well as in the small power unit sector.

9.1. Resumption of national construction projects

In 2017, President Moon Jae-In decided to scale back and then phase out the Republic's long-term nuclear program. In concrete terms this meant dismantling all reactors that had been in operation for forty years. Fulfilment of this policy would have meant that Korea's nuclear share of the electricity mix would have reached zero by the 2060s. The project to build two reactors at Shin-Hanul was suspended even before construction could begin. Now however, the new government is looking at relaunching this project, with construction due to start in 2024, enabling unit 2 to be commissioned in 2032 and unit 3 in 2033 (both are 1,400 MW Korean reactors (APR1,400)).

9.2 Ambitious export targets

In terms of exports, the Ministry of Trade, Industry and Energy (MoTIE) has expressed the ambition "to export ten nuclear power plants by 2030" and to develop an innovative small modular reactor (SMR). To this end South Korea holds an alluring trump card, namely the nuclear power plant in the United Arab Emirates. In 2009, the UAE selected this Korean APR 1,400 technology for its first nuclear plant at Barakah. In 2012 concrete pouring commenced, between 2020 and 2022 three of the four units were connected to the grid, and the fourth is awaiting fuel loading. While this export success story has not as yet had any follow-up business, South Korea is currently in discussions with several countries, including Poland, the Czech Republic, and the Netherlands.



10

Other nations adopting nuclear

10.1. First time nuclear power plant construction

The **United Arab Emirates** started up its first three reactors in 2020, 2021, and 2022. A fourth unit, which completed its hot functional testing in July 2022, is due to come online in the coming months. The UAE chose Korean APR 1400 reactors (1,400 MW) for this first nuclear power plant and its four units will provide the equivalent of 25% of the electricity needs of the seven emirates' 9.3 million inhabitants. The state is also considering small modular reactors (SMR) for both desalination and hydrogen production. Lastly, the UAE is also discussing the potential for units 5 and 6 with the South Korea's Ministry of Trade, Industry and Energy (MoTIE).

Turkey has ordered four 1,200 MW units from Russia. Concrete for the first unit started pouring in 2018, the Turkish government aim being for it to be commissioned on time to mark the Republic's 100th anniversary (29 October 2023).

Egypt is building a nuclear power plant at El-Dabaa. A Russian state loan is supplying 85% of the financing. The site will house four VVER-1200 reactors, two of which started construction in 2022, and a third which commenced construction in May 2023. The facility has two purposes namely, electricity generation and seawater desalination. Since 2017, Russia has also been building the first two reactors in Bangladesh, as well as a two-unit power plant in Belarus (unit one started commercial operations in 2021 and unit two was connected to the grid in May 2023).

10.2. Shifting to nuclear

In 2020, the **Philippines** government commissioned the Nuclear Energy Program Inter-Agency Committee (NEP-IAC) to study the launch of a nuclear power program. The country has no nuclear power plants apart from the 'ghost' Bataan plant, which was completed in 1984 but never commissioned. The archipelago intends to build small modular reactors (SMR) in conjunction with various partners (Russia, South Korea, USA).

Uzbekistan has signed an agreement with Russia for two 1,200 MW units.

Saudi Arabia is aiming to build its first nuclear power plant, comprising two units rated between 1,000 MW and 1,600 MW. The Kingdom is expected to select the plant supplier in 2024, with the first unit expected to be commissioned in 2036. The Kingdom is also looking at SMRs for hydrogen production.

Kazakhstan is seeking a partner to develop its first nuclear power plant, aside from a defunct small fast neutron reactor (BN-350), inherited from the USSR era and permanently shut down in 1999. Included around the Kazakhstan negotiating table are Chinese, Korean, French, and Russian industrial stakeholders.

Data



Data

Nuclear reactors worldwide in 2023 (Source: IAEA - PRIS, September 2023)

Reactors currently in operation	411
Reactors currently in suspended operational mode	26
Reactors under construction	58

Nuclear power worldwide in 2023 (Source: IAEA - PRIS, September 2023)

Country	Nuclear capacity (GW)	Under construction (GW)	Number of reactors in operation
United States	96	1	93
France	61	1.6	56
China	53	21.6	55
Russia	27.7	2.7	37
Republic of Korea	24.5	4	25
Canada	13.6	0	19
Ukraine	13	2*	15
Japan	9.5	2.6*	11
Spain	7	0	7
Sweden	7	0	6
India	6	6	19
United Kingdom	6	3.26	9
Finland	4.4	0	5
United Arab Emirates	4	1.3	3
Czech Republic	4	0	6
Belgium	4	0	5
Pakistan	3.2	0	6
Switzerland	3	0	4
Slovakia	2.3	0	5
Belarus	2.2	0	2
Bulgaria	2	0	2
Hungary	2	0	4
Brazil	2	1.3	2
South Africa	2	0	2
Taiwan	1.9	0	2
Argentina	1.6	0	3
Mexico	1.5	0	2
Romania	1.3	0	2
Iran	1	1	1
Slovenia	0,7	0	1
Netherlands	0.4	0	1
Armenia	0.4	0	1
Turkey	0	4.5	0
Egypt	0	3.3	0
Bangladesh	0	2	0

* Project suspended - resumption date unknown.

Data

Growth in the world's nuclear fleet (2005-2022) (Source: IAEA - PRIS)

Year	Nuclear Capacity (GW)	No. of reactors in operation
2005	368	442
2010	372	438
2015	364	423
2020	375	422
2022	374	416

Construction time for third-generation reactors

Korean reactors (APR1400)

Reactor	Construction start date	Grid connection date	Construction time period (no. months)
Saeul-1	2008	2016	85
Saeul-2	2009	2019	116
Barakah-1	2012	2020	97
Shin-Hanul 1	2012	2022	125
Barakah-2	2013	2021	101
Barakah-3	2014	2022	97

Chinese reactors (HPR1000)

Reactor	Construction start date	Grid connection date	Construction time period (no. months)
Fangchenggang-3	2015	2023	98
Fuqing-6	2015	2022	86
Hongyanhe-5	2015	2021	75
Fuqing-5	2015	2020	66
Hongyanhe-6	2015	2022	94
Karachi-2	2015	2021	67
Karachi-3	2016	2022	70

Russian reactors (VVER-1200)

Reactor	Construction start date	Grid connection date	Construction time period (no. months)
Novovoronezh 2-1	2008	2016	98
Leningrad 2-1	2008	2018	113
Novovoronezh 2-2	2009	2019	118
Leningrad 2-2	2010	2020	126
Astravets-1	2013	2020	84
Astravets-2	2014	2023	109

Data

French reactors

Reactor	Construction start date	Grid connection date	Construction time period (no. months)
Taishan-1	2009	2018	103
Taishan-2	2010	2019	108
Olkiluoto-3	2005	2022	199

American reactors (AP1000)

Reactor	Construction start date	Grid connection date	Construction time period (no. months)
Sanmen-1	2009	2018	110
Sanmen-2	2009	2018	106
Haiyang-1	2009	2018	107
Haiyang-2	2010	2018	112
Vogtle-3	2013	2023	120

Glossary of terms

AMR: Advance Modular Reactor – advanced technology

AP1000: American third-generation reactor (1,100 MW)

APR1400: Korean third-generation reactor (1,400 MW)

ASN: Autorité de sûreté nucléaire (French nuclear safety authority)

Construction time: a reactor's construction starts with the first concrete pour and ends when it is connected to the grid

EPR: third-generation French reactor (1,650 MW)

EPR2: optimized version of the EPR (1,650 MW)

FNR: fast neutron reactor

Gen III+: third generation reactors

Haleu: High-Assay Low-Enriched Uranium

HTR: high-temperature reactor

Hualong-One: third-generation Chinese reactor (1,000 MW)

IAEA: International Atomic Energy Agency

IEA: International Energy Agency

MW: megawatt

MWe: Megawatt electric

MWth: Megawatt thermal

Na: sodium

SMR: Small Modular Reactor – small light water modular reactor

VVER-1200: third-generation Russian reactor (1,200 MW)

WNA: World Nuclear Association.



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