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NUCLEAR ENERGY IN THE GLOBAL ENERGY LANDSCAPE: ADVANCING SUSTAINABILITY AND ENSURING ENERGY SECURITY?

INTRODUCTION

Bassam Fattouh, Sara Vakhshouri, and Jim Henderson

Following the Russia-Ukraine war, the issue of energy security has once again surged to the forefront of global discussions. The disruption and threats to global energy security caused by the war have starkly exposed the vulnerability of energy supply chains, accentuating the pressing need for robust and secure energy sources. In this context, different countries, notably in the European Union, have emphasized the pivotal role of nuclear power generation in addressing these concerns and ensuring energy security. The recently signed global stocktake agreement at COP28 also emphasizes the significance of nuclear energy in the broader context of the energy transition and the acceleration of zero- and low-emission technologies.

As we find ourselves at the vanguard of an unprecedented energy transition towards sustainable, low-carbon, and environmentally responsible energy supplies, nuclear power emerges as a compelling solution to the energy trilemma. Nevertheless, expanding the role of nuclear energy is far from straightforward, characterized by intricate challenges spanning economic viability, cost-effectiveness, fuel supply dynamics, evolving technologies, regulatory frameworks, public acceptance, and the intricate geopolitics intertwined with the expanding role of nuclear energy.

This issue of the *Oxford Energy Forum* remains resolutely committed to nurturing insightful discussions on nuclear energy, offering a diverse array of perspectives. To enable a comprehensive exploration of nuclear energy's multifaceted role, our discussions are organized into four distinct categories.

The cases for and against nuclear power

The initial section presents articles that provide compelling arguments both for and against nuclear power generation, facilitating a balanced discourse on its merits and limitations.

Jan Horst Keppler explores the role of nuclear energy in advancing sustainability and ensuring energy security. The author argues that to fully leverage nuclear energy's potential contribution to achieving global and national net-zero targets by 2050, several challenges must be addressed. These challenges include securing access to substantial capital at competitive rates to make nuclear energy an attractive investment, ensuring a resilient supply chain through international cooperation to enhance cost competitiveness, building public trust and confidence through transparent engagement and science communication, and developing a skilled workforce capable of sustaining a significant increase in global nuclear capacity. By implementing these measures, nuclear energy can play a vital role in reducing greenhouse gas emissions to net zero by 2050 while maintaining energy supply security during global and national energy transitions.

Tomas Kåberger and *Lars Nilsson* observe that the nuclear industry, historically plagued by delays and high costs, is being touted as a solution to the climate crisis with promises of economical small modular reactor (SMR) designs. However, the authors' assessment finds no compelling evidence or arguments supporting the notion of a nuclear renaissance, whether on a large or modular scale. The direct costs of electricity production in nuclear power are prohibitively high, and rapidly advancing alternative technologies, mainly renewables in the power sector, further diminish the economic viability of civilian nuclear power. Additionally, nuclear energy carries substantial external and often socialized costs. In reasonably efficient and liberalized electricity markets, nuclear power is expected to be outcompeted. Construction in such markets typically relies on subsidies and government guarantees, often motivated by the need for nuclear capabilities for military purposes or misguided political beliefs about the necessity of nuclear power for grid reliability.

Lars Schernikau notes that nuclear is the most net energy efficient and raw material efficient. Nuclear is also one of the safest forms of power generation measured in deaths per MWh generated, with the least environmental impact. Despite these characteristics, nuclear contributes only a relatively small share of global electricity. Even more startling is the fact that the share of nuclear has continuously declined, as its buildout did not keep up with global electricity demand growth. While nuclear accounted for almost 17 per cent of global power generation in 2002, this number declined to 9 per cent in 2022. This might change after COP28 with 22 nations pledging to triple nuclear power by 2050. The author argues that this is a very welcome development but stresses that even if COP28 nuclear targets are achieved, they would only fulfil a fraction of the energy demand growth until 2050, necessitating the continued use of oil, coal, gas, hydro, and other reliable energy sources to meet the rest of the demand.

Wade Allison argues that for 70 years, the lack of acceptability has been the main reason to reject nuclear energy—a cultural argument that is evidently flawed. The author argues that current regulations and outdated bureaucracy are obstructing the exceptional benefits of nuclear energy, and emphasizes the importance of aligning the school curriculum with scientific evidence to build trust in nuclear energy from a young age.

Technological advancements in nuclear energy

In the second section, the Forum delves into the latest technological advancements in the field of nuclear energy including SMRs and nuclear fusion, shedding light on innovations poised to enhance safety and efficiency. It kicks off with a trilogy of articles probing into the issue of whether small modular reactors (SMRs) will drive the envisioned expansion of nuclear energy as an integral part of the energy transition. The trilogy papers were prepared, coordinated, reviewed and endorsed by the authors of the three articles.

H-Holger Rogner, Adnan Shihab-Eldin, and *Noura Mansouri* note that SMRs have garnered significant interest due to their potential to support sustainable development objectives and climate commitments. As the need to reduce greenhouse gas emissions intensifies, SMRs offer a reliable and adaptable energy alternative that can drive socioeconomic development and enhance safety. Their growing acceptance, backed by international policy and cooperation, signifies a shift from optimism to action in securing nuclear energy's place in the energy transition. The authors note that there are two critical questions surrounding the future of SMRs and advanced reactors: whether costs and risks can be significantly reduced and whether these reactors can fulfil baseload demands in the grid. Additionally, there are positive aspects, such as improved safety, enhanced security, and advancements in high-level waste management, to consider.

Robert Budnitz, Olli Heinonen, and *Anita Nilsson* note that as countries increasingly align their regulatory systems with the international legal framework for nuclear safety, security, and safeguards, there's a growing recognition of the interconnectedness of these areas. This alignment, crucial for distinguishing between the International Atomic Energy Agency's (IAEA's) roles in assistance and verification, parallels the development of nuclear technology and the strengthening of the international legal framework. This framework, supported by conventions, international agreements, and the IAEA, is particularly pertinent to the deployment of SMRs. The implementation of this framework must adapt to the challenges posed by the diverse applications of SMRs, both on land and at sea. Strengthening national regulatory systems is key to leveraging nuclear energy as a major source of near-zero carbon emissions worldwide. Improved national-level interactions promise greater international effectiveness, essential for realizing the potential of new SMR designs and advancing global nuclear energy development.

Charles McCombie, Neil Chapman, and *Jake Kinghorn-Mills* note that the new generation of SMRs is anticipated to offer improved safety, lower costs, easier financing, better grid compatibility, and reduced project risks, making them a promising solution for a 'nuclear renaissance'. However, the authors argue that the success of SMRs depends on avoiding past mistakes in nuclear expansion. Besides addressing economic and construction challenges, a critical aspect is the safe disposal of spent fuel and radioactive waste. To overcome this challenge, the authors make a number of recommendations which include incorporating spent fuel disposal routes in SMR designs, promoting cooperation in back-end activities among SMR users, encouraging vendor nations to take back spent fuel or reactor modules, and supporting emerging initiatives for nuclear waste disposal. The authors conclude that realizing the potential of SMRs hinges on ensuring their safety, security, economics, and sustainability, with a particular focus on implementing geological disposal solutions for radioactive waste.

Francesca Ferrazza, Edoardo Fiorentini, and *Davide Martulli* explore the potential role of fusion energy. The authors note that fusion, the same process that powers stars like our Sun, holds the potential to revolutionize the energy sector. It offers a safe, non-intermittent, and nearly limitless source of zero-carbon energy. Interest in fusion has been rising fast in recent years. Fusion energy development and research in plasma physics are conducted across over 50 countries. These global initiatives share a common theme of empowering public–private partnerships to accelerate research, development, and demonstration efforts. Recently, the private sector has been drawn to fusion. New start-ups have been funded by corporate ventures and funds bringing to the market innovative ideas and concepts. While fusion reactions have been successfully generated in numerous experiments, energy generation on a commercial basis remains to be demonstrated. The authors conclude that while it is important to recognize the efforts of scientists and private companies, these are insufficient to fully unlock the potential of nuclear fusion. Regulators and policymakers play an equally crucial role by creating a stable and predictable environment for businesses and investors, making the projects bankable.

Country and regional experiences

The third section casts a discerning eye on the geographical expansion of nuclear energy, examining its adoption across various regions and the unique challenges and opportunities presented by this global diversification.

Giacomo Luciani contrasts the sharply opposing views of nuclear power in Europe, highlighting that those countries that have taken a more positive stance have much better environmental outcomes than those, such as Germany, that are hostile and have reduced their share of nuclear. He argues that the EU should take a proactive approach to developing the region's nuclear capabilities across the supply chain, and suggests that this could radically change the outlook for nuclear not just in Europe but around the world as countries look to avoid dependency on China or Russia for their nuclear expertise, technology, and resources.

Tomáš Vlček picks up this theme in an article discussing what could replace Russian nuclear fuel supplies in Europe. He highlights that countries that are still using Soviet-design technology, largely located in the centre and east of Europe, have historically had to rely solely on Russia for their fuel supply due to the nature of the fuel rods used in the VVER reactors. However, over the past few years, Westinghouse (a US company) has developed fuel for these reactors that was first used in the Czech Republic, and other companies (such as France's Framatome) are now entering the market. The Euratom Supply Agency is also encouraging further diversification efforts, which provide hope that all reliance on Russian fuel will have disappeared by the end of the decade.

James Henderson then looks at a case study of Ukraine to show how one country, with a clear political motivation, has managed to reduce Russian influence in its nuclear sector to zero not just in fuel supply but across the full front and back ends of the nuclear cycle. Energoatom is being supplied with Westinghouse fuel but has also managed to increase domestic manufacturing of critical parts, increase domestic mining of uranium, source enriched fuel from Canada, ensure non-Russian manufacture of fuel assemblies, and build its own waste storage facility. Furthermore, Ukraine is now planning to purchase western reactors to more than double the size of it nuclear fleet by 2040 as it seeks to place nuclear energy at the heart of its low-carbon regeneration plans.

Szymon Kardaś then concludes the arguments on nuclear in Europe by suggesting that the debate on the importance of nuclear power in the energy transition should be guided by the rule of reason. EU member states should respect each state's right to shape its own energy mix, as long as the changes lead to lower emissions. Nuclear energy can make a valuable contribution to achieving the EU's climate goals and can contribute to accelerating decarbonization processes in EU countries. However, even in countries pinning their hopes on nuclear energy, it should not be treated as the silver bullet for energy transition problems. Only by simultaneously developing renewables projects and improving energy efficiency indicators can member states increase their chances of meeting EU climate targets.

Claudio Steuer argues that SMRs have a strategic opportunity to demonstrate their potential in the United Kingdom, benefiting from the Great British Nuclear SMR funding competition, ambitious nuclear energy growth target, and supportive carbon price. The UK target represents the biggest expansion of nuclear power in 70 years, aiming to provide up to a quarter of the electricity in 2050, or 24 GW, from nuclear power, rising from 6 GW today. Utilizing publicly available information from the six shortlisted SMR contestants, the author develops a levelized cost of electricity (LCOE) framework which allows comparisons across various technologies. The base-case LCOEs of SMR manufacturers with larger reactor designs and more advanced projects tend to perform better due to more favourable capex scaling premises with lower diseconomies of scale in relation to larger conventional nuclear reactors. They also show that SMRs, as a group, at the current development stage, are expected to have an LCOE 18–20 per cent worse than a conventional or advanced pressurized water reactor but 10 per cent better than coal, an important economic signal with scope for further improvement. However, based on base-case LCOEs, wind, solar, and combined cycle gas turbines (CCGTs) outperform SMRs. When intermittency and carbon costs are included in coal and natural gas power generation assets LCOEs, SMRs as a group outperform coal by 70 per cent and natural gas by 42 per cent—confirming the economic viability of SMRs as a replacement for fossil fuels in power generation. The author notes that LCOEs aside, nuclear power plants in the United Kingdom still face many challenges such as high capital costs, long construction times, an uncertain regulatory environment, limited public support, and competition from renewable sources.

Thomas Hochman then takes us to the United States, where he asks, what is holding back nuclear in America? He suggests that if there is to be a future for nuclear power in America, then advocates will have to radically update the way they talk about energy policy. Rather than ignoring the fundamental cost and timing challenges that the industry faces, advocates will have to push for nuclear on the grounds that it provides a great deal of utility that cannot be captured by simple price estimates. New nuclear is unlikely to be able to compete with clean energy on price alone. And yet there is plenty of reason for the United States to build it anyway. He argues that other characteristics that nuclear does possess—reliability, resistance to foreign price shocks, and low carbon output—are also crucial components of American energy security.

Jennifer Gordon and *Landon Derentz* continue the US theme but from a foreign policy and energy security perspective, asserting that the increasing global recognition of the role of nuclear energy in addressing climate change must also be matched by a realization that the United States and its allies are the best suppliers of nuclear energy technologies. In order to compete in the global market, the United States and its allies must work together—especially on co-financing and on international regulatory cooperation—to offer a counterweight to Russia and China. Decarbonization and global energy security depend on these measures, with SMRs set to play a crucial role in smaller countries with limited nuclear experience and expertise. The authors argue that the United States and its allies must be at the forefront of this new technology and must not allow adversaries to take the lead.

Philip Andrews-Speed underlines the level of competition that can be expected in his article on the nuclear industry in China. He emphasizes the importance of nuclear to the Chinese authorities in terms of both energy security and foreign policy, and he reminds us that China will likely host the world's largest fleet of civil nuclear reactors in 10 years' time at 100 GW or more. Despite the emphasis on energy security, though, China is heavily dependent on imports of uranium, and the current strategy is to source one-third of uranium requirements domestically, one-third through trade imports, and one-third from overseas mining. This links to China's foreign policy goals as Chinese companies now have equity joint ventures in uranium mines in several countries including Canada, Kazakhstan, Namibia, Niger, and Uzbekistan, underlining the importance of nuclear in a domestic and global context.

The issue then turns to the Middle East, where few countries are embracing nuclear power. *Noura Mansouri* examines the status of nuclear energy in Kingdom of Saudi Arabia. The Kingdom is taking a transformative leap into nuclear energy, aligning with its Vision 2030, energy diversification goals, and sustainability. An important aspect of Saudi Arabia's nuclear strategy is its focus on self-sufficiency in the nuclear fuel cycle, which also enhances its energy security. However, the author recognizes that the leap into nuclear energy is not without challenges, and addressing public perception, ensuring regulatory compliance, developing a skilled workforce, and managing environmental considerations are all essential aspects of Saudi Arabia's nuclear energy programme. Mansouri concludes that Saudi Arabia's strategic approach to nuclear energy Is Integral to the responsible development of nuclear power, as it based on collaborating with international partners, adhering to the highest standards of safety and security, and achieving self-sufficiency in the nuclear fuel cycle.

Robin Mills looks at developments in nuclear energy in the Gulf Cooperation Council (GCC) countries. He notes that only two of the GCC states have serious civil nuclear activity. The United Arab Emirates (UAE) began its nuclear programme in 2008, and the fourth and, for now, final reactor at the Barakah plant is starting up now, which will bring total capacity to 5.6 GW. Saudi Arabia's nuclear journey has been longer and more complicated. Mills argues that the UAE's nuclear programme, though not originally justified on climate change grounds, seems in retrospect to have worked out reasonably well. It has accelerated the economy's decarbonization at a tolerable cost, far beyond where it would be today based on solar power alone. However, he cautions that improvements in solar power and batteries make it much more questionable whether large additions of nuclear capacity are economically optimal either in the UAE or Saudi Arabia, or indeed their GCC neighbours. Bringing down nuclear costs and making use of synergies with industries and users of waste heat have promise but are not straightforward. Otherwise, strategic or technological imperatives will have to bear most of the weight in justifying multi-billion-dollar decadal commitments.

Geopolitics of nuclear energy and medical isotopes

The final section delves into the geopolitics of nuclear energy and recognizes the interconnectedness between the growth of the nuclear industry and the geopolitics of nuclear medical isotopes. This symbiotic relationship underscores the need for a comprehensive understanding of its intricate global implications.

Philip Andrews-Speed compares the strategies and outlook for nuclear reactor exports from Russia and China and asks whether these countries are likely to make a major contribution to the growth of nuclear power outside their borders. The author argues that before 2022, it would have been reasonable to suggest that Russia would continue to be the leading global player in the reactor export market in the coming years. However, the Russia-Ukraine war has dented the nation's reputation, resulting in some countries switching to other potential vendors. In addition, the war may deplete the government's ability to continue providing generous financial support for these exports. In China, the export of nuclear reactors has yet to become a high priority, with the focus likely to remain on domestic construction for the next decade or two. Individual projects may be undertaken, but probably under terms less generous than those of Russia. This would be hindered further by a reluctance among some governments to allow Chinese involvement in such critical infrastructure.

In the realm of nuclear energy geopolitics, Russia emerges as a pivotal and influential player with significant implications for the United States and the European Union. *Sara Vakhshouri* argues that nuclear energy offers both promise and challenges in the context of global energy security. Russia's dominance in uranium mining and the nuclear fuel cycle grants it substantial influence over the nuclear energy landscape. China's rapid ascent in uranium mining adds complexity to the global uranium market. The United States and the European Union find themselves heavily reliant on Russia for critical aspects of the nuclear fuel cycle, raising concerns about vulnerability in times of geopolitical tensions or supply disruptions. To navigate this intricate landscape, strategic investments, diplomatic efforts, and diversification of nuclear supply chains are essential to ensure energy security while harnessing the benefits of nuclear energy for a sustainable future. Cooperation and transparency on a global scale are crucial for addressing the multifaceted dynamics of nuclear energy geopolitics and maintaining energy security in a dynamic geopolitical environment.

In the final article, *Sara Vakhshouri* delves into the intricate and evolving relationship between nuclear medicine, radioisotope production, and the nuclear industry. It highlights Russia's dominant role as a leading producer of medical isotopes and its global influence, particularly through Rosatom. The text underlines the vulnerability of Western countries, especially the United States, due to their dependence on foreign sources, primarily Russian, for essential isotopes, emphasizing the need for diversified and secure supply chains. The intersection of nuclear energy and medical isotopes, along with geopolitical complexities, demands a comprehensive approach that includes technological advancement, strategic planning, and international collaboration to ensure a stable and reliable supply of medical isotopes while navigating the global landscape of nuclear medicine.

NUCLEAR ENERGY IN THE GLOBAL ENERGY LANDSCAPE: ADVANCING SUSTAINABILITY AND ENSURING ENERGY SECURITY

Jan Horst Keppler

The climate crisis is one of the defining challenges of this generation. Yet countries are not on track in their efforts to limit global warming. In order to reduce greenhouse gas emissions in line with the pathways outlined by the Intergovernmental Panel on Climate Change (IPCC), all available options must be pursued.

Analysis by the Organisation for Economic Co-operation and Development's (OECD's) Nuclear Energy Agency (NEA) demonstrates that tripling global installed nuclear capacity is part of a realistic path to meet net-zero goals by 2050 and to keep the rise in global mean temperatures below 1.5°C. Such an increase in nuclear capacity could avoid more than 80 gigatonnes of cumulative emissions between 2024 and 2050 through a combination of the long-term operation (LTO) of existing reactors, new large-scale reactor builds, and the deployment of small modular reactors (SMRs). By 2050, nuclear energy could thus displace 5 gigatonnes of emissions each year, which is more than the annual emissions of the economy of the United States today.

The deployment of new nuclear capacity will take place at the national level in the frameworks of country-specific commitments to attain net-zero targets. A large set of country-level studies indeed show that including significant shares of nuclear energy is, in the vast majority of cases, the most cost-effective way to realize these targets. The precise level of the cost-minimizing share of nuclear energy in the generation mix depends on the following three country-specific parameters that affect the overall functioning of the electricity and energy systems:

1. the relative costs of nuclear energy compared to other low-carbon technologies such as hydro, wind, and solar PV;
2. the availability of flexibility resources to balance the intermittency of wind and solar PV generation;
3. the correlation of wind and solar PV generation with electricity demand.

System-level analysis is indispensable for understanding the relative contribution of different technologies in low-carbon electricity systems. As a baseload technology that reliably generates large amounts of low-carbon electricity, nuclear energy possesses very favourable system characteristics. However, relative plant-level costs do remain an important determinant of system performance, and the nuclear industry will have to rise to the challenge, at both the national and global levels, to deliver sizeable amounts of new nuclear capacity on budget and on time.

This report sets out the potential for nuclear energy to advance sustainability and ensure energy security first at the global and then at the national level, before presenting a number of policy conclusions.

The contribution to carbon emission reductions of a tripling of global nuclear capacity

Worldwide, 444 nuclear power reactors with 394 gigawatts provide around 2,500 terawatt-hours of electricity per year, roughly 10 per cent of the total global supply. In addition, 50 more reactors are under construction to provide an additional 55 gigawatts of capacity, and more than 100 additional reactors are planned. Widely accepted models show that nuclear energy has a decisive role to play in global climate change mitigation.[1] As already highlighted by the 2018 IPCC synthesis report,[2] the world is not on track to meet the decarbonization objectives of the Paris Agreement, as the sustained reductions in greenhouse gas emissions are not occurring at the required speed. Things have worsened since. Global emissions are expected to increase by 2030, rather than undergoing the steep reductions called for by leading climate scientists.

The window for action is rapidly narrowing. Carbon emissions must peak within the next decade and reach net zero by 2050. This will require comprehensive policy changes globally, substantial investments in innovation and infrastructure, and the large-scale deployment of non-emitting energy resources. Electricity grids must be decarbonized; vehicle fleets must be electrified or transitioned to non-emitting fuels; and industries must be transformed across sectors, including off-grid mining, buildings, and the production of chemicals, iron, steel, and cement.

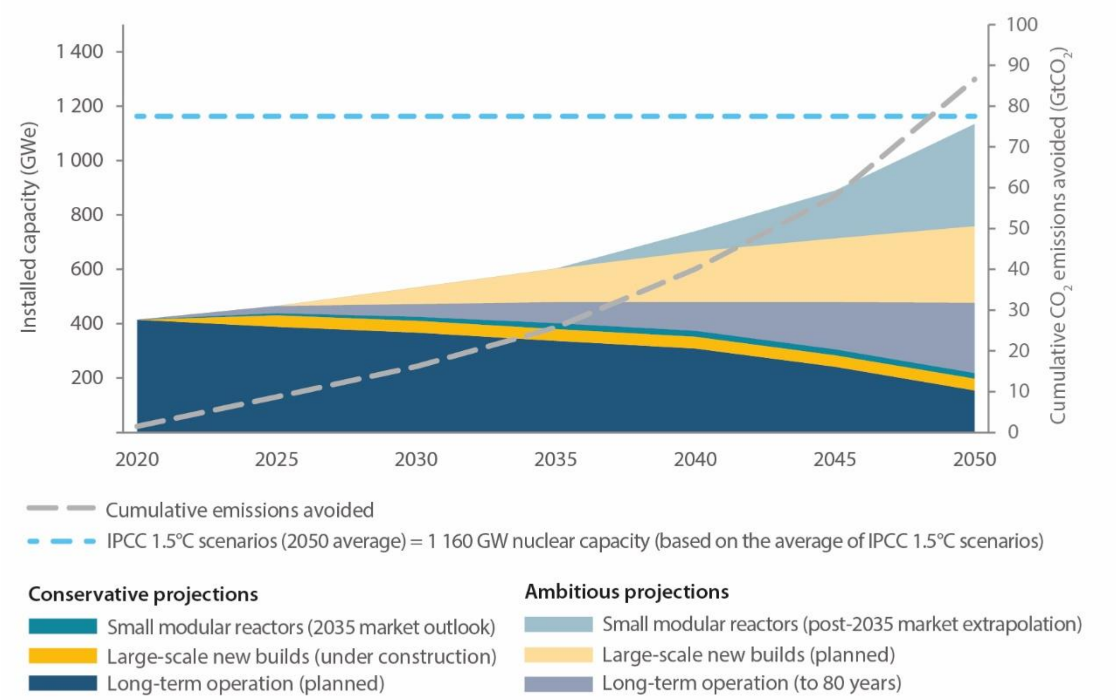
[1] For example, International Energy Agency (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector,* Paris: IEA, http://www.iea.org/reports/net-zero-by-2050; International Institute for Applied Systems Analysis (2021), *NGFS Scenario Explorer*, Release 2.2, https://data.ene.iiasa.ac.at/ngfs/#/login; Bloomberg New Energy Finance (2023), *New Energy Outlook Sector and Regional Reports*, https://about.bnef.com/new-energy-outlook-series/.

[2] Intergovernmental Panel on Climate Change (2018), *Global Warming of 1.5°C*, www.ipcc.ch/sr15.

The nuclear sector supports climate change mitigation in many different ways. Existing large-scale installed nuclear capacity already plays an important role, and the LTO of existing reactors will continue to contribute for decades, displacing 1.6 gigatonnes of carbon dioxide emissions every year—a cumulative 66 gigatonnes of carbon dioxide so far since 1971.[3] Additional measures will be required to meet climate action imperatives. In its 2018 special report, the IPCC considered 90 pathways with emissions reductions sufficient to limit average global warming to less than 1.5°C. The IPCC found that, on average, the pathways to this 1.5°C scenario require nuclear energy to reach 1,160 gigawatts of electricity by 2050, up from 394 gigawatts in 2020.[4]

This is an ambitious target for nuclear energy, but not beyond reach. It can be achieved through a combination of LTO, large-scale new builds, and the deployment of SMRs, as shown in Figure 1.

Figure 1: Nuclear contributions to net zero under different scenarios



Source: Nuclear Energy Agency (2022), *Meeting Climate Change Targets: The Role of Nuclear Energy*, Paris: OECD Publishing, www.oecd-nea.org/jcms/pl_69396.

In 2022 nuclear energy was the largest source of non-emitting electricity generation in the countries of the OECD and the second largest source worldwide after hydropower. Reaching the IPCC target of 1,160 gigawatts of electrical capacity from nuclear energy would, in this scenario, avoid 87 gigatonnes of cumulative emissions between 2020 and 2050, preserving 20 per cent of the world's carbon budget consistent with a 1.5°C scenario. With the development of Generation IV reactors and SMRs, a new wave of innovative nuclear technologies promises to help provide clean energy baseload power and decarbonize hard-to-abate industrial sectors. These innovations include sector coupling, combined heat and power (co-generation) for heavy industry and resource extraction, hydrogen and synthetic fuel production, desalination, and off-grid applications. The main contribution of nuclear energy in pathways to net zero by 2050 can be seen by estimating its potential contribution for emissions reductions through clean power generation, the supply of industrial heat, and the production of clean hydrogen (Table 1).

[3] Nuclear Energy Agency (2020), *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, Paris: OECD Publishing, www.oecd-nea.org/jcms/pl_30653.
[4] Intergovernmental Panel on Climate Change (2018), *Global Warming of 1.5°C*, www.ipcc.ch/sr15.

Table 1: Projected contributions of nuclear energy to global emissions reductions, 2020–2050 (Gt CO_2)

Cumulative emissions avoided from …	Electricity	Heat	Hydrogen	Total
Long-term operation	38.3	6.7	4.3	49.2
New builds of large Generation III reactors	16.2	4.2	2.4	22.8
Small modular reactors	9.7	3.6	1.8	15.1
Total	64.1	14.5	8.5	**87.1**

Clearly, such a dramatic increase in nuclear capacity would pose a significant industrial challenge. However, both recent and historical experiences show that, under the right policy frameworks and with a robust industrial approach, nuclear capacity can have rapid delivery times. This was the case historically for countries such as France and jurisdictions such as Ontario in Canada, which decarbonized their electricity mix in less than two decades with nuclear energy and hydropower. Today, countries with established nuclear programmes such as China and South Korea have demonstrated construction lead times of five to six years or less for large-scale reactors with increased safety. Newcomer countries, such as the United Arab Emirates with the Barakah project, also have demonstrated their ability to deliver new nuclear energy projects on time and on budget.

The role of nuclear energy in minimizing the costs of attaining national net-zero targets

The imperative to reduce carbon emissions and achieve net-zero targets while maintaining the security of supplies is transforming national electricity and energy systems. Decarbonization sets in motion a number of interrelated developments that challenge traditional understandings of the way energy systems work. These changes also require a reappraisal of established notions of costs at the level of the integrated electricity system. Different technologies with comparable costs at the level of the individual plant can thus have very different impacts on the total costs of a system. This relates, in particular, to optimizing the trade-offs between dispatchable low-carbon sources of electricity, such as nuclear energy or hydroelectricity, and variable sources, such as wind and solar PV, that will be the backbone of future low-carbon electricity systems. Among the different factors driving the changes under way, four play a particularly important role:

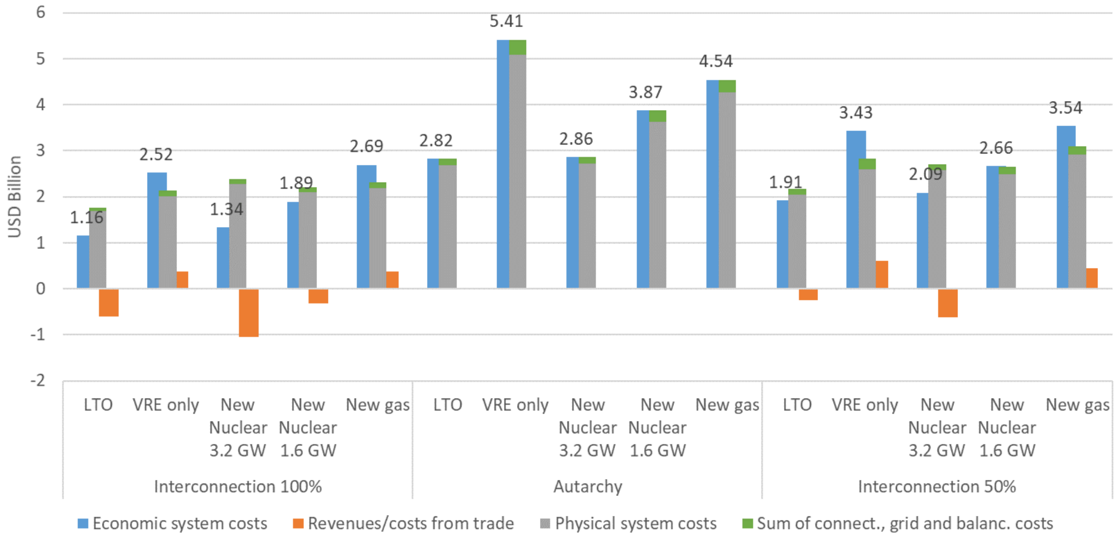
1. The variability of wind and solar PV requires dedicated backup capacity from dispatchable low-carbon generators such as nuclear energy or additional flexibility on the demand side, both of which imply added costs.
2. All low-carbon technologies are capital intensive. This holds not only for renewables and nuclear, but also for energy efficiency, electric vehicles, and hydrogen. This requires new risk management strategies and a rethink of the working of the electricity sector.
3. Technical and behavioural changes such as information gathering at the level of retail consumption, the remote operability of electrical equipment, flexible demand, batteries, and advanced network electronics all allow for better management of volatile generation and consumption patterns.
4. The electrification of energy consumption, also referred to as sector coupling, is growing in sectors such as transport, mobility, heating (co-generation), and industry.

Together, these changes establish one fundamental fact: the role, impact, and cost implications of individual technologies can no longer be understood in isolation. Understanding contemporary electricity systems requires the consistent adoption of a system approach. In order to assist policymakers in coming to terms with this new reality, the NEA developed system cost analysis around its proprietary POSY mixed integer linear programming model. Two early reports set out the theory and analysed the cost implications of different shares of variable renewables (VRE) such as wind and solar PV in electricity systems operating with strict carbon constraints.[5] Since then, the NEA has modelled the implications of achieving Switzerland's net-zero-emissions objective by complementing its hydroelectric resources either with a mix of solar PV and wind or with nuclear energy (Figure 2).[6]

[5] Nuclear Energy Agency (2012), *Nuclear Energy and Renewables: System Effects in Low-Carbon Electricity Systems*, Paris: OECD Publishing, https://doi.org/10.1787/9789264188617-en; Nuclear Energy Agency (2019), *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, Paris: OECD Publishing, https://doi.org/10.1787/9789264312180-en.

[6] Nuclear Energy Agency (2022*), Achieving Net Zero Carbon Emissions in Switzerland in 2050: Low Carbon Scenarios and their System Costs*, Paris: OECD Publishing, http://www.oecd-nea.org/7631.

Figure 2: System costs of different scenarios to reach net zero carbon emissions in Switzerland (billion USD per year)



Source: Nuclear Energy Agency (2022), *Achieving Net Zero Carbon Emissions in Switzerland in 2050: Low Carbon Scenarios and their System Costs*, Paris: OECD Publishing, http://www.oecd-nea.org/7631.

The Swiss study compared five scenarios for three different levels of electricity interconnections: 100 per cent of current levels, 50 per cent, and autarchy. Each time, the LTO scenario with current nuclear power plants had the lowest annual costs. The New Nuclear scenarios have the next-lowest costs. The VRE-only (solar PV, wind, and hydro) and the New Gas (with CO_2 emission prices at USD 100/tCO_2) scenarios have the highest annual costs (see below). Of course, outcomes depend on domestic circumstances. However, if nuclear energy reduces overall system costs in a country with a very high share of flexible hydroelectricity such as Switzerland, it is highly likely to also reduce costs in countries with less flexible systems.

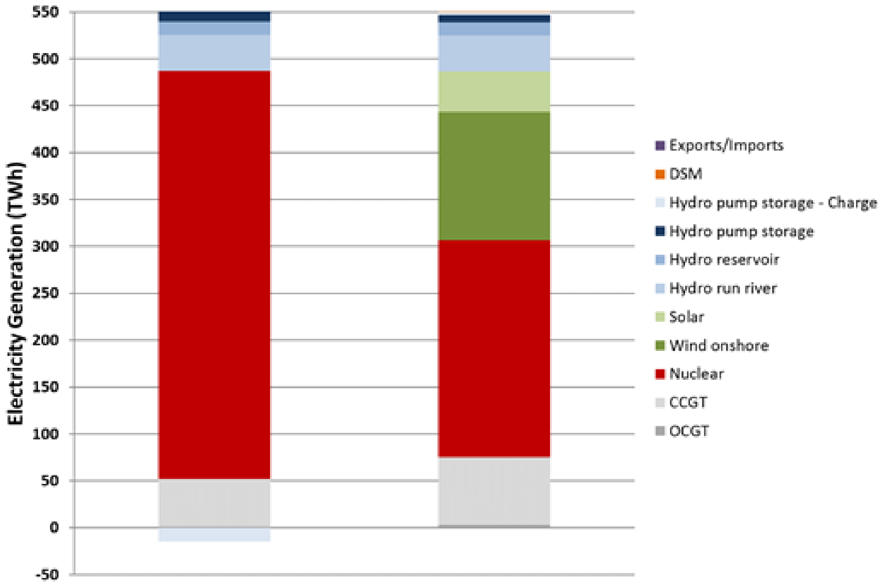
Drivers of system cost

The costs of low-carbon electricity and energy systems are determined by three categories of inputs—the plant-level costs of different technologies, the correlation of renewable generation with demand, and the availability and cost of flexibility resources. Each of the three categories is briefly presented below.

The inclusion of **plant-level costs** measured in terms of the levelized costs of electricity (LCOE) may come as some surprise, as system cost analysis is often presented as surpassing LCOE accounting and making it obsolete. This is, of course, half true. LCOE analysis on its own provides only a subset of relevant cost information and can be seriously misleading. Given that different technologies generate system costs in starkly differing measures, it is necessary to complement LCOE values with information about system costs. However, the relative plant-level costs of different technologies remain an important argument.

Minimizing the overall costs of an electricity and energy system thus means optimizing the trade-off between plant-level costs and system costs. This is shown in Figure 3. The left-hand column indicates an optimized system in which nuclear (in red) not only produces few system effects but also is the most cost-effective low-carbon source of electricity in terms of LCOE. Logically, a programming model such as POSY will thus choose to cover system needs primarily with nuclear.

Figure 3: The trade-off between plant-level generation costs and system costs



Source: Based on Nuclear Energy Agency (2019), *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, Paris: OECD Publishing, https://doi.org/10.1787/9789264312180-en.

Note: In the system represented by the left-hand column, nuclear has both lower system costs and lower LCOE than either wind or solar PV. In the system represented by the right-hand column, nuclear still has lower system costs, but wind and solar PV both have lower LCOE. Both columns show results of system-wide cost minimization.

The situation is more complex when looking at the right-hand column, which indicates an optimized system in which nuclear (in red) still produces few system effects but wind and solar PV have lower plant-level costs in terms of LCOE. The system achieving the lowest total system costs now contains significant parts of both variable renewables and nuclear energy. How can this be? Most observers are used to thinking about the competitiveness of energy generation in binary terms; the least-cost choice is constituted by either one or the other technology. Not so in system cost analysis, where the system costs of a technology are not constant per MWh but *increase* with the share of that technology in the generation mix. This underlies the arbitrage between plant-level costs and system costs. Below a certain threshold of their share in the generation mix, wind and solar PV, if they indeed have lower LCOE, will be the least-cost choice for generating low-carbon electricity. The model and, in a competitive market, investors will thus select wind and solar PV. However, as their shares increase, their system costs also increase. At a certain point, their increasing system costs will have exhausted the cost advantage in terms of LCOE, and nuclear energy will become, at the system level, the least-cost option to generate low-carbon electricity.

The **correlation of VRE generation with electricity demand** is another key point. The latter varies according to the year, season, day, and, importantly, the hour of the day. Consumption is lower at night and in most industrialized countries displays a smaller peak at around noon and a peak with maximum demand at around seven o'clock at night.

Imagine now a highly developed country with good sunshine, especially at noontime, that is beginning to install solar PV capacity. Imagine further that it uses electrically powered air conditioning to cool homes and offices. As it happens, these air conditioners will work hardest precisely over noontime when the sun is at its peak. However, this is precisely also the time when solar PV generation will be at its peak. In this situation, only very little backup will be required for the first few MW of solar PV capacity.

While this might sound very encouraging for VRE, three caveats are in order. First, only rarely is solar PV or wind production as nicely correlated with demand as in this stylized example. Second, the effect only applies to the very first MW of variable capacity. As soon as PV capacity has reached the level of peak air-conditioning demand, the correlation breaks down. Third, in many electricity systems, the key issue is not hourly demand variations over the day but seasonal or inter-annual variations, where correlation is absent.

NEA modelling is therefore moving towards multi-year assessments for solar PV and wind generation. Overall, the less VRE generation is correlated with demand, the more indispensable nuclear energy is to minimize the costs of low-carbon electricity systems with high levels of security of electricity supply.

The **availability of flexibility resources** is another essential determinant of the system costs of the variability of wind and solar PV and the optimal level of nuclear generation. The category of flexibility resources is a broad one. Following NEA,[7] one can identify six subcategories of flexibility provision:

- flexibility from dispatchable low-carbon generators such as nuclear or hydro
- electric energy storage
- network development and cross-border interconnections
- voluntary demand response
- involuntary demand response through rolling blackouts
- operational flexibility from VRE (curtailment).

The availability and cost of such flexibility resources is a key driver of the costs of electricity systems with significant shares of variable renewables. The more expensive the available flexibility options to compensate for the variability of wind and solar PV, the higher the need for dispatchable low-carbon generators. Nuclear energy, as the only dispatchable low-carbon source of electricity that is scalable at will, assumes a particular role in this context.

The decisive role played by these three determinants of system costs—relative plant-level costs, correlation of VRE generation with demand, and the availability of flexibility resources—requires a careful framing of scenarios to develop sustainable least-cost strategies for low-carbon electricity and energy systems, which in most cases will include significant shares of dispatchable nuclear energy.

Conclusions—mastering the policy challenges to leverage the contribution of nuclear energy

If the potential contribution of nuclear energy to reaching net-zero targets at both the global and the national level by 2050 is obvious, there remain a number of challenges to realizing it:

- Access to significant amounts of capital at competitive rates must be unlocked, and nuclear energy must become an attractive investment proposition for public and private investors.
- A healthy and resilient supply chain must be ensured. Countries will benefit from working together through public and private forms of cooperation to avoid supply chain redundancies and improve cost competitiveness to reach efficiencies of scale for a new industry.
- Building trust and public confidence will require sustained investments in open and transparent engagement, as well as science communication to inform citizens about the advancements in nuclear technology, safety measures, and waste disposal solutions through dialogue and education.
- Preparing the skilled workforce needed to sustain a tripling or more of global installed nuclear capacity will require both familiar and new, creative solutions to re-establish a robust network of nuclear education.

With these measures in place, nuclear energy will be set on a credible path to deliver the full extent of its contribution to reducing greenhouse gas emissions to net zero by 2050, while maintaining high levels of security of supply, as part of successful energy transitions at both the global and national levels.

[7] Nuclear Energy Agency (2019), *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, Paris: OECD Publishing, https://doi.org/10.1787/9789264312180-en.

THE ECONOMICS OF NUCLEAR POWER REVISITED

Tomas Kåberger and Lars J. Nilsson

> 'When you discover that you are riding a dead horse, the best strategy is to dismount.' - popular saying often attributed to Dakota Indian tradition

The stalled nuclear industry

Despite the urgency of climate mitigation, and repeated promises by the nuclear industry to be part of the solution, global nuclear developments have stalled during this century. Nuclear electricity supplied peaked in 2006 at 2,661 TWh and was only at 2,487 TWh in 2022, according to the International Atomic Energy Agency.[8] The share of total electricity production peaked in 1996 at over 17 per cent and reached only 9 per cent in 2022, the lowest share in four decades.[9] Global operational capacity, as noted in the International Atomic Energy Agency database, has fluctuated, sometimes retroactively due to reclassification of units not producing.[10] The number of units in operation is now lower than in 1995.[11]

The main reasons are economic. The cost of generating electricity from presented reactor investment opportunities is high and makes them uneconomic in the absence of subsidies. Even worse for the industry is that real costs when construction projects are concluded are higher than claimed when the investment decisions were taken.[12] Construction delay is one reason for cost increases. Only two out of 18 reactors taken into commercial operation in 2020–2022 succeeded in meeting the expected construction time; both were in China.[13]

Not only are reactor construction projects delayed and costs increasing. More than one out of ten reactor projects have been abandoned after construction has started and money has been spent. The most recent examples are the Vigil C. Summer reactors number 2 and 3 projects that were abandoned in 2017 after spending more than US$9 billion dollars.[14] Outside monopoly markets it is no longer possible to pass through high or increasing costs to consumers. The accumulated nuclear experience is discouraging to investors.

During the last 10–15 years the costs for competing electricity generation from solar and wind have decreased considerably.[15] The total cost of new solar and wind electricity is now at par with or below the direct cost of even operating existing and fully depreciated reactors.[16]

Increasing market shares of very low marginal cost solar and wind electricity are outcompeting higher marginal cost nuclear power during low price periods, thereby reducing profitable nuclear operating hours. Nuclear reactors cannot provide the supplementary flexible generation that may operate profitably in systems with low-cost renewable energy. As a result, the end of the civilian nuclear power era draws closer.

The cost of electricity from nuclear power

The direct average cost of producing a unit of nuclear electricity over the lifetime of a plant is a function of construction expenses, operation and maintenance costs, discount rates and build times, and load factors. Recent costs of electricity for

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[8] International Atomic Energy Agency Database, accessed January 2024, IAEA, Vienna, Austria. https://pris.iaea.org/PRIS/WorldStatistics/WorldTrendinElectricalProduction.aspx.
[9] International Energy Agency (2021): https://www.iea.org/data-and-statistics/charts/world-electricity-generation-mix-by-fuel-1971-2019
[10] International Atomic Energy Agency, Power Reactor Information System (PRIS), accessed January 2024, https://pris.iaea.org/pris/.
[11] International Atomic Energy Agency (2023) Nuclear Power Reactors in the World, IAEA, Vienna, Austria. https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-2-43_web.pdf, table 5.
[12] International Energy Agency (2022), Nuclear Power and Secure Energy Transitions From today's challenges to tomorrow's clean energy systems. https://iea.blob.core.windows.net/assets/016228e1-42bd-4ca7-bad9-a227c4a40b04/NuclearPowerandSecureEnergyTransitions.pdf, p. 23.
[13] World Nuclear Industry Status Report (WNISR) (2023) Figure 14 https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2023-.html
[14] The Post and Courier (2023): https://www.postandcourier.com/news/two-identical-nuclear-projects-one-in-georgia-and-one-in-south-carolina-only-one-survived/article_4954353a-b8f6-11e7-be85-f341791366a7.html.
[15] International Renewables Energy Agency (IRENA), accessed January 2024. https://www.irena.org/Data/View-data-by-topic/Costs/Global-Trends.
[16] Lazard (2023) Levelized Cost of Energy+. https://www.lazardcom/research-insights/2023-levelized-cost-of-energyplus/.

plants in operation or under construction in the United States (Vogtl 3 and 4) and Europe (Flamanville-3, Olkiluoto-3, and the two units at Hinkley Point C) are all well above US$100/MWh.[17]

Lower cost numbers appear possible for reactors supplied or operated by state-owned actors, or in nonmarket electricity systems involving the governments of Russia, China, South Korea, and France, though lack of transparency makes verification difficult. Still, there is no known market where electricity from new nuclear power is less expensive than new solar or wind power built in the same period.

System benefits and costs

An often-repeated argument for nuclear power is that it provides frequency control for stabilizing the grid without receiving any economic compensation for this delivery. Indeed, large synchronous generators and heavy turbines do provide frequency stabilization support because of their rotating energy. However, the same support can be provided at low cost through other rapidly developing technologies: rotating equipment such as wind turbines, as well as batteries, capacitors, and power electronics connected to the grid.[18]

The rotating energy available for grid stabilization from the rotating synchronous generators is already small in many systems compared to the energy in rapidly growing amounts of batteries available for the grid in homes, cars, and dedicated grid-connected battery units.

For the economic value of nuclear power plants, it should also be noted that if they are to be compensated for their contribution to stabilizing the grid, they should also have to pay for the disturbance they cause when they suddenly shut down production in unplanned outages.[19]

The stabilizing capacity is also limited to small disturbances. Outside a narrow range of frequency or voltage, nuclear power plants instead will contribute to the kind of chain effect that has caused many major system breakdowns. A recent case was the 26 April 2023 experience in Sweden when a disturbance caused by maintenance work was amplified as two reactors shut down at the Forsmark nuclear plant.[20]

The argument that nuclear power is necessary to handle periods of *dunkelflaute* (when lack of wind and sun prevent electricity production from those sources) can also be dismissed as insignificant for the economic competitiveness of nuclear energy. There are numerous other ways of balancing the grid at lower cost, e.g., demand flexibility—especially with industrial-process heat and hydrogen production, batteries, and gas turbines operating with renewable fuels. Exact costs and benefits are difficult to pinpoint due to rapid technology developments and different geographical contexts and system characteristics. But in competitive electricity markets with balance-responsible parties searching lowest-cost solutions, this is a market issue. As illustrated by real market experience, nuclear plants are unlikely to appear competitive for the purpose of providing flexible balancing power in systems with increasing shares of renewables.

Another motivation for civilian nuclear power is that it provides competence, equipment, and fissile materials that may also be used for military purposes, e.g. nuclear weapons and submarines. The ambition to acquire nuclear weapons, or nuclear capability (the ability to produce nuclear weapons in a short period of time if deemed desirable), may be important for some new nuclear countries. Even for existing nuclear-weapon states, these motives are explicitly used as arguments for civilian nuclear power.[21]

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[17] On Vogtl see: https://www.lazard.com/media/2ozoovyg/lazards-lcoeplus-april-2023.pdf, p. 2, and https://www.powermag.com/blog/plant-vogtle-not-a-star-but-a-tragedy-for-the-people-of-georgia/; On Flamanville see: https://www.ccomptes.fr/en/documents/53853, p. 12; On Hinkley Point C see: https://cfd.lowcarboncontracts.uk/ (search for Hinkley). Olkiluoto-3 is similar to the other EPR projects but less transparent due to the restructuring and government bail-out of the supplying company Areva/EDF.

[18] National Renewable Energy Laboratory (2020). https://www.nrel.gov/news/program/2020/inertia-and-the-power-grid-a-guide-without-the-spin.html; Energy Storage News (2022), https://www.energy-storage.news/upgrade-at-tesla-battery-project-demonstrates-feasibility-of-once-in-a-century-energy-transformation-for-australia/.

[19] Swedish Centre for Business and Policy Studies (SNS) (2023), "A technology neutral electricity market with an efficient market design and tariff structure", https://www.sns.se/artiklar/en-teknikneutral-elmarknad-med-en-effektiv-elmarknadsdesign-och-nattariffstruktur/ (in Swedish).

[20] Swedish Grid Authority (SvK) (2023) "Report on the disturbance 26 April 2023. https://www.svk.se/siteassets/om-oss/rapporter/2023/rapport-driftstorning-2023-04-26_slutversion.pdf. (in Swedish)

[21] French and UK Government sources including: https://www.federalregister.gov/documents/2017/04/05/2017-06463/production-of-tritium-in-commercial-light-water-reactors; .

This military value comes with a disadvantage that nuclear facilities may also become targets in a war, resulting in severe damages and long-term radioactive contamination. Pre-emptive strikes at reactors to make nuclear weapon manufacturing more difficult have been carried out at the Osirak reactor in 1981 and against a Syrian reactor in 2007.[22]

Threats to attack a reactor to cause radiological damage may also be used for political purposes. The threats and simulated attacks against the Slovenian Krsko nuclear plant during the Balkan war are one example.[23] In nuclear war scenarios, attacking reactors may be seen as a radiological amplifier of the Impact of nuclear weapons.[24] The costs and benefits of civilian nuclear power in this military context are of course difficult to monetize and quantify.

The additional external cost

The consequences of ionizing radiation from radioactive pollution have been seen as increasingly harmful to human beings. Cancer risks, as described by International Commission on Radiation Protection have increased by a factor 10 since the first nuclear power reactors were built[25]. The Sellafield studies increased the complexity,[26] while genetic effects and cardiovascular disease as a result of ionizing radiation are appearing more likely.[27]

Nuclear waste has gone from being seen as a potential source of income for nuclear power plants in the early days of the nuclear era,[28] to an increasingly expensive consequence of nuclear electricity generation. Such costs are now extensively socialized in most countries with commercial nuclear reactors and competitive markets.[29]

In Sweden, where the official policy for a long time was that the industry shall carry the full economic liability for waste management, the parliament changed the law in 2020 after scientists discovered that the copper cover on the iron containers intended for spent fuel repositories may corrode in 100 rather than 100,000 years. Future taxpayers will bear the liability once the repositories are closed.[30]

Despite the socialized long-term waste risks in Sweden, the required payments by the reactor operators have recently increased to levels on the order of US$4–8/MWh, or one-fifth to one-third of the expected future electricity generating costs in Sweden.[31]

Possibly even more significant economically are the costs associated with reactor accidents. The risks are no longer as abstract as they were in the 1960s. In close to 20,000 reactor years of operation, approximately 10 reactors have been closed after partial or complete core melts.[32]

Core melting events will result in a combination of lost generation and unintended high costs of decommissioning. As long as no external parties are involved, the costs may be covered by a combination of insurance and costs borne by the owners. Larger events may result in bankruptcies moving costs to taxpayers.

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[22] National Security Archive (2021). https://nsarchive.gwu.edu/briefing-book/iraq-nuclear-vault/2021-06-07/osirak-israels-strike-iraqs-nuclear-reactor-40-years-later; The Washington Institute (2018). https://www.washingtoninstitute.org/policy-analysis/israels-2007-strike-syrian-nuclear-reactor-lessons-learned-iran.

[23] The Nuclear Society of Slovenia (1992) "Vulnerability of the Nuclear Power Plant in War Conditions". https://www.osti.gov/etdeweb/servlets/purl/20892171#:~:text=On the other hand there,a protection of the core.

[24] Reference Scenario: How A Nuclear War Might Be Fought (1982). https://www.jstor.org/stable/4312774?searchText=&searchUri=&ab_segments=&searchKey=&refreqid=fastly-default:e3c17fdfaa0027e06317a19d713cb135&seq=1.

[25] Bengtsson, Gunnar 1985: Consequences of the new ICRP Recommendations in Sweden. Presentation at NVVS 30th anniversary congress, Arnhem, 4-5 October.

[26] Dickinson H.O. and Parker L. (2002) "Leukaemia and non-Hodgkin's lymphoma in children of male Sellafield radiation workers", International Journal of Cancer, Vol 99, Issue 3. https://onlinelibrary.wiley.com/doi/10.1002/ijc.10385.

[27] Little et al (2023) "Ionising radiation and cardiovascular disease: systematic review and meta-analysis", The British Medical Journal. https://www.bmj.com/content/380/bmj-2022-072924.

[28] Goldring, Mary S. (1957), *The Economics of Atomic Power*, New York: Philosophical Library, pp. 69–77.

[29] For Britain see Thomas S (2023) "UK Nuclear Waste Policy: 50 Wasted Years", Chapter in Arentsen and van Est ":The Future of Radioactive Waste Governance Lessons from Europe, Springer. https://link.springer.com/chapter/10.1007/978-3-658-40496-3_8; For Germany see Clean Energy Wire "German utilities buy out of nuclear waste liability for 23.6 bln euros": https://www.cleanenergywire.org/news/german-utilities-buy-out-nuclear-waste-liability-236-bln-euros.

[30] Swedish Government (198471992) "Legislation on nuclear activities". https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/lag-19843-om-karnteknisk-verksamhet_sfs-1984-3/ §5J (in Swedish)

[31] Swedish National Debt Office (2024) "Decision on nuclear waste charges 2014", https://www.riksgalden.se/sv/press-och-publicerat/pressmeddelanden-och-nyheter/nyheter/2024/beslut-om-karnavfallsavgifter-for-2024/ (in Swedish)

[32] While the definition of core melts, as well as which reactors to include among power reactors, may be challenged, a rough list may include St Lucens GHHWR in 1966, Bohunice A1 in 1977, Three Mile Island 2 in 1979, Chernobyl 4 in 1986, Greifswald 5, and finally three reactors at Fukushima Dai-ichi in 2011. This list may also include The Sodium Reactor Experiment, Sankt Laurent A-1 and A-2 as well as Chapel-cross-2. There are also non-power-producing reactors where core melting has occurred.

The most extreme costs have been associated with Chernobyl's reactor no. 4 explosion in 1986 and the core melts of three reactors at Fukushima Daiichi in 2011. Unlike car owners, reactor owners do not have to be able to pay for the damages they cause. The costs of large accidents are assumed to lie with victims not being compensated for their losses or with taxpayers. The direct costs in these cases are in the order of hundreds or thousands of billions of dollars, and additional health effects are difficult to assess.

Based on the relative frequency of accidents, and the available data on the estimated costs of Chernobyl and Fukushima excluding the health effects, this may appear as a subsidy in the order of US$2–40/MWh.[33]

Thus, the socialized costs for nuclear waste and accidents per unit of energy may well be of the same magnitude as the total cost of new solar and wind electricity. As they are at the same time difficult to quantify, this provides a strong case for market valuation so that those who claim low costs are forced, as much as possible, to assume the economic liability.[34]

We must also acknowledge that there is an intergenerational issue where decisions taken today will impose costs on future generations—both physically and economically—something that should be avoided.

Small modular reactors - the nuclear Industry's last battle?

As conventional, large-scale nuclear power plants struggle with economic competitiveness, new, visionary reactor concepts have been presented. Claims regarding the low-cost potential of small modular reactors (SMRs) and possibly other advantages are frequently made.

SMRs are typically defined as smaller than 300 MW-electric. A key argument made In their favour is that their modular design would allow them to be produced in large numbers—which, like with solar PV systems and wind turbines, would allow for learning effects and reduced costs. Other arguments are that immediate shutdowns would be less problematic for the grid, and that their small size would make them suitable for combined heat and power generation if located close to district heating systems or industries in need of process heat.

Many of the SMR concepts are of the kind that were already dismissed by nuclear engineering veteran Hyman Rickover in 1970 as unrealistic 'academic reactors', able to seduce politicians who are unable to understand the complexities of real reactors.[35]

Although SMR developers often claim that they will achieve (or target) levelized costs of electricity of US$50–60/MWh, there is no evidence that this can ever be achieved. Amory Lovins explained, in a 2022 analysis, why SMRs can never become competitive: electricity from small reactors has higher cost than electricity from large reactors, which already costs several times more than solar or wind electricity. The learning potential is limited since about four-fifths of the non-nuclear components in these designs are common to thermal power plants, where experience is already extensive. Given the continued learning effects and reduced costs of solar and wind electricity, SMRs can, he argues, never be competitive. He concludes that, even if the industrial learning on the nuclear reactor part of the power plant is so successful that the reactor can deliver steam for free, the SMRs will still not be able to compete with solar or wind electricity, due to the capital costs of non-nuclear SMR components.[36]

In addition to the cost challenges, the former chairman of the US Nuclear Regulatory Commission, Allison Macfarlane, has also pointed to the increased waste problems, as well as safety and safeguard issues with SMRs.[37]

Conclusion

The nuclear industry has struggled with delays and high costs throughout its history. Yet new promises are being made that nuclear power is part of the solution to the climate crisis. Hopes are created and promises made that SMR designs that are on

[33] Kåberger t. (2019) "Economic Management of Future Nuclear Accidents" in Haas et al. *The Technological and Economic Future of Nuclear Power.* Springer. https://doi.org/10.1007/978-3-658-25987-7_9
[34] ibid
[35] US Government Printing Office (1970) Hearing before the joint committee on atomic energy congress of the United States. https://www.google.se/books/edition/AEC_Authorizing_Legislation_Fiscal_Year/s0-W6Hq_wX0C?hl=en&gbpv=1&dq=Hearing+before+the+joint+committee+on+atomic+energy+congress+of+the+united+states+ninty-first+congress+second+session+on+special+nuclear+materials;+light+water+breeder+reactor+(LWBR)+part+4&pg=PA1619&printsec=frontcover
[36] Lovins A.B. (2022) "US nuclear power: Status, prospects, and climate implications". The Electricity Journal, Vol. 35, Issue 4. https://www.sciencedirect.com/science/article/pii/S1040619022000483
[37] See Krall et al (2022) "Nuclear waste from small modular reactors", PNAS. https://www.pnas.org/doi/10.1073/pnas.2111833119; and also Institute of Art and Ideas (2023) " The end of Oppenheimer's energy dream, Modular reactors are supported by ideology alon". https://iai.tv/articles/the-end-of-oppenheimers-energy-dream-auid-2549

the drawing table will be inexpensive and lead to a revival of nuclear power. However, the assessment presented in this paper concludes that there are no convincing facts or arguments to support the idea of a nuclear renaissance, whether large-scale or modular. The direct costs of producing electricity are simply too high, and competing power system technologies are developing rapidly, further eroding the economic prospects for civilian nuclear power. It is also associated with substantial external and often socialized costs.

Thus, nuclear power will be outcompeted in all reasonably efficient and liberalized electricity markets. It is only through subsidies and government guarantees that new construction will occur in such markets, typically motivated by the need for nuclear capabilities to support military applications, or by misguided political beliefs that nuclear is necessary for a reliable power system.

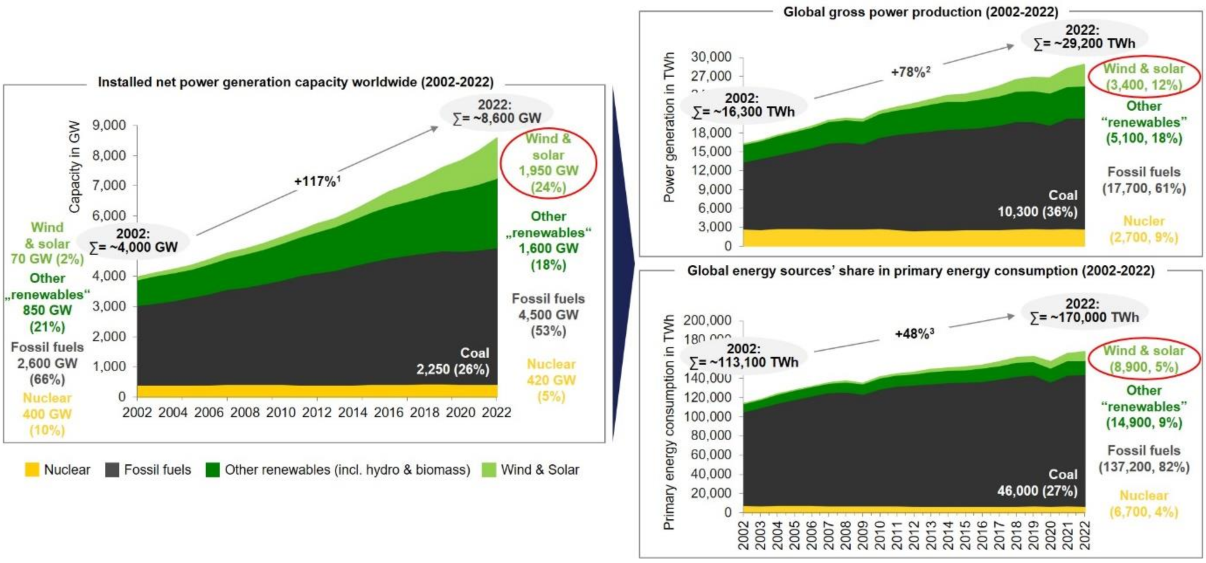
THE ROLE OF NUCLEAR IN THE GLOBAL WORLD OF ENERGY

Lars Schernikau

The world's first nuclear power plant started operation near Moscow in 1954. The following decades saw hundreds of nuclear reactors being built around the world, with the United States, France, and China leading the build-out, making up about half of today's global installations. About 90 per cent of today's operating nuclear reactors were built during the 1970s and 1980s, with a global average reactor age of about 32 years. Apparently over 90 per cent of US reactors received extensions to operate up to 60 years.

The world hosts about 420 GW of installed nuclear capacity, expected to rise to about 620 GW by 2050. Thus, today about 5 per cent of a total of 8.6 TW of installed power capacity is nuclear.[38] The over 400 nuclear reactors contributed almost 10 per cent of global electricity generation of about 29,000 TWh in 2022 (Figure 1). (Only about 40 per cent of global primary energy of over 170,000 TWh is used to generate electricity; the other 60 per cent is used for industry, heating, and transport.)

Figure 1: Global power capacity, power production, and primary energy



Sources: Schernikau based on International Energy Agency (2023), https://www.iea.org/reports/world-energy-outlook-2023; Energy Institute (2023), *Statistical Review of World Energy*, (https://www.energyinst.org/statistical-review)

Note: the author writes "renewables" because they are in fact not truly "renewable" when the life cycle and raw material and energy input as well as entire environmental impact is considered. For instance hydro energy has large scale environmental impacts.

Nuclear is the most net energy-efficient and raw-material-efficient source of power, with an energy return on energy investment (eROI) possibly twice or more that of coal, gas, or hydro. Nuclear is also one of the safest forms of power generation, measured in deaths per MWh generated, with the least environmental impact.

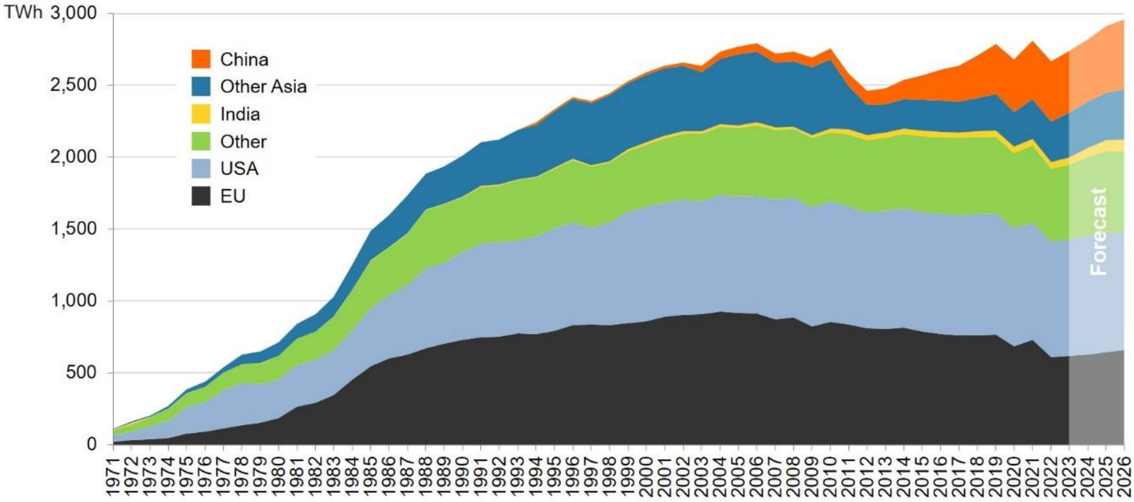
[38] IEA WEO (2023), https://www.iea.org/reports/world-energy-outlook-2023.

That makes it more surprising that nuclear contributes only a relatively small share of global electricity. Even more startling is the fact that nuclear's share has continuously declined, as its build-out did not keep up with global electricity demand growth. While nuclear accounted for almost 17 per cent of global power generation in 2002, this number declined to 9 per cent in 2023, because absolute generation remained largely unchanged at about 2,700 TWh (Figure 2).

This might change after COP28, with 22 nations pledging to triple nuclear power by 2050. This would imply about 30 GW per year until 2050—a five-fold increase from the past decade, but in line with the boom times during the 1980s. But will this make a difference or solve the global energy problem?

Primary energy demand is likely to increase 40–50 per cent by 2050, driven by a population increase of about 20 per cent and per capita energy consumption growth of about 25 per cent. Electricity demand will certainly increase faster, not only because of the current, not always energy efficient, push to 'electrify everything'. It is therefore obvious that nuclear will contribute to this growth. However, in absolute terms, other sources—most likely dispatchable coal and gas, but also, if direct and indirect subsidies continue,[39] intermittent wind and solar—will make up the majority of capacity growth.

Figure 2: Global nuclear power generation



Source: IEA Electricity 2024 (https://www.iea.org/reports/electricity-2024)

Fuel and technology

Uranium is abundant globally, in granitic rocks and dissolved in the ocean, but not all of it is viable for use in energy generation. In theory, the amount is easily sufficient to supply all human energy requirements. However, there are concerns about getting access to sufficient uranium, enriched uranium, and nuclear fuel assemblies.[40] Over 50 per cent of commercially viable uranium resources are found in Australia, Kazakhstan, and Canada;[41] Kazakhstan mines over 40 per cent of the world's uranium. The United States now depends entirely on uranium imports, and even Russia consumes twice what it produces.

A serious concern about fuel availability may throw shadows over some exciting technological advances, such as fourth-generation reactors or small nuclear reactors, or may encourage further funding for thorium reactors. The world's first fourth-generation high-temperature gas reactor nuclear power plant—which contains a pebble bed reactor, run by the China National Nuclear Corporation—started operating at the end of 2021.[42] Thorium-based nuclear power promises various advantages, including better fuel availability, higher efficiencies, less waste, and low weaponization potential. Small modular nuclear reactors

[39] Global average subsidies for wind and solar per MWh are far higher than subsidies for coal, gas, or nuclear—https://robertbryce.substack.com/p/actually-solar-is-getting-302-times?publication_id=630873&utm_campaign=email-post-title&r=79kdr; www.unpopular-truth.com.

[40] Nuclear News Wire (2023), on the verge of a crisis, https://www.ans.org/news/article-4909/on-the-verge-of-a-crisis-the-us-nuclear-fuel-gordian-knot/.

[41] World Nuclear Association.

[42] Global Times (2021), https://www.globaltimes.cn/page/202112/1242878.shtml.

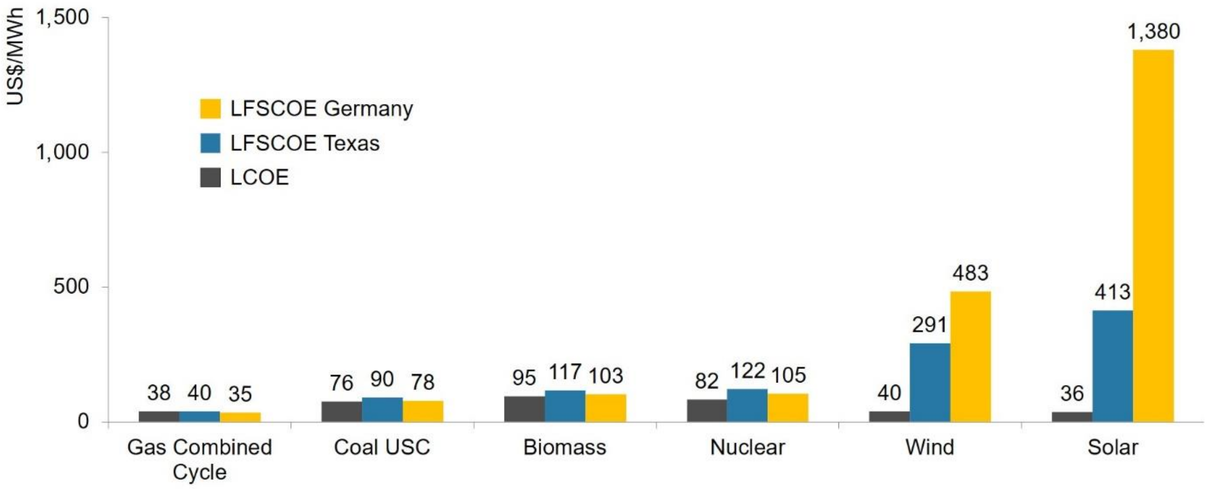
(SMRs) are an interesting development as they may allow more cost-efficient, standardized, high-volume mini-reactor construction. SMRs, rarely ‘small’, are usually defined as being less than 300 MW in size and may be as small as 5 MW; they could generate thermal and/or electrical power. There are currently probably around 70 SMR projects worldwide in development. SMRs could be more flexible in use, and may even ramp up and down faster.

Costs

Current nuclear power plant costs vary as widely as the time it takes to build one. US$2–13 million per MW and 4–25 years are the widely known ranges. While 40 per cent of nuclear power plants were built within six years, mostly in China, the lowest-cost plants are built in China, India, and South Korea. The most expensive ones stand or will soon stand in the United States and the United Kingdom. The high cost and construction delays in the West stem primarily from regulation—which, in the author’s opinion, cannot be justified economically or scientifically. It is hoped that the recent increase in support for nuclear, as demonstrated in COP28, may change this.

At full system cost (full cost of electricity, FCOE, or levelized full system cost of electricity, LFSCOE), nuclear is likely the most expensive of all conventional or dispatchable ways of generating power (Figure 3). Yet it is still significantly cheaper than wind and solar and offers negligible emissions. However, the stated levelized cost of electricity (LCOE), a marginal cost measure, of wind and solar is very low.

Figure 3: Full system cost of nuclear vs alternatives



Sources: Bank of America, https://advisoranalyst.com/wp-content/uploads/2023/05/bofa-the-ric-report-the-nuclear-necessity-20230509.pdf, based on Idel (2022), https://www.sciencedirect.com/science/article/pii/S0360544222018035.

Note: The author supports Idel’s principle of full system cost and its impact on wind and solar costs compared to dispatchable power from nuclear, coal, or gas[43], USC = Ultra super critical, LCOE = Levelized Cost of Electricity, LFSCOE = Levelized Full System Cost of Electricity

The claim that renewable energy from wind and solar is cheap and comes without environmental consequences is a crucial and detrimental energy-economic misunderstanding. LCOE is not appropriate for use in comparing intermittent sources of power with dispatchable ones.[44] LCOE is a microeconomic instead of total system view, excludes seven cost categories (listed below), and therefore will never be an accurate indicator for governments to base energy policy decisions on. It does not consider or account for intermittency, low natural capacity factors, correlating wind and solar availability across continents, and the locational disparity of demand and supply.

[43] The author does not support Idel 2022 numbers for coal and gas, as coal, on average, has lower costs than gas. For instance, BloombergNEF recently confirmed that coal is lower cost than gas, but the actual cost differ by country, BloombergNEF (2023), https://about.bnef.com/blog/cost-of-clean-energy-technologies-drop-as-expensive-debt-offset-by-cooling-commodity-prices/.
[44] Schernikau (2024), https://www.eurasiareview.com/17012024-the-energy-trilemma-and-the-cost-of-electricity-oped/.

Obvious costs omitted from LCOE include the following:

1. **Backup or long-duration energy storage**—wind and solar require at least 100 per cent backup or storage for every installed MW. This is due to energy losses in backup and storage systems as well as the fact that usually more than one backup/storage system is required, for instance for short and long-duration energy storage.
2. **Network integration**—this includes costs for transmission, distribution, balancing, and conditioning.

Not so obvious costs omitted from LCOE at grid scale include the following:

1. **Efficiency losses**—more wind and solar means less asset utilization of backup or grid systems.
2. **Room costs**[45] or space requirements—these are driven by low energy density (per m²) of wind and solar. There is an economic and environmental cost to utilizing thousands of km² to capture the diffuse energy from the sun and wind.
3. **Recycling costs**—these are driven by the low energy density (per kg) and short lifetime of wind and solar.
4. **Environmental costs** during operation—these include the damage to plant and animal life and negative effects on climate systems from power generation, including from warming, wind extraction, and atmospheric changes.
5. **Raw material and net energy inefficiency** along the entire value chain—this includes production, processing, transportation, upgrading, manufacturing, and recycling, and the environmental impacts independent from the power generation itself.

If one considers the above-mentioned network integration, backup/storage, operational lifetime, energy density, and (of course) intermittency issues, then wind and solar are in fact by far the most expensive. In reality, wind and solar's full system cost rises exponentially with higher penetration levels in the system, which has been indirectly confirmed by the Organisation for Economic Co-operation and Development OECD, International Energy Economics Institute IEEJ, International Energy Agency IEA, and other energy economic institutions.[45]

Conclusion

It appears that the COP28's push to advance and support nuclear power globally is the right thing to do. A lot of potential remains with much larger nuclear penetration globally. A pledged tripling of nuclear from 2022 (2,700 TWh or 9 per cent of about 29,000 TWh globally) would translate to about 8,000 TWh of nuclear by 2050. If the electrification continues, the International Energy Agency's *World Energy Outlook 2023* estimates 50,000 TWh global electricity generation by 2050. Thus, nuclear's share would then increase to just over 15 per cent, still shy of its 17 per cent share in 2002.

Thus, from a macroeconomic point of view, there is no realistic scenario in which nuclear will suffice to meet the growing energy demand of the next 30 years, because of (1) timing, (2) costs and regulation, and (3) the sheer volume of energy demand growth. The sobering unpopular truth is that, even if COP28 nuclear targets are met, which is necessary but still a stretch, it will only satisfy a fraction of the energy demand growth until 2050, and we will require oil, coal, gas, hydro, "renewables", and all other reliable forms of energy-dense supply to make up the rest.

[45] Schernikau et al. (2022), https://dx.doi.org/10.2139/ssrn.4000800.

ESTABLISHING CONFIDENCE IN NUCLEAR ENERGY: A STUDY OF 120 YEARS OF EVIDENCE AND 80 YEARS OF MYTH

Wade Allison

Plentiful energy, available anywhere and at all times, is essential to a thriving society. But there are only three types of primary energy source widely available on Earth today: sources commonly called the renewables, fossil fuels, and nuclear. Secondary sources, like hydrogen and electricity, are important but rely on a primary source. The contrast between the three is evident from the weight of fuel—energised material—sufficient for one person in an advanced nation to cover food, heating, transport, and other needs throughout their life. For the three primary energy source types this might be 10 million tonnes of water from a dam 100 metres high, the combustion of a thousand tonnes of coal, or the fission of one kilogramme of uranium-235. (The masses of other energy sources in any given category are similar.) These numbers are based on firm natural science, not speculative technology. But why are they so different? And how are the sources stabilised and controlled?

The recent international agreement at COP28 calls on the world to 'transition away from fossil fuels in energy systems' and 'accelerate technologies including renewables [and] nuclear'. But only nuclear has the energy to fill the gap left by fossil fuels sufficiently to avoid economic collapse. Though many are fearful of nuclear energy as being too powerful, everybody should ask whether this matches experience. Posters exhort rail passengers in the UK today, *If you see something that doesn't look right, report it—See it, Say it, Sorted!* But leaving judgement to higher authority, as the tale of the Emperor's New Clothes illustrates, easily leads to neglect of evidence. Indeed, does the pressure on authority to continue the inherited mantra on nuclear energy involve such blindness?

The misunderstanding of nuclear energy

The Fukushima Daiichi accident in March 2011 was perceived throughout the world as a major disaster. It precipitated near-panic in Japan and worldwide changes in energy policy. However, the released nuclear radiation caused no casualties—no one was hurt at the time or is likely to be in future. The reactions were not justified. The same happened following the accident at Three Mile Island in 1979. At Chernobyl in 1986 there were 28 fatalities from acute radiation syndrome, but no evidence for the thousands of fatalities predicted by experts. And no other radiation accident has recorded a significant loss of life at a nuclear power plant, anywhere in 70 years.

In such accidents, mass evacuation and food restrictions, hurriedly arranged by ill-informed authorities, contribute to public fear and a loss of trust in society. The payment of compensation and misdirected mitigation measures amplify the damage to mental health and add to the bewilderment. Whenever confidence ebbs, lawyers and accountants search for somebody responsible, insurance is reassessed, and cost estimates rise inevitably. Everybody thought that these were exceptional exposures to nuclear energy and its radiation—but that was incorrect.

Ever since life appeared on Earth, it has been bathed in radiation. Although we cannot feel them, some 7,000 radioactive decays occur in our bodies every second, and more radiation from space, nearby rocks, and other materials passes through us, too. Because life evolved in this environment, it learned to cope with it safely long ago; otherwise we would not be here. Fortunately, it devolved the job of replacing cells, repairing DNA, and neutralising the molecular garbage that radiation leaves, to cells and local groups of cells in the body. The central nervous system and the brain are not alerted. So animals, and plants too, are fully protected from the effects of low and medium doses of radiation without knowing it. That is why the flora and fauna in the Chernobyl evacuation zone survive unscathed, and today they are flourishing despite their residual radioactivity. They are fortunate to be spared the exciting accounts of the accident that continue to stimulate human society.

Humans suffer by having made instruments that detect radiation. This then frightens them, and although they cannot feel anything, their imagination urges them to protect themselves—somehow. Such worries attract the services of regulators, insurers, and other authorities, who can often do little. But provided the radiation level is not too high, their services are unnecessary anyway.

In fact, most humans have a friend or relative who has received rather high doses of radiation for their own health, as part of a course of cancer therapy. Such benefits are not new. They are built on the legacy of Marie Curie, who won Nobel prizes in both physics and chemistry before applying the science in medicine more than a century ago. The threshold at which a radiation dose rate becomes possibly dangerous was settled by international agreement in 1934. Whereas many of the biological mechanisms have been elucidated and the data available have vastly increased, there has been no reason to doubt the safety threshold chosen 90 years ago.

The energy of chemical and nuclear fuels

Human supremacy on Earth began with the ability to control fire, perhaps a million years ago. This required study to establish how it worked and the ability to then teach others how to use it safely. Critically, unlike other animals, humans were able calmly to overcome their innate fear. However, the fuel supply was inadequate until the Industrial Revolution. Then fossil fuels became widely available and the technology of engines translated the heat of combustion into mechanical work. At that point the ideal provision of energy seemed to have been found. The population of the world quadrupled and life expectancy doubled. Admittedly, not everybody had access to fossil fuels, and this inequality became a principal driver of economic and political activity.

Beyond naming it ‘chemistry’ and sorting out its pattern of behaviour, the underlying science of combustion remained obscure. A lump of coal has no apparent moving parts or springs—its energy resides internally. All matter is composed of atoms containing electrons, and at the centre of each atom is a nucleus containing protons and neutrons. In 1924 a young French PhD student, Louis de Broglie, provided an amazingly simple universal explanation of the motion (speed v) of these electrons, protons, and neutrons (mass m). His thesis was that they are described by waves of length, h/mv, where h is Planck’s constant. This wavelength of vibration is set by the size of the region, L, like the pitch from a musical instrument. The smaller the region, the higher the pitch. The kinetic energy of an electron in an atom is $h^2/8mL^2$, and this well matches the energy scale of chemistry, electronics, batteries, food, and other forms.

But the same calculation can be made for neutrons and protons in any nucleus. There, L is 100,000 times smaller and the particles have mass m 2,000 times larger than an electron. Thus, the kinetic energy is 5 million times greater—that is the scale of nuclear energy relative to fossil fuel energy. A follower who got the message early was Winston Churchill. In 1931 he wrote an article in the *Strand Magazine*:

> The coal a man can get in a day can easily do five hundred times as much work as the man himself. Nuclear energy is at least one million times more powerful still … The discovery and control of such sources of power would cause changes in human affairs incomparably greater than those produced by the steam-engine four generations ago.

He was right. In 1931 nobody knew how to extract this energy, but that was solved in a few years. A greater problem was that human society was culturally ill prepared for a million-fold increase in available energy—and still is today.

The control and safety of nuclear energy

Except at temperatures of millions of degrees, nuclei are prevented from ever reaching one another. This nuclear celibacy is enforced by the intense electric barrier that surrounds each. The uncharged neutron is the only key to penetrating the barrier and releasing the energy within. But neutrons are rapidly absorbed and decay in a few minutes, giving prompt control and ideal security. Exceptionally, a neutron can fission a nucleus, leaving two nuclear fragments, a few more neutrons, and considerable energy. The process is simply halted by absorbing the neutrons.

A secondary process is the radioactive decay of the unstable nuclear fragments with the emission of radiation some time later. Unlike fission, this decay is uncontrollable, and its energy, a few percent of fission, must be dispersed; otherwise, the temperature rises, and materials melt or burn, chemically. However, in such a meltdown, the elevated temperature has no effect whatever on the release of nuclear energy. Some radioactivity may be scattered in the environment by physical or chemical explosion, as happened at Fukushima Daiichi after the cooling failed.

Radiation damages atoms and molecules but does not affect nuclei. Consequently, neither radioactivity nor its radiation can spread by contagion, like an infection, or by ‘catching’, like fire. This is useful to know following an accident, but is seldom stated! Radiation does not make materials or people radioactive. In fact, for an exposure below the 1934 threshold there is nothing for radiological protection authorities to worry about. But they have jobs—and so readily don a hazmat suit as a uniform that signals fearsome danger. This is not reassuring for the public.

This situation is not without precedent. The public have been scared of technological change before. Prior to 1896 the public were alarmed that high-speed steam engines might be permitted on the roads. So the speed was limited to three miles per hour with someone walking in front waving a red flag. When smaller cars appeared, the authorities acknowledged the economic case for change, and the Red Flag Act was repealed. Today, a similar economic uplift is expected with the introduction of small, simpler nuclear reactors, deliverable as a whole or in modules from a factory by road. But first, the restrictive precautionary regulations, like the Red Flag Act, should be replaced by ones based on evidence.

The era of nuclear fear

Every new energy revolution has increased the power to destroy life and property. The chemical energy of gunpowder, dynamite, and TNT increased fear, overtaking the power of archery and the sword to strike an adversary. So in 1945 the arrival of nuclear weapons with their million-fold energy enhancement traumatised society. Talk of widespread mass annihilation provoked a political frenzy as access to nuclear weapons spread to more nations. Large political demonstrations, public marches, and organised petitions were part of public life for three decades and more. The secrecy of weapons development and the threat of large opposing arsenals effectively demonised the image of nuclear energy and radiation. Some countries outlawed nuclear technology completely—except in medicine, notably. More widely, radiation regulations were enacted with safety set some 500 times more cautiously than in 1934, but without supporting evidence. Today we inherit a legacy of inept regulation with a frightened and ill-informed populace. In democracies this obstructs the deployment of the civil nuclear technology that we need.

But what are the dangers to life from radiation? In the early decades of the Cold War it was feared that genetic damage from exposure to radiation might be inherited by later generations. However, thorough studies of all survivors of Hiroshima and Nagasaki and their descendants show no evidence of this. Unfortunately, such ghoulish stories are kept alive in the public imagination by science fiction.

Cancer is not inheritable, but radiation is carcinogenic at high dose rates. Among the Hiroshima and Nagasaki survivors who received doses below 30 times the chronic threshold agreed in 1934, there is no evidence of additional cancer or leukaemia. Published evidence for those with greater doses suggests 573 additional cancer deaths between 1950 and 2000. This is about a third of the 1,600 to 2,000 who died from the inept evacuation at Fukushima Daiichi, suggesting that fear can be more dangerous than radiation, even from nuclear weapons. Contrary to what many have been led to believe, the huge death toll from the bombs dropped on Japan was from the immediate blast and fire, not the delayed effects of radiation such as cancer and leukaemia.

Nuclear versus renewables on sustainability and security

Exorcising this image of nuclear in the public mind may take a generation or two. School teachers should study the evidence, and the syllabus they teach should match the science. Trust should grow as school children explore what radioactive sources do in smoke detectors and what they see on school visits to radiotherapy units and nuclear power plants. Children explaining to their parents what they have learned at school is a potent tool of social education.

Energy security is also a matter of confidence. Nuclear fuel supplies can be stockpiled at power stations, safe for future use whatever the weather. A network of small, relatively local nuclear stations, built close to consumers, would reduce the necessity for a large, expensive grid, vulnerable to sabotage and the extreme weather events that now seem likely. With short supply lines, the losses from megawatt-miles would be minimised. Community confidence grows from local security.

If nuclear capacity is matched reliably to provide peak demand, there is no need for separate base-load and backup supplies. Then off-peak energy is available for desalination, hydrogen production, and heavy industrial use. The thermal heat produced can be used for district heating and intensive horticulture or vertical farming, reducing food-miles too. The high energy density of nuclear means that little fuel is required and little waste is produced. Currently there are some 70 realistic reactor designs in development and enough uranium and thorium fuel for many centuries. There is nothing inherently expensive about these designs, but, as in all human activity, a lack of confidence invariably increases perceived risks and inflates costs.

The technology of renewables requires many minerals of limited availability. Batteries, turbine magnets, and solar panels make hungry demands for lithium, cobalt, rare earth, and other elements. Solar and wind installations last about 20 years, a quarter of the time for nuclear. Their energy production is intermittent, only 20–30 per cent, depending on the weather. The success of the Industrial Revolution relied on energy being available in all weathers. Even hydro suffers when the climate shifts. As sources of energy, renewables fail on every criterion except primitive popular acceptability. Yet for 70 years, the lack of such acceptability has been the only reason to reject nuclear energy—a cultural argument that is evidently flawed. Current regulations and outdated bureaucracy are obstructing the exceptional benefits that Churchill foresaw for nuclear energy nearly a century ago. Reform is overdue.

WILL SMALL MODULAR REACTORS DRIVE THE ENVISIONED EXPANSION OF NUCLEAR ENERGY WITHIN THE ENERGY TRANSITION?

H-Holger Rogner, Adnan Shihab-Eldin, and Noura Y. Mansouri

The worldwide adoption of the 2030 Agenda for Sustainable Development and the Paris Agreement in 2015 underscored the need for a profound transformation in the global energy system. The Paris Agreement aims to limit global temperature rise to below 2°C, ideally 1.5°C, above pre-industrial levels by 2050, a goal interlinked with the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda. Affordable, accessible, and clean energy (SDG 7) is crucial for sustainability, climate protection, and operationalizing the Agenda. A transition based on electrifying energy end-uses to the extent possible while decarbonizing electricity generation would go a long way towards meeting the Paris Agreement and SDG objectives, resulting in a steep increase in global electricity demand.

Such a transition involves transforming the entire energy system, economy, and society, not just individual technologies or fuel sources. The transition is more than decarbonization. It can be disruptive and be a continuous challenge balancing the trade-offs while simultaneously implementing all SDGs. And it requires utilizing all available zero greenhouse gas (GHG) mitigation options, including technologies like nuclear energy.

Nuclear energy, a mature, safe, and almost zero-GHG-emitting energy chain, generates steady baseload electricity while maintaining grid stability. It contributes directly and indirectly to all SDGs; without it, net zero emissions cannot be achieved by 2050 under any credible scenario. On balance, from a system perspective, nuclear energy compares favourably with other low-carbon alternatives.

Despite its GHG mitigation potential, nuclear energy has faced opposition from influential stakeholders in sustainable development and climate change discussions, has often been excluded for ideological reasons,[46] and was omitted from key international agreements and discussions since 2002 to avoid derailing negotiations. The opposition stems from purported concerns about radiological safety in the event of rare but potentially catastrophic accidents; nuclear security risks involving cybersecurity, terrorism, and nuclear weapons proliferation; lack of economic viability; and the absence of demonstrable safe options for disposal of spent nuclear fuel. This has delayed numerous national plans and projects. Many of these apprehensions are rooted in sociopolitical factors and public perceptions, often influenced by misconceptions or misinformation.[47]

However, recent geopolitical events and a growing recognition that current efforts are insufficient to meet climate targets point to a shift towards including nuclear energy as an essential component of the energy transition. This change is reflected in significant international decisions, including the conclusions of the 2023 G20 Summit in India; the COP28 Agreement; the pledge by 22 countries, announced during COP28, to triple nuclear energy capacity by 2050; and the EU Parliament's inclusion of nuclear in the EU taxonomy rulebook as climate-friendly and sustainable technology.

Still, this pivotal shift requires widespread buy-in from all stakeholders including governments, businesses, and communities, to collaboratively drive and support the transition towards sustainable energy practices and policies.

By the end of 2023, 412 nuclear power reactors with a total generating capacity of 370 gigawatts-electric were operating in 32 countries and supplying about 10 per cent of the world's electricity. About 60 reactors are under construction globally, with a further 110 planned. Most reactors under construction or planned are in Asia. New builds coming online in recent years have largely been balanced by old plants being retired.[48]

The global nuclear-energy industry has been readying itself for change for quite some time by turning its attention to designing advanced reactors, including an entirely new generation called small modular reactors or SMRs, characterized not only by their smaller size (smaller than 300 megawatts-electric (MWe), in contrast to today's large reactors, which are typically in the 1,000 to 1,700 MWe range) but also by other attractive economic, safety, and security features. Among a multitude of different designs, the first two SMRs are actually in operation, and other designs are in the early stages of construction. In several countries, negotiation is ongoing between a developer and a host electric utility about the terms for deploying projects.

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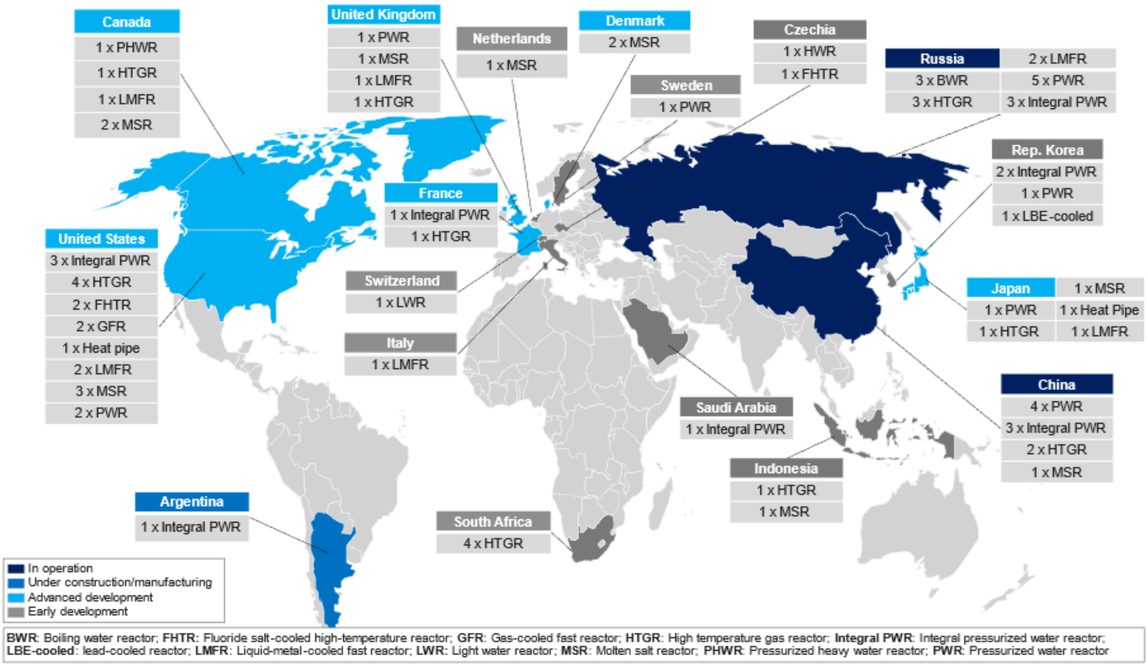
[46] Shihab-Eldin, Adnan, et al. (2021), 'Keeping the nuclear option open', *Oxford Energy Forum,* 129, 45–49, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/09/OEF-129.pdf.
[47] Mansouri, Noura Y., et al. (2023), *The Role of Nuclear Power in Clean Energy and Green Transitions*, Think20, https://t20ind.org/research/the-role-of-nuclear-power-in-clean-energy-and-green-transitions/.
[48] International Atomic Energy Agency Power Reactor Information System (2023), *The Database on Nuclear Power Reactors*, https://pris.iaea.org/pris/.

The SMR reactor designs under development span a wide range of coolant types (water, gas, liquid metal, molten salt, etc.), neutron-spectrum types (thermal neutrons, fast neutrons), moderators (water, heavy water, various other liquids, graphite), and sizes (from as small as a few MWe to a few hundred MWe). Some SMRs also target non-electricity applications such as process heat, desalination, other industrial uses, and marine applications. Also, the prospect of factory-manufactured modules, many of them deployed on the same site, with lower capital cost per unit and significant advances in safety, opens up new perspectives. The SMRs are intended for deployment in both urban and remote areas due to their safety features and ability to connect with existing grids.

About 80 SMR designs are at various development stages in 18 countries (Figure 1). The initial diversity, beneficial for innovation, will eventually need to be streamlined to a few key designs for each energy service category. As of now, over 40 countries have expressed interest in adding SMRs to their energy systems.

Figure 1: Status of the most advanced SMR design and prototype projects by country.[49]



Economics of nuclear energy

Nuclear economics are characterized by large up-front capital costs and long amortization times, but low and stable fuel and operating costs, hence predictable generating costs. Existing nuclear power plants have very low short-run marginal costs, i.e. the costs of an additional kWh of electricity, as only fuel costs arise.

In contrast, long-run marginal costs reflect expected generating costs of new plant and equipment. Traditionally, LCOE (levelized cost of electricity) has been the metric for comparing and ranking electricity capacity investment options before a final decision is made.[50]

Investing in a state-of-the-art 1,000 MWe light-water reactor requires a substantial financial commitment, ranging widely from approximately $2 billion to $8 billion or more, based on numerous factors including the reactor's design, its geographical location, the intricacies of financing and construction schedules, the prevailing regulatory landscape, and the level of sociopolitical backing it receives.

Based on LCOE alone, today on a cost per kWh, new nuclear power projects are generally not competitive versus intermittent low-carbon alternatives as long as the sun shines and the wind blows. But when this is not the case, other costlier or less clean generating options and/or storage need to fill the void left by renewables. These costs are not considered in LCOE quotations.

[49] Kearney Energy Transition Institute (2023), *Nuclear Small Modular Reactors: Holding Disruptive Hopes*, https://www.energy-transition-institute.com/insights/nuclear-small-modular-reactor-holding-disruptive-hopes.
[50] LCOE applies to the level of the individual plant and does not address the value that different generation technology options add to the electricity system at different levels of penetration to provide grid stability with 24/7 supply reliability.

Generation which is out of sync with demand is of greatly reduced value. The expansion of generating capacity, particularly with the integration of intermittent renewables characterized by low capacity factors, will likely outpace the rise in generation itself and thus increases the value of 24/7 generation to the electricity system.

Weighing system benefits against sociopolitical challenges

The energy transition is the last-resort response to potentially cataclysmic climate change caused by anthropogenic GHG emissions. Comparative life cycle assessments of energy chains from resource extraction to conversion, transmission, end-use, and waste management have persistently shown that all technologies without exception generate environmental and health impacts. They also show that nuclear power compares very well with alternative low-emission technologies in terms of emissions, land use, water use, materials, and waste management issues. For example, emissions per kWh of the nuclear chain are among the lowest of all generating options, comparable with the best-performing renewable chains.[51]

Similarly, nuclear power, as well as wind and hydro, offer the lowest health risks per unit of electricity output, including immediate and long-term health impacts of major accidents like Chernobyl and Fukushima. Nuclear regulators persistently ensure the incorporation of state-of-the-art engineered safety features in the design, manufacture, and operation of nuclear power plants to minimize releases of ionizing radiation from nuclear facilities. Multiple levels of defence protect workers and the public from any significant releases of radioactive materials from possible, but low probability, severe accidents.

Nuclear energy in transition

Energy transition involves a continuous interplay between evolutionary, and often revolutionary, structural change and innovation. With regard to nuclear energy, the transition may proceed in three overlapping phases.

Phase 1 involves the long-term operation of the existing global nuclear fleet. Extending the operating licenses of these plants through investments in safety enhancements and overall plant modernization is a least-cost and readily available option for low-carbon generation. Long-term operation is also important for maintaining nuclear expertise, workforce, and a robust safety culture, making it a priority for the next decade.

Phase 2 might see a resurgence in construction of large reactors, even though some may present significant financial and logistical challenges. Western countries grapple with cost overruns and delays, but Asian countries have shown efficiency and cost-effectiveness in their nuclear projects. This contrast indicates a shift in nuclear leadership, with advanced economies having for now lost their edge to more cost-effective Russian, South Korean, and Chinese designs. Sustained nuclear capacity expansion in Asia would be at the centre of Phase 2; its continued success may eventually spill back to the OECD countries and lead to lower-financial-risk nuclear construction projects. While these evolutionary nuclear developments are important elements of the energy transition towards decarbonization, they follow past patterns of nuclear expansion.

Phase 3 could herald a revolutionary paradigm shift with the advent of SMRs which represent a break with the traditional pattern of increasing reactor sizes driven by economies of scale. These innovative reactors offer solutions to the complex challenges of flexibility, economic viability, and safety. SMRs are versatile, capable of being used, in addition to grid integration, in applications like hydrogen production, and supporting industries like water desalination or oil refining. Their designs offer simplicity, modularity, passive safety features, and proliferation resistance, and they can serve in large as well as small grids in remote locations or regions with less developed infrastructure.

SMRs for sustainable energy in emerging economies

Nuclear energy holds the potential to address the ongoing lack of energy access encountered by many developing nations. However, these countries face unique challenges in adopting nuclear energy due to inadequate infrastructures and financing constraints. While adequate legal and regulatory frameworks, physical infrastructure, human resources, and management of sociopolitical factors, including public acceptance, are necessary irrespective of the particular reactor design, SMRs offer numerous benefits for emerging economies. They are more suitable for small grids than large reactors. Their lower capital per unit is easier to finance. SMRs offer effective measures to mitigate energy poverty, increase energy security, and implement the SDGs.

Economic dynamics of SMRs

The economics of SMRs in the absence of traditional economies of scale present a unique setting. SMRs compete in different market niches than large reactors, focusing on aspects beyond just electricity generation. These reactors leverage their modular

[51] United Nations Economic Commission for Europe (2021), *Life Cycle Assessment of Electricity Generation Options*, https://unece.org/sites/default/files/2021-11/LCA_final.pdf.

design for efficient in-factory manufacturing, leading to shorter market entry times and increased likelihood of remaining within budget. In the energy transition, global nuclear capacity expansion would heavily rely on the deployment of SMRs. Their mass manufacturing is expected to harness economies of multiples, effectively offsetting the traditional economies of scale of large reactors, thereby overcoming the initial higher first-of-a-kind (FOAK) costs.

Factory-built SMRs could provide flexible (off-grid) power with shorter ramp-up timelines and lower up-front costs, but they are not yet commercially mature. The scale-up of SMRs relies on the standardization of licensing requirements for plant construction and operation, which can help avoid delays and cost overruns. Public–private consortia are also key to accelerating less mature technologies—and coordination between industry and governments will be essential to address skilled-labour shortages through capability building.

Furthermore, considerable initial investment is required in development, demonstration, supply chain, and human resources to establish the techno-economic feasibility of SMRs. For the most advanced designs, cost information is scarce. The estimated FOAK costs are typically at least double that of the n^{th}-of-a-kind (NOAK) unit, once economies of multiples come into effect. Thus, a sufficient large number of SMR projects is crucial to demonstrate these economies. Early adoption in niche markets, where factors other than FOAK costs drive decisions, and supportive public policy are essential for initiating cost-reduction dynamics. The timeline is critical; a substantial order volume must be achieved before 2030 for SMRs to play a significant role in a tripling of nuclear capacity by 2050.

Once a design’s technological readiness is established, addressing FOAK issues becomes imperative to gain investor confidence. SMR manufacturers must convincingly demonstrate their ability to deliver projects on time and within budget, even if not yet at full commercialization. This process requires substantial funding for technical feasibility and market readiness. Achieving this will be critical for attracting orders to scale up manufacturing, develop supply chains, and build a skilled workforce.

Investing in SMR industrialization and achieving commercial adoption are interdependent, necessitating certainty in planning, favourable public policy frameworks, financing, and reliable regulatory bodies. It also necessitates significant public subsidies and incentives for a reasonable initial teething period (5–10 years), and public-private partnerships.

Internationally harmonized regulation and licensing could be the key to rapidly increasing order volumes, thus facilitating faster technological learning and transitioning from FOAK to NOAK costs.

Conclusion

The global community is increasingly acknowledging nuclear energy’s essential role in achieving sustainability. The challenge ahead is to ensure that these advanced nuclear technologies not only meet stringent safety and economic criteria but also gain societal acceptance.

The current intense interest in development and deployment of SMRs lies in their potential to enable society to meet the sustainable development objectives and climate commitments agreed in global accords. As the urgency to reduce greenhouse gas emissions intensifies, SMRs emerge as a source of innovation, offering a reliable, flexible, and adaptable energy alternative. This aligns with the diverse energy needs of different nations, including in developing economies, that could drive socioeconomic development with enhanced safety and lower financial risk. Specifically, SMR integration in the energy transition represents a critical part of the solution for the proposed expansion of nuclear energy within the transition; this could be pivotal in the quest for sustainability while addressing energy needs across different nations with their scalability and cost-efficiency. The growing acceptance of SMRs, supported by international policy and cooperation, signals a critical shift from cautious optimism to decisive action in the energy landscape, securing nuclear energy its place in the energy transition with a larger number SMRs and fewer large reactors.

The two questions most strongly determining the future of SMRs and advanced large reactors are whether the costs and associated risks of new reactors can be significantly mitigated, and whether the grid's baseload demands can be satisfied in its absence. There are, however, also many important positive attributes to account for, including recognition of improved safety, enhancing security, and the incremental demonstration of management of high-level waste in geological disposal.

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SAFETY, SECURITY, AND SAFEGUARDS FOR SMALL MODULAR REACTORS

Robert J. Budnitz, Olli Heinonen, and Anita Nilsson

In recent years, increased attention has been given to the growing need for energy in virtually all countries, but especially in developing countries working toward achieving the UN Sustainable Development Goals. However, energy growth and especially electricity growth is in tension with the need to reduce greenhouse gases worldwide to address climate change. This situation has triggered a major change in the global nuclear-power industry, building on the fact that nuclear energy is the only credible option that can produce steady base-load electricity while emitting almost no carbon dioxide. The industry has turned its attention to designing an entirely new generation of reactors called small modular reactors or SMRs, characterized not only by their smaller size—less than 300 MW-electric, in contrast to today's power reactors, which are typically in the 1,000 MW-electric range—but with several other attractive features too.

The broad features of the SMRs now under development have been described in the previous article and will not be repeated here. In addition to the issues related to financing, it is broadly recognized that SMR development also requires that the highest standards of safety, security, and safeguards will be maintained. Several decades of worldwide deployment of the current larger power reactors has created a strong framework of standards that are based on operating experience and that are accepted everywhere. This article explores safety, security, and safeguards implementation, and summarizes the opportunities and challenges for significant advances in each area.

Nuclear safety

The international nuclear safety system has evolved over decades, underpinned by several international safety conventions and other legal agreements, established under the auspices of the International Atomic Energy Agency (IAEA). The system has general application, although in the accompanying safety standards issued by the IAEA, the light-water reactor (LWR) technology has received the most attention. The regulatory assessment and review of new SMR technologies will require new competences and procedures, including features for maritime use of SMRs.

There is a broad consensus that most new SMR designs offer significantly enhanced safety compared to today's large reactors. There are three principal reasons for this:

1. Significant advances have occurred over the past decades in engineering, materials, software used for control, the effectiveness of human-influenced operations, and equipment reliability. These advances have made today's operating fleet much safer than 20–30 years ago, and are fully taken advantage of in the new SMR designs. This means that the abnormal conditions that could lead to a potential accident sequence will be far less likely to occur in most SMRs. Several designs do not depend on external power during emergencies, which often is critical in today's large reactors. These safety features are also important for the possible radiological consequences of a security event.

2. The SMRs' smaller size means less heat to cope with in abnormal conditions and less radioactivity to be potentially released in an accident. Furthermore, several designs are to operate with very low coolant pressure, which will lower the actual release of radioactivity in case of an accident.

3. National regulatory systems, backed up by the international legal framework, have been in place for many years and are broadly accepted. The implementation of a strong safety culture is emphasized, along with thorough analysis and monitoring of reactor designs and operations to detect potential weaknesses and problems in a timely way. By applying the same broad principles that have worked well in the past, and due to their advanced features, these new SMRs will have a much-reduced risk profile, and less severe consequences if an accident were to occur. The size of their offsite emergency-planning zones can also be greatly reduced. These technical features are equally important for security, in particular concerning attempts at dispersal of radioactivity through an act of sabotage.

Nuclear security

The security risks associated with SMRs are, in principle, the same as those that have been considered in the existing international legal framework for nuclear security, namely theft of nuclear material and dispersal of radioactivity for malicious purposes. The international legal framework includes the 2005 Convention on the Physical Protection of Nuclear Material and the 2005 International Convention on the Suppression of Acts of Nuclear Terrorism. In addition, bilateral cooperation agreements for the supply of materials and technology and the international export control system through the Nuclear Suppliers Group guidelines give attention to nuclear security and nonproliferation as important conditions in the supply of materials and technology for nuclear facilities. The security principles to deter, detect, and delay an intruder and mitigate any consequences will not change for SMRs. The system will, however, potentially need to accommodate situations including numerous co-located small units, SMRs in remote locations (possibly with remote operations), and maritime applications. In relation to the second risk, dispersal of radioactivity, the extent of the threat depends on how easily the contained radioactivity could be dispersed, and if dispersed, whether it would cause unacceptable radiological consequences. Again, a small nuclear power unit will have much less radioactive material than a large LWR.

The challenge, and the opportunity, can be understood best by completing a thorough risk assessment and related radiological consequence analysis, tailored to a particular design. If the radiological consequences at the site boundary are small in relation to the limits established through regulation, that would mean that the units can operate safely and securely, even for multi-unit sites or in remote areas.

Nuclear safeguards

The Non-Proliferation Treaty requires each non-nuclear-weapon state to conclude a Safeguards Agreement with the IAEA, accompanied by the voluntary Additional Protocol from 1996, which expands the obligations of the state and gives additional verification rights to the IAEA to generally go deeper into the state's peaceful nuclear programme. The Additional Protocol has now been legally accepted by a clear majority of states with Safeguards Agreements. The undertakings made are verified by the IAEA, which gives the IAEA a different role for safeguards than for safety and security. Theft of nuclear material is a common concern for nonproliferation safeguards and security. The concern depends on its potential use in nuclear explosive devices. Nuclear material from an operating reactor would have to undergo further, technically advanced, physical or chemical processes to become usable in a nuclear weapon. This includes plutonium and higher uranium enrichments in the reactor fuel, which may have various forms depending on the reactor design, and that if separated from either fresh or used fuel could be used in nuclear weapons. Some advanced reactors have new fuel designs, with novel physical properties, that need further study before they can be accepted. In any case, a small or very small unit uses less, sometimes much less, nuclear material than the large LWR units, and the safeguards and security concerns relate to the quantity: lesser quantity, lesser risk. The responsibilities of the state are clear and straightforward: the declaration of all nuclear material, its uses (past, present, and future), and where it is located. Based on these declarations and together with the verification results, the IAEA draws conclusions annually for each state, and these conclusions are made public.

The challenges and opportunities with a potentially large number of SMRs in many more countries and potentially in numerous maritime applications is primarily one of the availability of resources—for the state, the operator, and the IAEA. Based on the principles established for current reactors, a cost-effective system for safeguards verification has evolved. However, a significantly increased number of sites, diversity in the fuel design, and increased uranium enrichment present new challenges. If many more countries operate nuclear power plants in small units, the verification system will require methods that are more routine and easier to implement. Remote surveillance, for example for units with an operating cycle of several years, may present both a challenge and an opportunity.

Contemporary approaches to the regulation of a nuclear energy programme

Achieving the SMRs' full potential is closely connected to the effectiveness of the national regulatory system and its country-specific requirements. Specifically, it could pose a potential impediment if the regulations deprive designers of the needed flexibility to achieve optimum safety, and these issues could also indirectly affect security and safeguards. The traditional large LWRs have achieved today's very high safety level due in part to much improved understanding of the technical processes involved, along with the use of modern risk-informed and performance-based regulatory approaches. In the early days, process and technical conservatism was used in the regulatory schemes worldwide to assure adequate safety. In addition, prescriptive technical requirements prevailed, rather than the more modern performance-based approaches relying on risk goals and acceptance criteria. Today, the regulatory processes under active development worldwide for SMRs emphasize a performance-based system that is also technology-neutral where feasible. Worldwide, the regulation of any reactor and its nuclear material is the responsibility of the country in which it is based. This requires an independent national regulatory agency, with its own regulations, inspectors, and enforcement procedures.

Modernizing the national regulatory systems is underway worldwide. One issue that is being discussed is the compatibility between regulations adopted in different countries, as well as the wider acceptance of the initial safety analysis that will be required for each new SMR model. This would enable a license granted in one country to be more easily accepted or validated in other countries. Finally, there is a worldwide move to use modern safety-analysis methods as a basic principle to frame the regulations, including tying the regulations more directly to the risks being designed against. The acceptance worldwide of these improvements and new processes—including efforts to integrate safety, security, and safeguards—will be important for realizing the full potential of the new SMR designs.

The role of the IAEA

The mandate of the IAEA, as established in its statutes and as agreed by its member states, is basically twofold: the provision of services and the verification of commitments made in Safeguards Agreements and voluntary Additional Protocols. It is essential that all states with nuclear activities universally adhere to and fully implement the IAEA legal instruments related to nuclear safety, security, and safeguards. To support the implementation of the legal instruments, the IAEA provides services which include a broad range of activities, from the development and publication of nuclear safety standards and security guidance to various supports required for their application. Safety analysis methods, inspection protocols, and assistance may be requested—but are not mandatory—from any member state to evaluate its regulatory system/agency against the approved IAEA nuclear safety standards, and for services in many technical, procedural, and administrative areas. The IAEA should continue to enhance annual reporting, with the consent of member states, on actual findings of its review activities. However, for nuclear safety and security, the IAEA has no enforcement authority, and the interaction with states is voluntary, although critical in many technical areas. This will also be the case for the new SMRs. The IAEA role for safeguards is fundamentally different than the role for safety and security: the commitments made in Safeguards Agreements are verified by the IAEA. The strengthening of the IAEA's mandate towards becoming more of an international authority may seem desirable, because it could strengthen and simplify the system, but making such a change would be complex and time-consuming. The IAEA can, however, promote new procedures for licensing of SMRs, along the lines that are already being discussed within the international community. Validation of safety analyses performed by the country of development of a new reactor model is an important example. Another task for the IAEA is to account for the new SMR technologies in its guidance documents and inspection protocols, which will need to be revised, updated, and tested. An effort to address safety from a technology-neutral view is underway, but another few years will be required before new guidance is fully in place. To summarize, the importance of the IAEA role in coordinating and promoting activities across many countries cannot be overemphasized.

SMR deployment in countries with limited nuclear experience

In a country without a nuclear-power programme today, dedicated efforts are required to establish both the technical competence and the independent administrative and regulatory infrastructure necessary to operate nuclear power plants and supporting facilities. One significant investment in infrastructure is the establishment of a national regulatory agency empowered by law to license and regulate nuclear facilities and support them as they are built and operated. This is a complex and time-consuming effort that can be facilitated by guidance issued by the IAEA. Partnerships with countries that are willing to share their experiences, including financial assistance in some cases, would be a significant benefit. A country new to nuclear energy will require time, up to a decade, for its programme and related infrastructure and the other regulatory and support structures must be developed to reach maturity. Achieving an acceptable safety and security culture may be challenging, in particular to keep corruption at bay. It is essential to ensure that corruption, lack of economic resources, or a weak or ineffective government does not impact the effectiveness of the nuclear-power programme. To this end it essential that states implement fully all relevant nuclear safety, security, safeguards, and nonproliferation-related elements of the IAEA legal instruments. The worldwide nuclear-power industry is diligently working on approaches to ensure that the regulatory issues mentioned above will not become a barrier to widespread SMR deployment. It will be essential to have closer interaction between the SMR developers, national regulators and their organizations, and the IAEA.

Concluding remarks

An increasing number of countries are implementing a regulatory system that reflects requirements in the international legal framework, and that recognizes interactions, synergies, and interdependence among nuclear safety, security, and safeguards. The implementation of national regulatory systems also needs to recognize and account for the different roles of the IAEA in safety and security *assistance* versus safeguards *verification*. Nuclear technology has developed in parallel with the successive strengthening of the international safety, security, and safeguards legal framework. The international agreements that underpin the legal framework have been strengthened when there has been a critical need, and a solid common ground for effective implementation now exists. The present set of conventions, international agreements, and undertakings, supported by the IAEA, will also serve the broad deployment of SMRs. The implementation will need to account for the differences in widespread application of small units in addition to large units in fewer places, and in maritime as well as land-based applications. The strengthening of national regulatory systems as the main vehicles for implementation of the international legal framework will be key to enabling nuclear energy to become a major source worldwide of close-to-zero carbon release. The benefits of a more interactive approach on the national level will enhance the potential for increased effectiveness also at the international level. These are key factors in realizing the full potential of the new SMR designs.

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ENSURING SAFE AND SECURE MANAGEMENT OF SPENT FUEL FROM SMALL MODULAR REACTORS

Charles McCombie, Neil Chapman, and Jake Kinghorn-Mills

The benefits of nuclear technologies are directly related to the 17 United Nations Sustainable Development Goals (SDGs). The first paper of this trilogy on the role of Small Modular Reactors (SMRs) in nuclear energy and the energy transition emphasizes how nuclear power provides affordable, clean energy (SDG 7) and also addresses climate change concerns by replacing unmitigated fossil fuels (SDG 13 and 12). Nuclear plants also contribute to other goals: their construction and operation provide work and economic growth (SDG 8), and they greatly reduce land use compared to new renewables (SDG 15). Nuclear power can also be used in remote and arid locations (e.g. for desalination), providing clean water and good health (SDGs 3 and 6). These are powerful arguments for the expanded use of nuclear power—provided that the technology can be shown to be truly sustainable. Today, high hopes are being placed on all the SDGs mentioned being effectively addressed by the development and widespread deployment of small modular reactors (SMRs), which have rapidly come to centre stage in discussions of the world’s nuclear power future.

Amidst the current SMR enthusiasm, however, a prevalent ‘elephant in the room’ is that—like all nuclear plants—SMRs generate long-lived radioactive wastes. The core Brundtland Report[52] definition of sustainability is ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs’. We cannot claim that nuclear energy is truly sustainable unless we provide for future generations a solution ensuring that these hazardous wastes will not require ongoing active care and maintenance. It must be shown that they can be disposed of in facilities providing permanent, passive safety and security. This is a key challenge that is too often neglected in new nuclear planning and will certainly affect consideration of SMRs, especially in countries contemplating the introduction of nuclear power through their deployment.

For spent fuel and high-activity wastes, geological disposal is the accepted safe, permanent solution. But, as described below, progress towards establishing the necessary deep geological repositories (DGRs) has been slow and controversial in almost all countries. These facilities are expensive, they require advanced scientific expertise and technical implementation capabilities, and they need to be sited in regions that are socially and technically acceptable. But it may not be necessary for all SMR users to implement their own DGR; this is the philosophy underpinning a renewed and accelerated interest in multinational repositories (MNRs) in which countries share a common DGR. A shared approach is particularly interesting for small or new nuclear power programmes and aligns perfectly with UN SDG 17: global partnership.

Will waste disposal be an obstacle to SMR deployment?

Slow progress in implementing waste disposal has been used frequently by opponents of nuclear power to erect barriers to its societal acceptance. Will it stand in the way of the new global enthusiasm for advanced reactors and SMRs? For decades, opposition to nuclear power has focused on arguments related to reactor safety, the cost of nuclear electricity, and the feasibility

[52] Report of the World Commission on Environment and Development: *Our Common Future World* (1987) Oxford University Press. p. 27. ISBN 019282080X.

of safe waste disposal. In practice, nuclear reactors have been proven to be safer than almost all competing power production technologies, and its holistic life cycle costs are not a major obstacle. However, the so-called 'unsolved waste disposal problem' is still put forward by many objectors to nuclear power. These objections ignore the fact that geological disposal is accepted as a safe and permanent solution and that the first DGR for spent nuclear fuel is under construction, with many more in advanced planning stages.

The nuclear community itself has been partly to blame for the common assertion that too little attention has been, and is being, paid to implementing disposal solutions. The challenges involved were ignored for too long; already back in 1994, the legendary reactor designer Alvin Weinberg expressed his regret: 'I paid too little attention to the waste problem. Designing and building reactors, not nuclear waste, was what turned me on.'[53] Physicists are still turned on by designing a plethora of exotic nuclear reactor concepts (at present there are over 80), whilst relatively little attention is paid to radioactive waste management and disposal issues.

However, there is today an increasing acknowledgement that planning any nuclear power plant requires a credible back-end solution—both at a conceptual level, and ultimately through specific action plans for that particular facility. Regulators are demanding decommissioning and disposal planning at the beginning of nuclear power implementation programmes. The newest programmes—for example, that of the United Arab Emirates—developed radioactive waste management roadmaps at the planning stage, with waste management issues fully integrated. Contrastingly, SMR waste management appears to be a nascent area of development. Whilst back-end studies have been published recently (although not by the SMR designer companies), much remains open, so that it is important to analyse what new back-end challenges and opportunities will arise from the deployment of SMRs.

Key factors affecting SMR waste management

A joint study by the US Department of Energy and the international ERDO Association is currently examining the potential strategic and technical impacts of widespread SMR adoption on radioactive waste management in existing large reactor programmes or in newcomer nuclear nations[54]. The focus is on the treatment, encapsulation, and disposal of spent fuel in a DGR (including the potential for deep borehole disposal), either in a national facility or in an MNR. An assessment of the wide range of SMR designs allowed definition of a selection of credible SMRs covering different technologies. Data referenced in the open literature was used to consider the readiness for commercialization based on published financial and strategic commitment, rather than technical feasibility. Five reactor types were examined:

- light-water reactors using water as both coolant and neutron moderator, with a solid fuel
- high-temperature gas-cooled reactors using inert gas as a coolant and graphite as a moderator, with a solid fuel
- molten salt reactors typically using a graphite moderator with a molten salt mixture as a combined fuel and coolant
- sodium fast reactors using liquid sodium as a coolant, and no moderator, with solid fuels
- heat-pipe-cooled reactors using heat pipe elements to draw heat from the reactor core, with different types of moderators and highly enriched solid fuel.

The safe geological disposal of radioactive waste depends on its ability to meet criteria outlined by regulatory bodies—its 'disposability'. These criteria concern characteristics that determine how it can be emplaced in a DGR or a deep borehole disposal facility[55], and how it is likely to behave in its geological surroundings thousands of years into the future. Table 1 summarizes considerations to determine a waste package's degree of disposability.

[53] Weinberg A., *The First Nuclear Era: The life and Times of a Technological Fixer*, American Institute of Physics, New York, 1994
[54] Kinghorn-Mills J., Chapman N., Kegel L., McCombie C., Tyson S. *How Will Backend Issues Affect The Global Deployment Of SMRs?,* NENE Conference, Slovenia, 2023
[55] The most advanced concepts for deep geological disposal involve emplacement of the waste in mined caverns some hundreds of meters deep in a suitable geological formation. Recently interest has been growing in the possibility of directly disposing in boreholes from the surface, possibly at much greater depths.

Table 1: Waste stream properties and their relevance when considering geological disposal

Property	Relevance when considering disposal
Volume	The volume of waste generated by an SMR over its operational lifetime impacts the size of the disposal facility. Size relates directly to cost and other strategic elements, such as siting.
Heat output	The heat output generated by SMR fuel (a function of fuel type, fuel enrichment, and fuel burnup) impacts disposal facility layout and size and hence costs and siting possibilities.
Fissile material	The amount of fissile material in an SMR waste stream impacts size, cost, siting, etc., as greater density of fissile material will require greater separation of waste packages.
Physical characteristics	The geometry, dimensions, and physical form of an SMR waste stream directly impact the waste package in which it can be disposed of and hence the handling, transport and emplacement technologies in the DGR.
Chemical characteristics	The chemical makeup of an SMR waste stream may impact, in particular, the long-term behaviour of the wastes in a closed DGR.

The preliminary results of the analysis indicate that, even for SMRs based on the technologies used in conventional large light-water reactors, amendments will be necessary for waste encapsulation and for detailed DGR design. For those high-temperature gas-cooled SMRs using small, particle-filled pebbles or graphite blocks, the only practicable disposal strategy seems to be direct disposal, which results in large volumes of spent fuel, even for smaller SMRs. More exotic technologies, such as molten salt reactors, will require conditioning and disposal methods which have not yet been proven on the commercial scale. Furthermore, logistical challenges will arise if deployment of many SMRs in remote areas leads to enhanced requirements for secure transports of spent fuel, or even of complete reactor modules. However, perhaps most challenging for newcomer countries that wish to deploy small numbers of SMRs will be ensuring that adequate financial and personnel resources are available to implement a safe geological disposal solution.

An important overarching goal of the study is also to assess how widespread deployment of SMRs might enhance the benefits of, and the opportunities for, multinational cooperation between countries operating a single facility for the disposal of waste from a fleet of SMR modules.

Overcoming potential waste-management-related impediments to SMR deployment

What can be done to overcome some of the technical, financial, and societal impediments to SMR deployment? To provide a truly sustainable solution, SMR designers will need to factor in considerations of waste quantities and characteristics early in the design stage. SMR vendors that wish to present a robust offering should be studying the radioactive waste management challenges, enabling them to better provide potential buyers with advice, support, and a cradle-to-grave solution. Compatibility with existing spent fuel treatment and packaging methods is important for countries with existing nuclear plants. For newcomer countries, potential vendors could support multinational user groups for their offered design. They could also promote take-back options, as expanded upon below. The provision of less expensive and more flexible options for geological disposal is of mutual benefit to SMR vendors and the nations deploying their designs.

Waste management benefits and opportunities resulting from SMR deployment

The high interest in deployment of SMRs might also have positive impacts on how management and disposal of radioactive wastes are carried out in the future. The intensive competition between the many potential suppliers may encourage designers to think more at the outset about how radioactive waste management might be simplified and how vendors might be more proactive in supporting takeback of the spent fuel (or even of complete reactor modules), or how they might encourage implementation of shared MNRs. Furthermore, for some reactor types, the necessity of reprocessing the fuel may increase interest in recycling—an option which has fallen out of favour, primarily because of the higher costs compared to direct disposal of spent fuel. With the current global interest in sustainability and a circular economy, the additional costs of reprocessing (which are a relatively small fraction of life cycle costs, and smaller still when holistic considerations regarding global sustainability are made) may appear more acceptable. Widespread deployment of SMRs may also act as an enhanced driver for multinational cooperation at the back end of the nuclear fuel cycle. Standard designs for packaging and disposal containers, whether for DGRs or deep borehole disposal facilities, are likely to benefit all actors involved; countries with widespread deployment to isolated regions are likely to see cost reductions and the alleviation of security concerns through centralized storage solutions; and countries that opt to deploy a common SMR design may choose to form user groups, supported by the relevant vendor. Multinational cooperation could also play a major role in the future when many almost identical SMRs are to be decommissioned worldwide.

The greatest global impacts on safety, security, and costs could be through the implementation of MNRs that make state-of-the-art disposal accessible to any country using nuclear technology, however large or small. The most plausible routes to the realization of a DGR that accepts radioactive wastes from a number of countries have been explored in some depth over the past two decades, covering partnering scenarios, commercial initiatives, and take-back of wastes by suppliers. A scenario in which SMR deployment is widespread may well act as a driver for one, or all, of these approaches to multinational disposal.

Summary and conclusions

The new generation of SMRs is anticipated to provide enhanced safety, lower cost, easier financing, better grid compatibility, and reduced project risks (which can improve social acceptance and attract private investment). Because of this, the nuclear community, the public, and the media are increasingly looking to SMRs to herald a long-awaited, but never yet observed, ‘nuclear renaissance’. But this will not happen if SMR developers and implementers repeat past mistakes that have blocked nuclear expansion. Getting the economics of SMRs right and shortening licensing and construction times is essential—but these alone will not solve the problem.

The other major challenge that conventional reactor designers ignored until too late was addressing the issue of safe disposal of spent fuel and highly radioactive wastes. Even today, although safe geological disposal facilities are being implemented, for example in Finland, this is still perceived by many as an objection to expanding nuclear power. Some recommendations that could help remove the waste disposal challenges facing SMR deployment are:

- consideration of spent fuel disposal routes in all proposed SMR designs;
- promotion of cooperation in back-end activities between users of SMRs;
- encouragement of SMR vendor nations to take back the spent fuel or reactor modules;
- encouragement of SMR vendors, SMR users, national nuclear programmes, and international bodies to actively support emerging initiatives for MNRs, whether through a commercial enterprise or via a partnered approach.

Not since its introductory phase around 50 years ago has the enthusiasm for the growth of clean, safe, sustainable nuclear energy been as high as it is today. Realizing the promise shown by the new SMRs will depend on ensuring that the safety, security, economics, and sustainability of these systems is guaranteed—and for the last of these, developing and implementing geological disposal solutions is essential.

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FUSION ENERGY, AN EXPANDING SECTOR FOR A GAME-CHANGING TECHNOLOGY

Francesca Ferrazza, Edoardo Fiorentini, and Davide Martulli

Fusion is the energy that governs the universe, as it is the process that powers our stars, such as the Sun. Fusion energy promises a true revolution in the energy sector because, once developed at industrial scale, it would enable the generation of large amounts of zero-carbon energy through a safe, nonintermittent, and virtually limitless process. The combination of these characteristics has the potential to make fusion a turning point in the global journey towards decarbonization.

The energy generated in the fusion process is immense, potentially providing about 4 million times more energy per kilogram of fuel than coal combustion[56].

The fusion process consists in the union of two light atoms, such as the isotopes of hydrogen (deuterium and tritium are the most studied and used as fuels), which creates an element (e.g. helium) lighter than the sum of the two initial atoms, a reaction that releases an enormous amount of energy, according to the famous Einstein equation ($E = mc^2$). It is essentially the opposite reaction of traditional nuclear plants, where a heavy atom is split into two smaller isotopes to generate energy.

The energy generated from the fusion reaction, in the form of heat, is converted into electricity through known processes. This electricity can be distributed into the existing grid, making fusion technology highly advantageous for integration with current and expected energy systems and an ideal match for intermittent renewables.

Although the fusion process is the basis of life on Earth, it is very complex to reproduce it artificially on our planet, which is why, according to the scientific community, obtaining energy from fusion is one of the greatest technical challenges that humankind has ever faced. Professor Stephen Hawking considered it the most important scientific discovery that he would like to see accomplished: 'I would like nuclear fusion to become a practical power source. It would provide an inexhaustible supply of energy, without pollution or global warming.'[57]

In the last few years, scientific and technological breakthroughs have brought the industrialization of this technology a step closer, and now more than ever it has the possibility to become a reality.

Technology for fusion

Despite the physics required for fusion being known since the 1950s, reproducing the fusion process in a controlled environment for energy production remains technologically challenging. This highlights the need for continuous innovation, study, and validation activities to harness fusion's full potential as a sustainable and efficient energy source.

The most important challenge that the worldwide fusion community must tackle nowadays is to achieve a net energy gain, in other words producing more energy from fusion reactions than the amount required to initiate and sustain the fusion process.

The main parameter for assessing the performance of a fusion reaction is the fusion triple product, which provides a correlation among plasma density (where the plasma is the ionized gas composed of charged particles that fuels the reaction), temperature, and energy confinement time. By evaluating the balance among these three parameters, it is possible to find the conditions for sustaining the reaction.

Different approaches have been studied and developed for reaching a fusion energy gain. Most research has focused on magnetic confinement fusion or on inertial fusion. But other hybrid approaches are also being investigated—like the magnetized target fusion concept that, while inherently inertial, utilizes magnetic fields during the implosion process to mitigate thermal conduction losses, and more innovative approaches that still need to be studied and physically validated.

Magnetic confinement

Magnetic confinement fusion currently remains the most mature solution for industrialization, in a relatively short time, of fusion energy, as demonstrated by the market analysis that follows.

The technology is based on the use of powerful magnetic fields to contain plasma and to help heat it to achieve fusion conditions (this requires a temperature of more than 100 million degrees Celsius, approximately 10 times that of the Sun's core).

One of the most mature magnetic confinement fusion concepts is the tokamak (a Russian acronym that is composed of 'to' for toroidal, 'ka' for the chamber containing the plasma, and 'mak' for the magnetic field confining the plasma), in which a helical

[56] IAEA (2023), "What is Nuclear Fusion?", https://www.iaea.org/newscenter/news/what-is-nuclear-fusion
[57] TIME (2010), "10 Questions for Stephen Hawking", https://content.time.com/time/magazine/article/0,9171,2029483,00.html

magnetic field is generated in a toroidal chamber through a combination of externally applied fields and currents induced within the plasma. The entire machine is surrounded by powerful magnets, capable of generating the strong magnetic fields that help to initiate, confine, and sustain the fusion reaction, minimizing plasma contact with the inner walls, to avoid wall damage that could otherwise result from the extreme temperatures of the process.

There are also other magnetic confinement fusion approaches with tokamaks at various stages of maturity. Notably, the stellarator design (still at an early stage) produces a helical magnetic field in a torus solely through external fields, offering the advantage of true steady-state operation but at the cost of elevated engineering complexity, including for designing and building the extremely elaborate shape of the torus and magnets.

As described, the complexity in achieving and maintaining the necessary conditions to recreate fusion on Earth makes the fusion process intrinsically safe, as there is no risk of meltdown and the process would spontaneously extinguish if any of the necessary conditions for the fusion reaction were lacking.

Finally, there is no production of long-lived radioactive waste; its production in the fusion process consists mainly of activated material limited to internal portions of the tokamak (primarily from the first wall material exposed to plasma), which can be safely replaced periodically using robotic methods currently in development. Recycling procedures are under study for subsequent utilization of these materials.

Inertial confinement

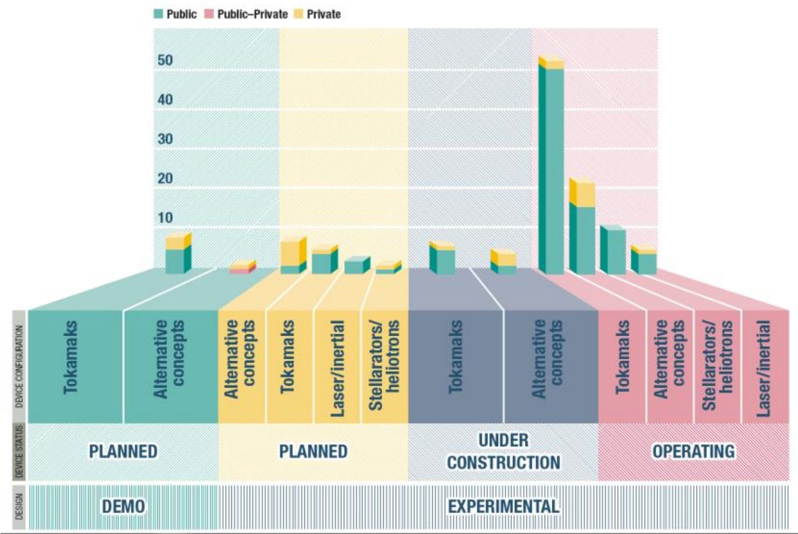
Inertial confinement fusion commonly relies on achieving high densities by initiating an implosion of the fuel. This is typically accomplished by directing high-energy lasers onto a small cryogenic fuel capsule. The ablation of the capsule's surface propels an implosion through rocket action. As the fuel undergoes implosion, the core heats up to fusion conditions, and the high density resulting from compression creates the necessary conditions for nuclear fusion to occur. Various inertial confinement fusion approaches exist, including indirect drive and direct drive, where laser energy is directly applied to the fuel capsule.

Market assessment

Fusion energy development and research in plasma physics is conducted across over 50 countries. While fusion reactions have been successfully generated in numerous experiments, energy generation on a commercial basis remains to be demonstrated.

The *Fusion Outlook 2023* report from the International Atomic Energy Agency highlights that there are more than 140 fusion devices around the world (Figure 1), involving both public and private efforts, including those already in operation, under construction, or in the design phase. In accordance with the slate of different technological and process alternatives mentioned earlier, experts are exploring various designs, such as magnet-based machines like tokamaks, the most developed solution, and stellarators; alternative approaches involving lasers, linear devices, and advanced fuels are also under development.

Figure 1: Number of fusion devices worldwide



Source: International Atomic Energy Agency, "*Fusion Outlook 2023*", https://www-pub.iaea.org/MTCD/Publications/PDF/FusionOutlook2023_web.pdf

Public development

Fusion is recognized as a crucial possible source of low-carbon energy with the potential to contribute significantly to the long-term goals of decarbonization and diversified energy generation. Governments worldwide are responding to the urgency of climate change by incorporating fusion energy into their long-term strategies for achieving net zero emissions.

Several countries, including the United Kingdom, the United States, Canada, and Japan, have emphasized fusion's role in mitigating greenhouse gas emissions and in limiting global temperature increases. Recently governments have developed and announced new strategies for the development of fusion.

In 2021, the United Kingdom introduced its first fusion energy strategy with a focus on leveraging the country's scientific expertise and commercializing fusion technology through collaboration on a global scale. This strategy is based on three pillars: international collaboration, scientific and technical expertise, and commercialization. In October 2023, the UK government unveiled the next phase, the Fusion Futures Programme, aiming to support the development of the fusion sector and enhance UK leadership.

In the United States, the White House in 2022 announced the launch of the Bold Decadal Vision, a 10-year strategy for fusion energy commercialization. The initiative, featuring key figures from the administration, Congress, and industry, signalled a significant commitment to fusion development. The subsequent months saw crucial legislative and regulatory measures to implement this decade-long strategy. More recently, during COP28 in Dubai, US special climate envoy John Kerry launched an international engagement plan to boost nuclear fusion, emphasizing its potential as an emission-free technology crucial in combating climate change. This initiative is cantered on advancing research and development, addressing supply chain challenges, and establishing regulations and safety measures.

In March 2023, the European Commission released the Net-Zero Industry Act, aiming to create a regulatory framework that facilitates reaching European climate and energy targets by 2030, specifically highlighting fusion energy as a priority for technology investments. On a European national basis, Germany has recently demonstrated commitment to this technology, releasing a fusion research position paper and announcing a new funding scheme for national fusion activities and a plan for substantial investment in fusion energy development.

In Japan, the minister of foreign affairs highlighted nuclear fusion for the first time as a prospective aspect of the country's future approach to tackling climate change in its foreign policy. Subsequently, in April 2023, Japan outlined a comprehensive national strategy for fusion energy.

The implementation of these high-level strategies is based on concrete outcomes, and notable progress has been achieved within the pivotal projects currently underway:

- In December 2022, a laser-based inertial confinement fusion research device, located at the National Ignition Facility of the Lawrence Livermore National Laboratory in the United States, achieved a significant milestone: for the first time in fusion history, through an inertial system, it was possible to reach plasma net energy gain. The experiment managed to produce more energy than was consumed at plasma level to reach fusion conditions. This achievement represented a fundamental first real step for the development of inertial fusion technology.
- In 2022, at the Joint European Torus facility, the world-leading experiment located in the United Kingdom, 59 megajoules of sustained fusion energy were produced. This facility will be decommissioned starting from 2024, after having produced extremely valuable research for several decades, but the UK government has recently announced the STEP (Spherical Tokamak for Energy Production) initiative, which aims to build a prototype fusion power plant capable of delivering net energy by 2040.
- In Germany, the Wendelstein 7-X achieved a new record in 2023 with a plasma discharge lasting eight minutes, demonstrating continuous energy coupling.
- In Korea, the Superconducting Tokamak Advanced Research facility produced a plasma with a temperature exceeding 100 million kelvins in September 2022.
- In China, the Experimental Advanced Superconducting Tokamak achieved the longest steady-state high-temperature plasma operation in December 2021.

- Finally, the intergovernmental project ITER is under construction in Cadarache, France, and stands as the world's largest international experimental fusion facility. It will serve as a global collaborative project with the objective of showcasing the scientific and technological viability of fusion energy production. Countries participating in the ITER project include China, the European Union, India, Japan, the Republic of Korea, the Russian Federation, and the United States.

Overall, these global initiatives share a common theme of empowering public–private partnerships to accelerate research, development, and demonstration efforts in the field of fusion energy, recognizing its potential to address climate change and contribute to a sustainable and low-carbon energy future.

Private sector

Together with public development, we have recently witnessed important growth in the private sector as well. New start-ups have been financed by big corporate ventures and funds, bringing to the market innovative ideas and concepts.

In its annual report on the global fusion energy industry[58], the Fusion Industry Association underlined that the industry has attracted over $6 billion in investment in the last few years. The global fusion landscape is experiencing a technology expansion, with 43 private fusion companies on the market, showing significant technological diversity and minimizing risk by exploring quite different approaches.

The report also highlights that 25 fusion companies predict the first fusion plant will dispatch energy to the grid before 2035, thus targeting a date by which fusion could substantially contribute to the global energy transition. Companies express growing confidence in meeting ambitious goals, emphasizing the need for midterm milestones, risk-taking, parallel pathways, new partnerships, and increased resources.

The industry's continued growth is notable, but the sector has a capital-intensive nature, as companies must scale up investment to construct proof-of-concept machines. In the near future, there will be an increase of requests to the capital market and to governments for more funding from private fusion companies, to satisfy a fundamental need for making commercialization of fusion energy a reality.

The commitment of the private sector is not only beneficial for driving industry forward but has also yielded significant tangible results in the development of fusion, particularly from a technological standpoint. Among the most funded companies in the fusion sector, it is possible to highlight the following recent achievements:

- In 2021, Commonwealth Fusion Systems, a spin-out of the Massachusetts Institute of Technology, based in Devens, Boston, demonstrated its revolutionary magnet technology, developed in-house, which will contribute to a faster path to achieving commercial fusion energy and a transformative opportunity for the sector. Commonwealth Fusion Systems constructed and validated a high-temperature superconducting magnet that reached significantly high magnetic fields (20 tesla). These high-performance magnets will enable the construction of smaller and more cost-effective fusion systems.
- In 2022, TAE Technologies, a company based in California, demonstrated a significant milestone in the development of its innovative C-2W/NORMAN reactor. This achievement supported TAE Technologies advanced beam-driven field-reversed configuration, a design that can maintain plasma confinement at temperatures required for confident scalability to reactor-level performance.
- In 2022, the British company Tokamak Energy reached a significant milestone, achieving a peer-reviewed plasma ion temperature of 100 million degrees Celsius in their ST40 spherical tokamak, meeting the threshold for fusion energy.

Regulation

Lastly, it is important to underline that the efforts of scientists and private companies alone are insufficient to fully unlock the potential of nuclear fusion. Regulators and policymakers play an equally crucial role by creating a stable and predictable environment for businesses and investors, making the projects bankable.

[58] Fusion Industry Association (2023), "The global fusion industry in 2023" annual report

Well-established regulations provide essential guidelines to ensure safety and fairness, reducing risks and uncertainties. This, in turn, catalyses innovation and lays the groundwork for long-term success. The new regulatory framework being developed for fusion must be tailored to fusion technology, considering its specific risks and proportional to its hazards; it should not be tied to the reference framework for other technologies such as fission.

Following this direction, in April 2023, the US Nuclear Regulatory Commission made a unanimous decision to separate regulation of fusion from fission one, with individual states overseeing regulation, an approach that better reflects industry's expectations and mirrors the UK approach.

The United Kingdom has also taken a proactive stance in establishing a regulatory framework tailored to fusion-specific technology risks. Fusion regulation in the United Kingdom is therefore distinct from traditional nuclear (fission) and is not subject to the same regulatory requirements.

In November 2023, the United States and the United Kingdom announced a strategic partnership between the US Department of Energy and the UK Department for Energy Security and Net Zero. The partnership aims to recognize and develop the complementarity between US and UK resources and facilities in fusion, including those in academia, industry, supply chain, and government, as well as to harmonize regulatory frameworks.

Other countries and regions now have the opportunity to get inspiration from UK's and USA's leading example, creating a fusion-tailored framework that can help attract investment and foster the development of a thriving fusion industry.

NUCLEAR ENERGY IN EUROPE: IT'S TIME TO CONSIDER OUTCOMES

Giacomo Luciani

Nuclear energy has been a battlefield in inter-European relations, but possibly the most acute tensions are now a matter of the past. As the difficulty of reaching stated decarbonization objectives becomes clearer, the time seems ripe for the EU and some of its member countries to abandon ideological positions and pay attention to actual outcomes.

Which European countries have achieved the lowest carbon content for their electricity production, and how did they do it? The answer is clear and stark: only countries that have adopted nuclear energy, or are richly endowed with hydroelectricity resources, or both, have achieved low-carbon electricity. Countries relying heavily on nondispatchable renewables (wind and solar) have reduced their carbon intensity, but remain much heavier emitters than countries relying on nuclear and/or hydro.

In Europe as of 2023 (Table 1), only three countries have achieved very low carbon content for their electricity consumption: Sweden, Norway, and France. Sweden relies on a combination of hydro (40 per cent), nuclear (30 per cent), and wind (18 per cent); Norway relies almost exclusively on hydro (74 per cent); and France relies overwhelmingly on nuclear (62 per cent in 2023).

Table 1: Average carbon content of electricity consumption (2023)

Country	CO_2 emissions (g/kWh)
Sweden	37
Norway	43
France	53
Switzerland	87
Finland	104
Portugal	105
Spain	136
Belgium	147

Country	CO_2 emissions (g/kWh)
Hungary	291
Ireland	304
Italy	323
Romania	335
Estonia	393
Bulgaria	405
Greece	406
Turkey	408

Country	CO_2 emissions (g/kWh)
United Kingdom	175
Austria	189
Croatia	208
Denmark	217
Slovenia	220
Netherlands	240
Latvia	259
Slovakia	266
Lithuania	270

Country	CO_2 emissions (g/kWh)
Bosnia	413
Serbia	423
Moldova	424
Germany	431
North Macedonia	509
Czech Republic	542
Kosovo	651
Poland	814
Cyprus	964

Source: *Electricity Maps* (https://app.electricitymaps.com/map).

These figures reflect electricity consumption, including imports and exports of electricity, rather than production. In the case of Norway and Sweden, their carbon intensity would be lower were it not for the fact that they export clean electricity to Denmark and import dirty (coal or gas) electricity from it. Denmark is a country normally associated with strong policies in favour of renewables, especially wind; yet the carbon content of electricity consumption in Denmark is 5.8 times that of Sweden and 5 times that of Norway.

Germany is the great champion of renewables within Europe, and has been heavily subsidizing their uptake for more than 20 years (the original *Erneuerbare Energien Gesetz* came into force in April 2000)—a time span that should be sufficient to judge its effectiveness. The outcome is clear: in 2023 Germany had one of the highest carbon contents for electricity consumption in the whole of Europe, more than 8 times that of France. This is not a difference of a few percentage points, or even tens of percentage points; it is a massive difference.

In fact, Europe is the region of the world most dependent on nuclear electricity (19 per cent of total generation in 2022): of the 15 countries in the world most reliant on nuclear power, 13 are in Europe (Table 2), and 12 of these are EU members (the exception is Switzerland). Although some of these countries have at some point decided to abandon nuclear, only Germany has done so. It is hard to believe that the remaining countries will in the end implement what they decided, as this could only be possible by increasing reliance on coal or gas to compensate for the nondispatchability of wind and solar, contradicting emission-reduction goals.

Table 2: Share of electricity from nuclear

Country	Share (%)
France	63
Slovakia	59
Hungary	47
Belgium	46
Slovenia	43
Czech Republic	37
Switzerland	36
Finland	35

Country	Share (%)
Bulgaria	33
Armenia	31
South Korea	30
Sweden	30
Spain	20
Russia	19
Romania	18

Source: IAEA PRIS (Power Reactor Information System): https://pris.iaea.org/PRIS/WorldStatistics/NuclearShareofElectricityGeneration.aspx.

Nuclear energy was one of the pillars of the creation of the European Union. Of the three original treaties, EURATOM is the only one that remains in force; it has been absorbed into the institutional setup of the European Union. EURATOM attributes to the European Commission important responsibilities with respect to nuclear safety and the procurement of nuclear fuel. Of the seven directorates composing the DG Energy, two are devoted to nuclear energy (Nuclear Energy, Safety and ITER, and EURATOM Safeguards). In addition, DG Energy is responsible for the EURATOM Supply Agency, an independent agency whose task is the procurement of nuclear fuel for the EU member countries. Nuclear energy therefore has some very deep roots in European institutions.

Nevertheless, Germany, which has decisive weight in EU affairs, has taken a ferociously hostile position against nuclear energy, aiming to impose its abandonment throughout the EU. This has been the case at least since 2011, when Chancellor Angela Merkel decided to pivot 180 degrees and abandon nuclear following the Fukushima accident—a process that concluded in 2023 with the closure of the last three nuclear power plants. Together with Merkel's attitude towards growing reliance on imports of Russian gas and continuing reliance on coal, this will probably be counted as one of her key strategic mistakes.

There is no denying that Fukushima has had a major negative impact on acceptance of nuclear energy in the wider European public opinion. Even in France, President Macron was originally elected on a platform that would have considerably reduced reliance on nuclear energy, and several other EU members either confirmed the decision not to rely on nuclear (such as Italy in a referendum that took place soon after the accident), or decided to gradually move away from it. Popular sentiment towards nuclear remains hostile in many member countries.

Nevertheless, outcomes must eventually be acknowledged. It is almost certain that Germany will miss its decarbonization targets for 2030. At the same time, the attempt to very quickly build up a green hydrogen industry, to substitute for natural gas in flexible power generation, will in all probability also fall very short of targets for 2030. It will become increasingly clear that the choice is between more emissions and continuing reliance on nuclear.

We may predict that, in the end, a degree of pragmatism will prevail, and decision makers will accept that nuclear energy is an indispensable component of the solution. Indeed, in Bavaria—possibly the German state most threatened with deindustrialization due to high energy costs—the governing party, the Christian Social Union, has advocated reopening the Isar nuclear power plant and possibly building new ones. There is also some evidence that the mood of the wider German public is changing, and acceptance of nuclear may be greater than politicians recognize. Within the governing coalition at the federal level, the liberal Free Democratic Party is also in favour of accepting a nuclear component.

The German position may therefore evolve by 2025, when the next Bundestag (legislative) elections are due. Undoubtedly, this would greatly change the equilibrium of forces within Europe and the attitude of the Commission, but putting in place an effective European nuclear energy policy will be difficult unless at least part of the environmentalist movement accepts that nuclear is an inevitable component of decarbonization.

A more likely result is reluctant acceptance of the fact that a number of member states intend to expand their nuclear generation capacity, while others are not so keen, and continuing absence of a strong European-level initiative. Existing nuclear power plants will be allowed to operate for longer, but few new projects may be launched outside of France. In the context of the liberalized and interconnected European electricity market, the temptation is to leave the final verdict to the market: countries heavily relying on nondispatchable renewables may expect that their respective national grids will be balanced through trade with their neighbours that rely on some, or a lot of, nuclear. This is what is happening at the moment: Germany and Italy routinely rely on imports of nuclear power from France while rejecting nuclear at home. But in this scenario the willingness of nuclear countries to keep their borders open to untrammelled electricity trade may at some point be challenged. In any case, as interconnection capacity is limited, prices may diverge, causing shifts in the competitiveness of energy-intensive industries, and calls for protection or subsidies.

The widely heard argument for not placing greater emphasis on nuclear is that it is expensive and its implementation is slow. However, it is almost universally recognized that the cost of grid integration for nondispatchable renewables increases exponentially with their penetration. Proponents of exclusive reliance on wind and solar assume that there is no limit to the increase in the use of batteries and the expansion of the grid, and no limit to the opening of new mines around the world and ready availability of the needed metals. But such a vision is hard to believe, as the environmental and social costs of intensified mining activities will become increasingly clear. In the end, market developments will tell whether indeed nondispatchable sources are bound to become cheaper and cheaper, as frequently claimed, or whether an inflection point will be reached beyond which further penetration of nondispatchable renewables becomes increasingly expensive.

That nuclear capacity additions may require long gestations is a fact, although the example of the United Arab Emirates demonstrates that a country can go from no nuclear expertise to having a significant share of electricity generation from nuclear in a relatively short time. The UAE decided to acquire a nuclear component in 2007, and now has three 1.3 GW units connected to the grid and a fourth one to start operating in 2024, with a goal of providing 25 per cent of total generation. If anything, the fact that nuclear needs a relatively long gestation should be an argument to anticipate the decision to create new capacity, rather than continuing to kick the can down the road.

That said, lost time is not easily recovered. European countries have allowed their nuclear know-how and industrial capabilities to be almost completely dissipated—starting at universities, where nuclear engineering is scarcely taught any longer. Even if a decisive rehabilitation of nuclear energy were to occur, the speed at which new capacity could be added would increase only gradually.

The Net Zero Emissions by 2050 scenario of the International Energy Agency envisages a doubling of global nuclear energy capacity, from 417 GW in 2022 to 916 GW in 2050. This would require 26 GW of new capacity to come online every year from 2023 to 2050, which does not seem very likely. Even so, the contribution of nuclear energy to total generation would slightly decline (from 9 per cent in 2022 to 8 per cent in 2050). Most capacity additions are envisaged to be in China and other emerging economies; new capacity in the industrialized countries would be minimal, at least up to 2040.

Nuclear know-how today is overwhelmingly in the hands of China and Russia. Out of 59 nuclear reactors under construction in the world, China has 23, close to 40 per cent of the total. Chinese companies will transform their accumulated experience into technological leadership, as they have done for solar panels, wind turbines, batteries, and electric vehicles. Russia controls the commercial nuclear fuel cycle through Rosatom, which has the largest enrichment and reprocessing facilities and has considerable influence on Kazakhstan, the foremost producer of uranium.

Opponents of nuclear in Europe may think that leaving the leadership of nuclear technology to China and Russia is not important, because in their mind the technology itself does not have a future. The mood in the United States is certainly not along these lines: the need to maintain and improve nuclear know-how seems to be fully understood in Washington, in contrast to Brussels. It is likely that in the not too distant future the mood in Brussels will shift radically, as it did following the Russian invasion of Ukraine.

While difficult, recovering nuclear competitiveness is not impossible. Nuclear technology has attracted little attention and investment over decades, but the potential for progress is very large, and numerous promising initiatives are underway—concerning both nuclear fission and nuclear fusion. The OECD countries still have the upper hand in this area and may leverage the advantage if appropriate conditions are established.

The EU is in fact heavily engaged in nuclear research, but its engagement is strongly focused on fusion and the giant ITER project under construction at Cadarache in southern France. The EU contributes nearly half of the budget of this project. ITER is a cooperative endeavour between the EU and the United States, the Russian Federation, China, Japan, India, and South Korea. It is noteworthy that this group of countries continues to cooperate in ITER, notwithstanding very tense geopolitical relations having affected other scientific exchanges. Curiously, the United Kingdom has fallen out of the ITER project since Brexit.

There is a tendency to consider ITER as too large and complex to succeed, and greater attention has been devoted to nimbler initiatives often launched by smaller start-ups. Yet the project may well be able to deliver on its stated objectives, opening the door to the eventual commercial development of fusion energy. That would radically change the game, in Europe as well as globally, and not just for the future of clean energy and decarbonization, but also for international relations more broadly. Outcomes are very important.

RUSSIAN NUCLEAR FUEL SUPPLIES IN EUROPE: WHAT COMES NEXT?

Tomáš Vlček

The Russian invasion of Ukraine in February 2022 has raised significant concerns in Europe, not only about coal, oil, and natural gas supplies from Russia, but soon afterwards also about nuclear fuel supplies. In 2022, there were 104 reactors in operation in the European Union,[59] about 25 per cent of the world's reactor fleet. Nuclear power generated the largest share of the EU's net electricity in 2021, accounting for 25 per cent of the total.[60] And some EU countries are quite dependent on electricity generation from this source in their national mixes (e.g. France 70 per cent; Slovakia, Belgium, and Hungary around 50 per cent; Slovenia, Czechia, and Bulgaria around 40 per cent).[61] This illustrates the importance of the nuclear fleet for the EU's energy security.

The majority of reactors are of Western design (e.g. there are 56 reactors in France alone) and benefit from the possibility of having several fuel suppliers. These Western-design reactors have not been exposed to any real or potential risk related to the supply of nuclear fuel following the Russian invasion of Ukraine. However, a group of countries on the eastern flank of the EU operate Soviet-design technology and have faced significant concerns about their nuclear fuel supply from Russia. These concerns are not technically new, and the Euratom Supply Agency has been highlighting the risks of single supplier dependency in this nuclear market niche in its annual reports for years.[62] Since the start of the war, the urgency of the issue has dramatically increased.

Countries using Soviet-design technology include Bulgaria, Czechia, Finland, Hungary, and Slovakia. Not yet formally integrated, but informally part of the 'West', Ukraine should also be included in this group. Historically part of the former Eastern Bloc, Ukraine has the largest nuclear fleet in eastern Europe and the largest Soviet-design nuclear fleet outside Russia. About 55 per cent of Ukraine's electricity is generated from nuclear power plants. There are 19 VVER reactors operating in the EU (with Slovakian Mochovce 4 to be started in 2024 as the 20th) and 15 more in Ukraine.[63]

The situation is somewhat diverse, as not all 20 EU reactors face difficulties related to potential Russian supply disruptions. The operating VVER family currently consists of three reactor generations, designated 440, 1000, and 1200 according to their power output. The VVER-440s entered commercial service at the turn of the 1970s and 1980s, the VVER-1000s at the end of the 1980s, and the VVER-1200s in 2018. The first two units of the new 1,300 MW-electric generation, VVER-TOI, are due to be commissioned soon at Kursk, Russia. Each reactor generation evolves from its predecessor and is Generation II, III, or III+ in the world nuclear reactor classification. However, the EU and Ukraine only have first- and second-generation reactors (VVER-440 and VVER-1000 units). One VVER-1200 unit was planned for the Hanhikivi nuclear power plant in Finland but cancelled in May 2022, and two VVER-1200 units are planned for the ongoing Paks II project in Hungary.

Starting with the VVER-1000 segment, there are only four units in the EU—two at the Bulgarian Kozloduy nuclear power plant (NPP) and two at the Czech Temelin NPP—and 13 in Ukraine. The main supplier of fuel for VVER-1000 units is the Russian company TVEL, a subsidiary of the Russian state nuclear corporation Rosatom. This segment is better positioned, as there is an alternative fuel supplier with an alternative design. In addition to Russia's TVEL, Westinghouse Electric Company (owned by Canada's Brookfield Business Partners) can supply fuel to these reactors. Westinghouse developed its VVANTAGE-6 fuel design for Soviet pressurized water reactors in the late 1990s. It was first used commercially at Temelin NPP in Czechia in 2000–2009.

Although problems with geometric stability and the resulting frequent outages eventually led the Czech operator to return to Russian fuel, the experience gained led to further modernization and development. The modernized TVS-RW fuel was then

[59] Schneider, M., et al. (2022), *The World Nuclear Industry Status Report 2022*, Paris: Mycle Schneider Consulting, p. 324, https://www.worldnuclearreport.org/IMG/pdf/wnisr2022-lr.pdf.
[60] Eurostat (2023), *Electricity Production, Consumption and Market Overview*, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview#Electricity_generation.
[61] Schneider, M. et al. (2022), *The World Nuclear Industry Status Report 2022*, Paris: Mycle Schneider Consulting, p. 41, https://www.worldnuclearreport.org/IMG/pdf/wnisr2022-lr.pdf.
[62] Euratom Supply Agency (2021), *Annual Report 2020*, Luxembourg: Publications Office of the European Union, https://euratom-supply.ec.europa.eu/system/files/2021-10/MJAA21001ENN_002.pdf.
[63] To complete the numbers in geographical Europe, there are also two in Belarus, one in Armenia, and 22 in Russia. VVER stands for *vodo-vodyanoi enyergeticheskiy reaktor*, a designation of pressurized water reactors of Soviet/Russian origin.

used in Ukraine without operational problems, and Westinghouse is now supplying the third generation (designated RWFA - Robust Westinghouse Fuel Assembly) of this fuel to the Pivdennoukrainsk and Zaporizhzhia NPPs in Ukraine. In April 2022, Westinghouse won the Czech nuclear fuel tender for a 10-year supply starting in 2024.[64] Bulgaria signed a 10-year contract with Westinghouse for unit 5 at Kozloduy in December 2022[65] In summer 2023, Ukraine signed a contract with Westinghouse to supply all fuel for its nuclear fleet.[66]

There is also the possibility of having other companies producing fuel for VVER units under licence, either from Westinghouse or from Russia. France's Framatome, for example, clearly has the capacity and experience with VVER technology, having worked with Rosatom for more than 30 years. Despite the long cooperation with Rosatom, Framatome still does not have its own fuel design for VVER reactors. The research, development, testing, and licensing would take a decade, not to speak about the massive financial investment needed. Framatome is expected to operate under a license from Rosatom to assemble fuel from Russian TVEL components, and then export it as French/European product. In fact, this solution was already adopted in Czechia, when Framatome won the Temelin NPP fuel contract along with Westinghouse in April 2022.[67] Framatome was also successful in Bulgaria, in December 2022 the company signed a 10-year contract to supply fuel to unit 6 at Kozloduy NPP.[68]

In December 2021 Framatome signed an agreement with Rosatom to expand collaboration on fuel fabrication.[69] The plan was to create a joint venture for fuel manufacturing with Rosatom in Framatome's facility in Lingen, Germany, to produce VVER fuel elements, where Rosatom was expected to take 25 per cent. However, due to opposition from the public and mainly from the German officials, the application for an investment review procedure was withdrawn in February 2022.[70] In March 2023, however, the state of Lower Saxony received Framatome's request to be allowed to produce hexagonal VVER fuel elements in the German facility.[71] Not achieving full diversification—on the contrary, with the creation of a new cooperation platform with Rosatom in Europe—this solution is likely to be politically very sensitive and could induce further opposition from both the official authorities and the general public, especially in Germany. A big question mark that would tremendously affect the project is the theoretical future extension of sanctions against Russia to the nuclear industry.

Still, the VVER-1000 segment in Europe either is already independent of Russian direct supplies or will be very soon. In a few years (depending on the fuel reserves of the individual operators), Russian fuel will most likely no longer be directly used in VVER-1000 reactors in the EU and Ukraine. The Ukrainian experience also suggests that fuel switching from TVEL to Westinghouse will not necessarily be associated with higher costs. In fact, the price of fuel has been 18–30 per cent lower for Westinghouse than for TVEL over the past three years (In 2019 US$0.74 million vs US$0.92 million per tonne of fuel; In 2020 US$0.76 million vs US$l.07million, and In 2021 US$0.83 million vs US$1.1 million).[72]

The situation is different for the VVER-440 subsector. These units are in operation in Ukraine (two units at Rivne NPP) and in four EU countries (four units at Dukovany NPP in Czechia, two units at Loviisa NPP in Finland, four units at Paks NPP in

[64] World Nuclear News (2023), 'Framatome and Westinghouse to supply fuel to Temelín', 13 April, https://www.world-nuclear-news.org/Articles/Framatome-and-Westinghouse-to-supply-fuel-to-Temel.
[65] World Nuclear News (2022), 'Bulgarian plant signs 10-year deal for Westinghouse fuel', 22 December, https://www.world-nuclear-news.org/Articles/Bulgarian-plant-signs-10-year-deal-for-Westinghous.
[66] NuclearNewswire (2022), 'Westinghouse to supply all fuel for Ukraine fleet, plus more AP1000 units', 6 June, https://www.ans.org/news/article-4022/westinghouse-to-supply-all-fuel-for-ukraine-fleet-plus-more-ap1000-units/.
[67] World Nuclear News (2023), 'Framatome and Westinghouse to supply fuel to Temelín', 13 April, https://www.world-nuclear-news.org/Articles/Framatome-and-Westinghouse-to-supply-fuel-to-Temel.
[68] World Nuclear News (2023), 'Kozloduy and Framatome sign nuclear fuel agreement', 4 January, https://www.world-nuclear-news.org/Articles/Kozloduy-and-Framatome-sign-nuclear-fuel-agreement.
[69] Robert Lansing Institute (2023), 'Blocking of sanctions against Rosatom increases risk of sabotage at region's nuclear facilities', 8 May, https://lansinginstitute.org/2023/05/08/blocking-of-sanctions-against-rosatom-increases-risk-of-sabotage-at-regions-nuclear-facilities/.
[70] Schultz, Stefan (2022), 'Russischer Einstieg in deutsche Atomfabrik vorerst geplatzt', *Spiegel*, 24 February, https://www.spiegel.de/wirtschaft/unternehmen/lingen-einstieg-von-rosatom-in-deutsche-atomfabrik-vorerst-geplatzt-a-f355e411-7635-4a44-8d4f-c9c9061888fb.
[71] Jordans, Frank (2023), 'Germany criticizes Russian role in French nuclear fuel plant', Associated Press, 30 March https://apnews.com/article/germany-france-russia-nuclear-power-rosatom-framatome-ce47027005349580306d55553c7f1142.
[72] State Statistics Service of Ukraine (2022), 'Non-irradiated fuel elements (cartridges) for nuclear reactors(UCG FEA code 8401300000) by country', http://www.ukrstat.gov.ua/.

Hungary, and six units in Slovakia—two at Jaslovske Bohunice NPP and three, soon to be four, at Mochovce NPP).[73] The fuel supplier for all these reactors has always been Russian TVEL, with only one historical exception. In 1996, British Nuclear Fuels Limited signed a contract with Finnish and Hungarian operators for the design, development, licensing, and supply of alternative fuel for VVER-440 reactors. In 1999, British Nuclear Fuels acquired Westinghouse and eventually sold the company and its entire nuclear fuel business to Toshiba in 2006. The fuel developed, known as NOVA-E3, was eventually used only at Finland's Loviisa NPP between 2001 and 2007. The Russian company responded by offering a substantial discount, thus winning back the Finnish contract in the next tender, and there was no expression of interest from other VVER-440 operators. In fact, TVEL has the capacity to tailor the fuel to the individual needs of each operator, and there has never been a problem with stability of supply. Given the (mainly financial) risks associated with fuel switching in NPPs, there were no operators willing to undertake the fuel switch, and Westinghouse was therefore unable to find a market for its product and eventually lost the operating licence.

It was quite clear that the impulse to diversify or at least create the opportunity for potential diversification would not come from the operators themselves, and it was the Euratom Supply Agency that finally started to confront the situation. This small segment of NPPs in the EU has not even secured the basic N-1 rule, which means that in case of supply disruptions, the power plants would live only on their fuel reserves. Depending on storage capacity and country, these reserves cover only one to three years of operation. EU legislation only recommends strategic reserves of nuclear fuel, so the actual situation varies widely between operators.

The Euratom Supply Agency therefore launched a Horizon 2020 grant call in 2013 to support the licensing of an alternative fuel design for VVER-440 reactors.[74] The €2 million grant was awarded to a consortium of VVER operators from Czechia, Slovakia, Finland, and Ukraine, and nuclear companies from Belgium, the UK, and Spain, all led by Westinghouse. The project was completed with the approval of the second-generation fuel in 2017 and the preparation for a simplified licensing procedure in all VVER-440 operating countries in the EU (and Ukraine).[75] However, given the general reluctance of NPP operators, it was not until 2021 that Westinghouse signed its first second-generation fuel supply contract with Ukraine's Rivne NPP.

The Russian invasion of Ukraine changed the dynamics. Although there were no sanctions against the Russian nuclear industry, and Russian airborne fuel deliveries have continued throughout the war, the nervousness of countries and nuclear operators soon turned into action. Countries became concerned about their energy security (some, e.g. Czechia, more than others, e.g. Hungary) and demanded diversification in the VVER-440 fuel sector. In 2022–2023, Westinghouse signed VVER-440 fuel supply agreements with Finland (November 2022), Czechia (March 2023), and Slovakia (August 2023).[76]

The process of licensing an alternative fuel supplier for the VVER-440 power plant segment, launched by Euratom in 2013, could hardly come at a better time. Although operational experience with the new fuel for VVER-440 reactors is limited, the fuel exists, and the company is ready to produce and supply it. The bottleneck is Westinghouse's fuel production capacity. Given the minimal production of this fuel so far, due to minimal orders in the past and the relatively small market, the question is how flexibly Westinghouse can respond to an unexpected increase in demand, how quickly it can increase production capacity, and how much capital this will require. The ability of the operators of these reactors in the EU to agree on a sequence and a common solution was therefore crucial. To raise the production capacity, in January 2023, Westinghouse concluded an agreement to use the production capacity of the Spanish company Enusa at its Juzbado plant to produce fuel for VVER-440 reactors.

In January 2023, a new consortium, APIS (Accelerated Program for Implementation of Secure VVER Fuel Supply), led by Westinghouse, was launched, co-funded by Euratom with €10 million. The project will run for three years and has 12 partners

[73] Vlček, T. (2016), 'Critical assessment of diversification of nuclear fuel for the operating VVER reactors in the EU', *Energy Strategy Reviews*, 13–14, 79, http://dx.doi.org/10.1016/j.esr.2016.08.006.
[74] European Commission (2015), 'Supporting the licensing of Western nuclear fuel for reactors of VVER design operating in the EU', https://cordis.europa.eu/programme/id/H2020_NFRP-16-2015.
[75] Höglund, J., and Kristensson, S. (2017), 'ESSANUF—European Supply of SAfe NUclear Fuel', in *Third International Seminar on WWER Fuel Performance Conference Proceedings*, 345–352, https://inis.iaea.org/collection/NCLCollectionStore/_Public/50/006/50006691.pdf.
[76] World Nuclear News (2023), 'Slovenské elektrárne and Westinghouse fuel supply agreement', 25 August, https://www.world-nuclear-news.org/Articles/Slovenske-Elektrarne-and-Westinghouse-sign-fuel-su; NuclearNewswire (2022), 'Westinghouse, Fortum strike fuel deal for Loviisa', 28 November, https://www.ans.org/news/article-4521/westinghouse-fortum-strike-fuel-deal-for-loviisa/; World Nuclear News (2023), 'Westinghouse to supply fuel to Czech Republic's Dukovany', 30 March, https://www.world-nuclear-news.org/Articles/Westinghouse-to-supply-fuel-to-Czech-Republic-s-Du.

from eight countries (NPP operators, fuel engineering and research organizations, and fuel manufacturers). It has several objectives, including the standardization of fuel licensing and the rapid development of improved and advanced VVER-440 and VVER-1000 fuel designs for the EU and Ukraine.[77]

In short, things have progressed over the years, and the Russian invasion of Ukraine only accelerated the change—and within a few years, both VVER-1000 and VVER-440 operators will have access to sufficient fuel supplies to maintain the safe and uninterrupted operation of their nuclear power plants. Most likely, this pressing political issue will not be on the table by the end of the decade.

It should be noted, however, that EU and Ukrainian operators would remain dependent on a single supplier, with only TVEL and Westinghouse fuel on the market. Switching from Russia to the West is a solution to current geopolitical and security concerns, but it does not solve the problem of a single supplier. A new supplier to the VVER-440 market is not expected to emerge; the market niche is too small, and a significant part of it will disappear in about 20 years. With the exception of two new units at Slovakia's Mochovce NPP, VVER-440 reactors are about 40 years old, and we can hardly expect more than two more decades of operation. This is not a propitious market in which to invest in lengthy and costly research, design, testing, development, and licensing of yet another alternative fuel design. However, a similar model, with the participation of Framatome and its Lingen facility in Germany, is being prospected. In other words, a Russian licence for French assembly of TVEL's fuel parts for VVER-440 reactors is one of the very recent solutions to the VVER-440 fuel supply problem. This solution is further supported with the fact Framatome recently signed fuel supply contracts with Slovakia (May 2023) and Hungary (September 2023), both operators of the VVER-440 reactors.[78]

A similar picture emerges for the VVER-1000 segment. Besides the 17 units in the EU and Ukraine, only China, India, and Russia operate this type of reactor—countries where it would be very difficult to compete with the Russian offer, hence a third supplier of a unique fuel design can hardly be expected.

Finally, there is still some concern among NPP operators about the potential changeover itself. Russian fuel has been tailored to the needs of individual reactors, has excellent properties, and has never had a problem with delivery. It remains to be seen what the operational and safety experience with the new fuel will be and how it will affect the economics of the plants. In addition, the current VVER-440 fuel contracts in this specific subsegment are usually for life,[79] and will likely have to be terminated. The jury is still out on this, and operators could face either high termination fees or even international arbitration.

PRESENT STATUS AND FUTURE PLANS FOR THE NUCLEAR SECTOR IN UKRAINE

James Henderson

Ukraine's nuclear power plant fleet

Nuclear power plays a huge role in Ukraine's energy system (Figure 1), accounting for over 50 per cent of electricity supply. The majority of the country's reactors were built in the Soviet era and all use the Russian VVER design, although the capacities differ. Twelve of the 15 units installed at four sites located across the country were constructed before independence in 1991, and since then three further units have been built by Ukraine itself. The two oldest units use the VVER-400 design with a capacity of 400 MW, while the remainder use the newer VVER-1000 design, with a capacity of 1,000 MW. A total of 13.8 GW of installed capacity therefore exists in Ukraine, although it is not all operational at present because of the continuing war. The Zaporizhzhia nuclear power plant is currently in Russian-held territory and is being managed by Energoatom staff under Russian control, but despite the Ukrainian involvement there are serious concerns about the state of the plant and the safety risks due to the continuing conflict. As a result, 6,000 MW of capacity is currently not producing power for the Ukrainian grid. Of the remaining capacity, 7,800 MW is currently producing electricity.

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[77] *Accelerated Program for Implementation of secure VVER fuel Supply*, https://apis-project.eu/; World Nuclear News (2023), 'European consortium focuses on VVER fuel', 7 July, https://www.world-nuclear-news.org/Articles/European-consortium-focuses-on-VVER-fuel.
[78] World Nuclear News (2023), 'Framatome and Slovenské elektrárne to cooperate on new VVER fuel', 1 June, https://www.world-nuclear-news.org/Articles/Framatome-and%C2%A0Slovenske-elektrarne-partner-on-deve; NuclearNewswire (2023), 'Framatome, Hungary extend cooperation on nuclear power', 15 September, https://www.ans.org/news/article-5355/framatome-hungary-extend-cooperation-on-nuclear-power/.
[79] Vlček, T. (2016), 'Critical assessment of diversification of nuclear fuel for the operating VVER reactors in the EU', *Energy Strategy Reviews*, 13–14, 79, http://dx.doi.org/10.1016/j.esr.2016.08.006.

Figure 1: Location of nuclear power plants in Ukraine

Source: Energoatom

As Table 1 shows, a number of the units at the four nuclear power plants have already seen their lives considerably extended. The original Soviet plants were mostly put into operation in the 1980s with a 30-year design life, and all but one of the plants built in this era have now seen their lives extended by at least 10, and sometimes 20, years. As a result, the plants at Khmelnitsky and Rivne will be operational late into this decade and beyond. Construction of two more units at the Khmelnitsky plant began in the 1980s but was paused after the accident at Chernobyl and has not yet been recommenced despite negotiations with various potential contractors.

Table 1: Ukraine's nuclear power plants

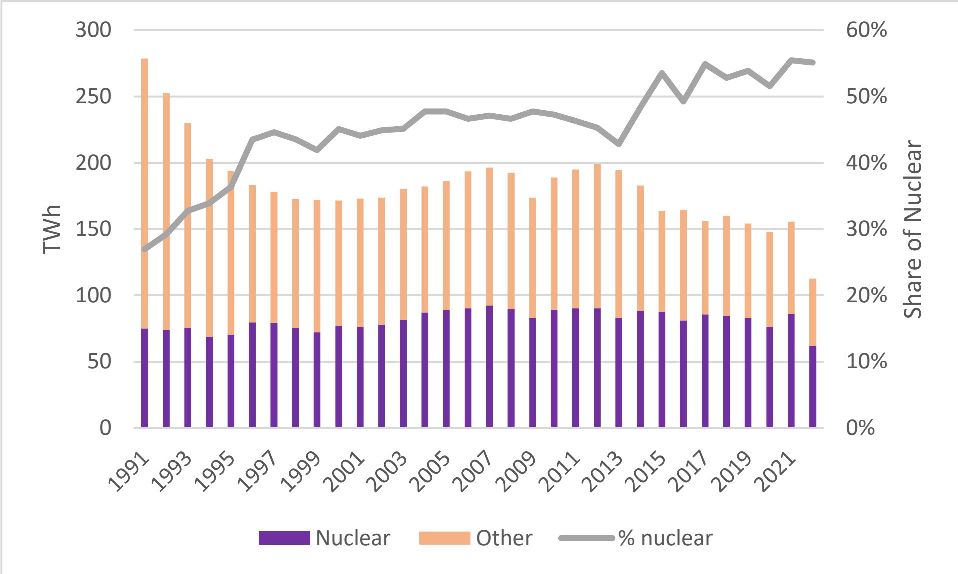
	Design	Capacity (MW)	Commissioned	Initial retirement	Extension	Current status
Zaporizhzhia						
Unit 1	VVER 1000/320	1,000	1984	2015	2025	Under Russian control
Unit 2	VVER 1000/320	1,000	1985	2016	2026	Under Russian control
Unit 3	VVER 1000/320	1,000	1986	2017		Under Russian control
Unit 4	VVER 1000/320	1,000	1987	2018	2028	Under Russian control

	Design	Capacity (MW)	Commissioned	Initial retirement	Extension	Current status
Unit 5	VVER 1000/320	1,000	1989	2028	2030	Under Russian control
Unit 6	VVER 1000/320	1,000	1995	2025		Under Russian control
Khmelnitsky						
Unit 1	VVER 1000	1,000	1987	2018	2028	Operating
Unit 2	VVER 1000	1,000	2005	2036		Operating
Rivne						
Unit 1	VVER 400	400	1980	2010	2030	Operating
Unit 2	VVER 400	400	1981	2011	2031	Operating
Unit 3	VVER 1000	1,000	1986	2017	2037	Operating
Unit 4	VVER 1000	1,000	2006	2036		Operating
South Ukraine						
Unit 1	VVER 1000	1,000	1983	2013	2033	Operating
Unit 2	VVER 1000	1,000	1985	2015	2025	Operating
Unit 3	VVER 1000	1,000	1989	2020	2030	Operating
Total capacity		**13,800**				
Total operating capacity		**7,800**				
Under construction: Khmelnitsky						
Unit 3	*VVER 1000*	*1,000*				*75% complete*
Unit 4	*VVER 1000*	*1,000*				*28% complete*

Sources: World Nuclear Association, Energoatom.

The importance of these power plants to the Ukrainian energy system cannot be overstated, as they produce more than 50 per cent of the electricity consumed in the country and have taken an increasingly important role over the past few years as the country has sought to reduce its consumption of gas in order to bring its purchases of Russian energy to an end. Figure 2 shows how electricity demand has fallen since the Russian annexation of Crimea and the occupation of the Donbass and Luhansk regions in 2014 and fell even further in 2022 as the current war commenced. However, during this period the importance of nuclear has increased, despite the recent loss of control over the Zaporizhzhia plant, reaching a high of 55 per cent of total electricity output in 2022.

Figure 2: Ukrainian power supply by source since 1991



Source: Energy Institute Statistical Review of World Energy, 2023.

Ukraine as an example of diversification in the nuclear fuel cycle

Given the importance of nuclear power in Ukraine, combined with the country's difficult relationship with Russia throughout the period since 1991, it is not surprising that the country has been actively seeking to break its dependence on Russia in all spheres of the nuclear supply chain. Rosatom, and its subsidiary TVEL, play a critical role in the global nuclear industry, as Russia has exported its technology both within the former Soviet Bloc and now further afield. Russian reactors are currently operating in 11 countries across the world; Ukraine and its neighbours such as Belarus and Armenia, European countries such as Bulgaria, Czechia, Slovakia, Hungary, and Finland, and global actors such as Iran, India, and China.[80]

Ukraine holds the largest number of Russian-made reactors, though, and historically was also reliant on Russian supplies of equipment, fuel, and expertise to maintain its industry. One of Rosatom's major competitive advantages is that it has traditionally supplied an all-inclusive package for nuclear energy, or a one-stop shop, which has been helpful to its customers but which has bound them into a long-term strategic relationship with Russia.[81]

Russia's competitive position is based on the fact that, although it is a relatively small player in the mining of uranium, it plays an outsize role in other parts of the nuclear fuel supply chain, accounting for 40 per cent of global conversion services (which turn uranium oxide in uranium hexafluoride) and 46 per cent of global enrichment capacity (which converts the uranium hexafluoride into enriched uranium oxide with a higher share of U-235).[82] Rosatom, via TVEL, has also dominated in the fabrication of the fuel rods which are used in its VVER reactors. The configuration of the fuel assemblies for the VVERs differs from other international reactors, and for many years no other companies had any incentive to produce fuel that could vie with Rosatom's supply, which was often offered at low cost to undermine any potential competition.

Furthermore, Rosatom not only has a very strong position in the front end of the nuclear fuel cycle, but also offers services at the back end which few, if any, of its competitors can match. It owns and operates one of the only uranium recycling plants in the world,[83] and offers a disposal and storage service which allows its customers to manage this difficult process at the end of a fuel rod's useful life. For example, Krasnoyarsk in Siberia is home to the Mining and Chemical Complex, where Rosatom can

[80] Bowen, M., and Dabar, P. (2022), *Reducing Russian Involvement in Western Nuclear Power Markets,* New York: Centre for Global Energy Policy, Columbia University
[81] Szulecki, K., and Overland, I. (2023), 'Russian nuclear energy diplomacy and its implications for energy security in the context of the war in Ukraine', *Nature Energy*, 8, 413–421.
[82] World Nuclear Association, 'World uranium mining production', https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx.
[83] https://www.lemonde.fr/en/energies/article/2022/12/03/russia-owns-the-only-plant-in-the-world-capable-of-reprocessing-spent-uranium_6006479_98.html#:~:text=Once%20the%20spent%20fuel%20assemblies,95%25)%20is%20sent%20to.

offer the ability to handle spent fuel at many different stages within one huge facility.[84] This places it in a unique position to maintain a strategic relationship with its customers throughout the life of their nuclear assets and beyond.

Ukraine has worked hard to disentangle itself from this Russian-dominated supply chain over the past two decades, and its efforts have accelerated since 2014. It is valuable to explore how it has made progress and whether this can provide an example for other countries looking to diversify their nuclear fuel supplies.

In terms of manufacturing, two important companies are located in Ukraine. The first is Energomashspetstal, which manufactures castings and forgings used in large reactor pressure vessels. It is potentially a source of significant competitive advantage for Ukraine but is currently owned by Rosatom and is located in Kramatorsk in the Donetsk region, under Ukrainian control at present but close to the front line of the war with Russia. As such, its operations are limited at present and its future unsure. More positively, JSC Turboatom is a world-class turbine manufacturer and has constructed more than half the turbines currently in operation in Ukraine's power sector. Importantly, it is now cooperating with US company Westinghouse on the uprating of 13 of the VVER-1000 units in Ukraine and hopes to develop the ability to carry out similar operations across Europe. Furthermore, Turboatom has also been involved in building 190 casks for Ukraine's new Central Spent Fuel Storage Facility (see later discussion).

From a mining perspective, Ukraine is estimated to be the 11th largest producer of uranium in the world, although in 2022 its production fell sharply from 455 tonnes to only 100 tonnes (in comparison, the largest producer, Kazakhstan, produced 21,227 tonnes).[85] Historically, Ukraine's state-owned uranium miner VostGOK has produced as much as 30 per cent of the country's domestic needs, but the Ukrainian authorities have now set a target for the country to be self-sufficient by 2027. This aggressive goal is based on maintaining output at two existing mines and opening a further two by 2026, in tandem with the renovation of two sulphuric acid plants where the uranium is extracted from ore.[86]

Perhaps most importantly, though, the entire output of Ukraine's uranium mines has been committed to Canadian company Cameco in a back-to back deal which will then see the Canadian company convert it into uranium hexafluoride and provide Ukraine with enough converted uranium to meet its entire needs, topping it up with Canadian-sourced supply as necessary.[87] This agreement will run from 2024 to 2035 under a contract combining fixed and market prices and will allow Ukraine to completely stop relying on Russian conversion facilities.[88]

Moving on through the front end of the cycle, the Ukrainian authorities have agreed to extend an agreement for enrichment services with UK company Urenco.[89] Urenco will take the converted uranium hexafluoride from Cameco and provide the enriched uranium needed for fuel assembly. The company has been working with Energoatom since 2009, but the contract has now been extended until 2035 with an option for a further extension to 2043 in a deal that was supported by the UK government.[90]

The final part of the fuel cycle involves the manufacture of the fuel assemblies for use in Ukraine's VVER reactors, and here Energoatom's growing partnership with Westinghouse has come to full fruition. The relationship started as early as 2005, when the Ukrainian authorities first planned to break the monopoly of Russian fuel supply to the VVER-type nuclear plants, and Energoatom implemented a Ukraine Nuclear Fuel Qualification Project to seek alternative vendors.[91] An initial contract for a three-year trial was signed with Westinghouse in 2008, but controversially came to an end when Energoatom claimed that the fuel had flaws. Instead, a long-term contract was signed with TVEL, with Ukraine spending $500–600 million per year on fuel.

The 2014 annexation of Crimea dramatically changed the political and commercial landscape, and the contract with Westinghouse was renewed through to 2020. By 2018 Westinghouse was supplying around 30 per cent of Ukraine's VVER fuel,

[84] https://www.iaea.org/newscenter/news/under-one-roof-russias-integrated-strategy-for-spent-fuel-management.
[85] https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx.
[86] https://www.world-nuclear-news.org/Articles/Ukraine-pushes-for-domestic-uranium-supply.
[87] https://www.world-nuclear-news.org/Articles/Energoatom-sends-first-uranium-mined-in-Ukraine-to#:~:text=Energoatom%20President%20Petro%20Kotin%20said,natural%20uranium%20hexafluoride%20(UF6).
[88] https://www.reuters.com/world/ukraines-nuclear-deal-with-canadas-cameco-carries-big-risks-rewards-2023-05-05/.
[89] https://www.energoatom.com.ua/app-eng/eng-2811232.html.
[90] https://www.theengineer.co.uk/content/news/ukraine-s-nuclear-operator-signs-long-term-enrichment-contract-with-urenco/.
[91] https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine.aspx.

and the contract was extended to 2025, by which time it was expected that the US company would be supplying seven of the country's 15 reactors.

However, the Russian invasion in February 2022 changed the picture completely, with Ukraine accelerating plans to move completely away from Russian nuclear fuel. By June 2023 an agreement had been signed with Westinghouse that all of Ukraine's fuel would come from the US company's fabrication plant in Vasteras in Sweden.[92] Energoatom has confirmed that a number of steps have been taken to ensure that both VVER-440 and -1000 units can operate on the new fuel, including the purchase of new monitoring equipment, transport facilities, and loading equipment, as well as training for Energoatom specialists. A dummy fuel assembly has been trialled, and Energoatom CEO Petro Kotin has now claimed that 'Ukraine once again demonstrated to European states ways to overcome Russian influence in the nuclear industry.'[93]

One final element of Ukraine's nuclear diversification has been in the back end of the cycle, as in December 2023 it opened the Central Spent Fuel Storage Facility, which is now used for storing spent fuel from the three nuclear plants which remain under Ukrainian control. Energoatom, which used to spend around $200 million per year for use of Russian storage facilities, is now able to save this cost as well as reduce a critical and strategic dependence on Russia. The plant was built in partnership with the US company Holtec International and has now entered a three-year trial period. According to local press reports, 13 containers of fuel have already been placed at the facility, and a security analysis will now be prepared as part of an application for full industrial operation.[94]

Overall, then, Ukraine has taken significant steps to diversify away from Russian influence in its nuclear supply chain. With new contracts signed for conversion, enrichment, and fuel fabrication, a planned increase in domestic mining of uranium, and the opening of a new waste storage position, it would appear that Ukraine has demonstrated that it is possible to change the boundaries of this complex value chain with high barriers to entry. It would be wrong to be complacent, though. The potential increase in uranium output is yet to be proved, and Russia continues to exert influence across the European nuclear supply chain, which could have implications for Ukraine in a crisis situation.[95] Nevertheless, the country finds itself in a much more comfortable position than a decade ago.

Future plans for expansion using international technology

Ukraine's energy strategy sees nuclear continuing to have a vital role in the country's energy system, both as a source of domestic energy and as a potential source of zero-carbon power exports to Europe. It could also form the basis of a green energy regeneration in Ukraine, providing the zero-carbon electricity to support the production of hydrogen and other green products for export to the EU. To support this plan, the government plans for nuclear capacity to be expanded to 24 GW by 2040, and agreements to facilitate this have been signed. In September 2021, Energoatom and Westinghouse signed an initial agreement for the construction of four US-designed AP1000 reactors to be located at existing sites in Ukraine, as well as the completion of the two units under construction at Khelmnitsky. This agreement was then upgraded in June 2022 to increase the number of AP1000 reactors to be built to nine, and in January 2023 the Ukrainian government also approved the go-ahead for a proposal to construct two brand new reactors at Khelmnitsky.

In addition, Energoatom plans to work with Holtec on the construction of a number of small modular reactors (SMRs) around the country, mainly to replace existing reactors as they come to the end of their lives, and the Ukrainian company has also signed a memorandum of understanding with NuScale to explore the possibility of deploying their SMR plants. This deal was further enhanced at COP27 by an announcement that a US consortium will collaborate with Ukraine on a plan to use SMRs to produce hydrogen and ammonia.[96] While completion of all these plans will of course be dependent on the conclusion of the war in a manner which allows for future investment, they nevertheless demonstrate the clear potential for nuclear power to play a vital role in the rebuilding of the Ukrainian economy over the next two to three decades.

[92] https://www.reuters.com/business/energy/ukraine-signs-deal-with-westinghouse-end-russian-nuclear-fuel-needs-2022-06-03/.
[93] https://www.energoatom.com.ua/app-eng/eng-2712233.html.
[94] Nucnet (2023), 'Kyiv "removes dependence on Russia" with commissioning of central spent fuel storage facility', 20 December.
[95] Dolzikova, D. (2023), 'Catch-235: Western dependence on Russian nuclear supplies is hard to shake', Royal United Services Institute Commentary.
[96] https://world-nuclear-news.org/Articles/USA-Ukraine-announce-cooperation-on-clean-fuels-fr.

STRIKING A BALANCE: ASSESSING THE ROLE OF NUCLEAR ENERGY IN THE EUROPEAN UNION'S ENERGY TRANSITION

Szymon Kardaś

Nuclear energy can play an important role in the energy transition of the European Union, which plans to achieve climate neutrality by 2050. This is because it is a low-carbon source of energy, thanks to which many countries, including in Europe, have avoided increased CO_2 emissions in recent decades. The planned nuclear projects may also help some European countries still heavily dependent on coal (e.g. Poland and Czechia) in their plans to decarbonize their energy mix and other sectors of the economy. The political support for nuclear energy in many EU countries and the assessments of international bodies as to the positive role of nuclear energy in the energy transition also should not be wasted.

At the same time, the role of nuclear energy should not be overestimated in the context of the overall energy transition toolbox. Indeed, the implementation of new nuclear projects not only requires large expenditures, but also has a delayed effect. Consequently, the impact of nuclear projects on the pace of the energy transition and on increasing the likelihood of achieving the EU's climate goals will be smaller than, for example, the development of renewable energy sources (RES) or the improvement of energy efficiency. In addition, in the case of the development of small-scale nuclear reactors (SMRs), there are several question marks over the prospects for their implementation, raising doubts about when and to what extent they will have an impact on accelerating the pace of energy transition in the EU.

How can nuclear power help the EU's energy transition?

Nuclear energy is, above all, a low-carbon source of energy. The carbon footprint of nuclear power generation is only around 15–50 g CO_2/KWh, significantly less than that of gas-fired (450 g CO_2/KWh) or coal-fired (1,050 g CO_2/KWh) power stations.[97] The low carbon footprint of nuclear power allows countries to reduce CO_2 emissions from the power sector, which still has a significant share in total greenhouse gas emissions. Hence, exploiting all possible ways to decarbonize the energy sector is extremely important to achieve the EU's climate goals, as set out in the European Green Deal and Fit for 55, including the EU's 55 per cent reduction in greenhouse gas emissions by 2030.

According to a report by the United Nations Economic Commission for Europe, globally produced nuclear energy has avoided CO_2 emissions of 74 gigatonnes over the past 50 years.[98] The beneficial impact of nuclear energy on CO_2 emissions is also confirmed by data presented by individual countries. Unit 1 of the nuclear power plant in Romania, commissioned in 1996, had avoided a total of 130 million tonnes of CO_2 emissions by 2023. In Czechia, around 22.5 million tonnes of CO_2 emissions were avoided in 2022 thanks to nuclear energy. The Hungarian government asserts that it will manage to avoid emissions of 70 million tonnes per year thanks to the construction of new units at the Paks nuclear power plant.

Also important are the relatively low production costs of electricity from operating nuclear power plants, especially when compared to electricity generated from fossil fuels. The cost of producing electricity from nuclear power plants can be in the range of €70–90 per megawatt-hour, which is comparable to the cost of producing wind or solar power. In contrast, this cost is considerably, 2.5 to even 4 times, lower than from a coal-fired power plant. The lower cost of energy produced by nuclear power plants is mainly due to significantly lower fuel costs than in coal-fired power plants, for which the cost of CO_2 emission certificates must also be added. According to forecasts, the cost-effectiveness of fossil-fuel-fired power generation is set to decrease compared to nuclear and RES.

For many countries, nuclear power is already or is about to become an important element in decarbonizing the energy mix. According to Ember nuclear plants generated around 23 per cent of the total electricity produced in the EU in 2023. Nuclear power is used in the energy mixes of 12 EU countries (until April 2023, the 13th country was Germany), and outside the EU also in Switzerland, the United Kingdom, and Ukraine. As of the end of 2022, nuclear energy accounted for a significant share of electricity generation in countries such as France (almost 63 per cent), Slovakia (60 per cent), Belgium (46 per cent), Hungary (44 per cent), Slovenia (42 per cent), Czechia (37 per cent), Finland (35 per cent), Bulgaria (32 per cent), and Sweden (30 per cent). The level was also high in Germany (44 per cent), but the last operating nuclear units there were phased out in April 2023.

[97] What is the role of nuclear in the energy mix and in reducing greenhouse gas emissions?, 2 December 2022, https://www.lse.ac.uk/granthaminstitute/explainers/role-nuclear-power-energy-mix-reducing-greenhouse-gas-emissions/
[98] Nuclear Power. Technology Brief, UNECE, 2021, https://unece.org/sites/default/files/2021-08/Nuclear%20brief_EN.pdf .

Upgrades or new nuclear units are planned in many EU countries (France, Bulgaria, Poland, Romania, Czechia, Sweden, and Slovakia). In many countries, nuclear power will continue to be the main source of electricity generation. Although one of the most important prerequisites for the success of the energy transition in Europe is the development of RES, at the same time in only a few countries could RES constitute an almost independent component of the energy mix. Nuclear power could therefore be an important long-term complement to low-carbon sources of power generation in many EU countries.

Nuclear power plants can not only produce relatively cheap electricity and heat, but also contribute to decarbonization of energy-intensive industries. There is a potential for increased production of low-carbon or zero-carbon steel, hydrogen, or chemicals. In this context, there has been interest in several countries in implementing SMR projects. The advantage is that these types of projects are expected to be implemented more quickly than large nuclear projects, and consequently their effects would be felt more quickly (although their generating capacity averages about 10 per cent of that of a large nuclear power plant). SMRs could help to decarbonize electricity and district heating generation, in particular replacing coal-fired power plants. In Poland, for example, large energy companies (Orlen, KGHM) also regard SMRs as an important element of their strategy to achieve climate neutrality. The implementation of smaller nuclear projects is also in line with EU goals. In April 2023, the European Commission (EC) announced the *Declaration on EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education & Training*.[99] In February 2024, the European Commission has launched the European Industrial Alliance on Small Modular Reactors, which aims to facilitate the development of SMRs In the EU by 2030.

Nuclear energy has the potential to be an important driver of the development of hydrogen projects. On the one hand, Brussels, considering climate targets, is prioritizing the development of so-called green hydrogen projects (production of 10 million tonnes in 2030 and imports of 10 million tonnes in 2030). The EU plans to increase electrolyser production capacity to 40 GW by 2030, with hydrogen expected to account for 14 per cent of the energy mix by 2050. On the other hand, however, the International Energy Agency's latest projections indicate that only 7 per cent of the world's planned RES-based hydrogen projects will succeed.[100] Such projections may be an incentive for the EU and its member states to consider using nuclear energy to produce hydrogen.

An exceptionally high demand for hydrogen will come from the heavy-duty transport, large-vehicle fleet, railways, shipping, aviation, and building heating sectors. The World Nuclear Association estimates that demand for clean hydrogen could be higher than today's electricity production levels. Currently, 95 per cent of the world's hydrogen is produced from fossil fuels. The emission intensity of the production of so-called pink/purple hydrogen is comparable to that of green hydrogen; the production costs of both types of hydrogen are similarly estimated today. However, the future of hydrogen production using nuclear energy would require increasing the generating capacity of nuclear power plants in the EU.

In addition to objective indicators confirming the role of nuclear energy in meeting climate targets, political support for the development of nuclear projects at the level of European countries or international bodies is also an important factor. Many EU member states believe that nuclear energy can play an important role in reducing CO_2 emissions. The informal nuclear alliance—which has been established in Europe and is steadily growing in membership, with France as the unofficial leader—already includes more than a dozen countries. Members include countries with nuclear power plants in operation, as well as those which are just planning to realize nuclear projects (e.g. Poland). Diplomatic efforts, illustrated by regular consultations and common positions presented, have resulted in decisions taken within the EU. The nuclear alliance regularly sent letters to the EC on the recognition of nuclear energy as low carbon.

The success of the nuclear alliance's efforts was, in the first instance, the EU's agreement in 2022 to include nuclear power in the taxonomy (EU Regulation to increase the level of environmental protection by diverting capital from environmentally

[99] Commission Declaration on 'EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education & Training', European Commision, 3 April 2023, https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/commission-declaration-eu-small-modular-reactors-smrs-2030-research-innovation-education-training-2023-04-04_en.

[100] Renewables 2023. Analysis and forecasts to 2028, International Energy Agency, January 2024, https://www.iea.org/news/massive-expansion-of-renewable-power-opens-door-to-achieving-global-tripling-goal-set-at-cop28.

damaging investments to greener alternatives).[101] However, this is conditional on meeting the premises of environmental safety and compliance with the so-called do-not-harm principle. In addition, the Council of the European Union in December 2023 adopted an amendment by the European Parliament to add nuclear power to the list of strategic technologies under the Net Zero Industry Act. The regulation is intended to facilitate the financing of investments in zero-carbon technologies, the reduction of CO_2 emissions, access to markets, and the promotion of innovation in relation to zero-carbon technologies in the EU. If this form of regulation is eventually adopted (the legislative process is still underway), it would meet the expectations of many countries that call for nuclear energy and investment in this sector to be treated like other areas. Also of significance is the declaration by 22 countries, adopted at COP28, of the will to triple nuclear power generation capacity by 2050,[102] indicating that nuclear energy can play an important role in the energy transition.

Why should the role of nuclear energy in the transition not be overestimated?

At the same time, nuclear energy should not be approached in an obsessive manner and treated as a silver bullet in the energy transition plans of European countries. Nuclear projects, especially large nuclear power plants, are investments with a longer time horizon (construction of a nuclear unit takes up to 10 years). This means that their impact on changing the energy mix occurs after a decade. Thus, the development of nuclear projects does not serve to accelerate energy transition processes in EU countries to the same extent as RES projects. This is confirmed by data on the decline in emission intensity of electricity generation in countries with nuclear power plants. The largest decrease in emission intensity occurred in those nuclear countries that, with unchanged nuclear generation capacity, increased RES generation capacity (Finland and the Netherlands). The rate of growth of RES generation capacity and its impact on the transition is also well reflected in the latest International Energy Agency report on RES in the world.[103]

Although the cost of producing electricity in nuclear power plants is low, the implementation of nuclear projects itself is very expensive. The cost of building a large power plant is usually $5–10 billion (for example, the cost of building new nuclear units in Romania is estimated at €7 billion), and the Polish project to build its first large nuclear power plant (three units) is tentatively valued at around $20 billion. To realize the plans in the nuclear power sector announced by individual EU countries, investments of a total of €649–755 billion would be required by 2050 (against the background of the €3.2–4.2 trillion needed to realize all plans for overall EU energy supply by 2050).[104]

Although nuclear energy is low carbon, projects in this area generate additional environmental challenges—among others, the disposal of nuclear waste. In addition, some nuclear projects are water-intensive. Some also point out that nuclear power is problematic from a circular-economy perspective, due not only to the problem of nuclear waste disposal, but also to the finite nature of uranium deposits.

While many European countries have high hopes for the development of SMRs, there are currently many question marks over when and to what extent they can affect the pace of the energy transition in Europe. Currently, no country in the EU is building reactors of this type. France does not plan to start building its first SMR until 2030. Many EU countries, including Bulgaria, Romania, and Poland, have ambitious plans to build SMRs together with foreign partners (United States, South Korea), but the prospects for their realization are not clear. One of the potential partners, the US company NuScale, is struggling to implement the first projects of this type in the United States.

One of the reasons for the abandonment of the first NuScale project being implemented in Utah was the profitability of the investment. The problems of the pilot projects raise questions about the operating costs of SMRs if they are built in Europe. An additional factor lowering the cost-effectiveness of SMRs over the next decade may be the development of the energy storage sector, which is also important for RES development. It is not clear whether, in the 2030s, the costs of producing energy from

[101] This occurred in a complementary Delegated Act of the EU Taxonomy Regulation. Commission Delegated Regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities (Text with EEA relevance), C/2022/631, OJ L 188, 15.7.2022, p. 1–45, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R1214

[102] Declaration to Triple Nuclear Energy, 3 December 2023, https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key.

[103] Renewables 2023. Analysis and forecasts to 2028, International Energy Agency, January 2024, https://www.iea.org/news/massive-expansion-of-renewable-power-opens-door-to-achieving-global-tripling-goal-set-at-cop28.

[104] Nuclear Power in the European Union, World Nuclear Association, https://world-nuclear.org/information-library/country-profiles/others/european-union.aspx.

SMRs will not turn out to be higher than the costs of producing and storing energy from RES. Besides, it is very likely that the rate of innovation in nuclear power will be lower than the rate of improvement in RES technologies.

Finally, although many European countries support the development of nuclear projects as an important part of the energy transition, there is also strong opposition to nuclear energy in the EU. Germany and Austria oppose treating nuclear energy as deserving similar treatment to truly green technologies. This position was evident in discussions on the EU taxonomy and electricity market design. Some members of the European Parliament have criticized decisions giving nuclear power the same privileges as RES, pointing out that the EU is thereby damaging its image as a leader in climate action. Also the EC's own position is not very optimistic towards nuclear energy. In March 2023, EC President Ursula von der Leyen stated that while nuclear power can play a role in the EU's decarbonization efforts, it is not treated as strategic compared to sources such as solar and wind power and therefore cannot count on the same subsidy treatment in the EU.

Conclusion

The debate on the importance of nuclear power in the energy transition should be guided by the rule of reason. EU member states should respect each state's right to shape its own energy mix, as long as the changes lead to lower emissions. Nuclear energy can make a valuable contribution to achieving the EU's climate goals and can contribute to accelerating decarbonization processes in EU countries. However, even in countries pinning their hopes on nuclear energy, it should not be treated as the silver bullet for energy transition problems. Only by simultaneously developing RES projects and improving energy efficiency indicators can member states increase their chances of meeting EU climate targets.

NUCLEAR POWER AND THE STRATEGIC ROLE OF SMALL MODULAR REACTORS IN THE UNITED KINGDOM

Claudio H. Steuer

The 28th meeting of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change concluded on 13 December 2023 in Dubai, reaching important resolutions and commitments regarding nuclear energy and nuclear small modular reactors (SMRs):

- The 2015 Paris Agreement's Global Stocktake, for the first time, incorporated nuclear energy, signifying a global consensus on scaling up this clean and reliable technology for deep and rapid decarbonization, addressing challenges in hard-to-abate industrial sectors, and facilitating low-carbon hydrogen production.
- The Ministerial Declaration to Triple Nuclear Energy was signed by 24 countries from four continents, announcing the aspirational goal of tripling nuclear energy in order to reach net-zero emissions by 2050 and keep the 1.5°C limit.
- COP28 and the Nuclear Energy Agency held a separate event, Accelerating SMRs for Net Zero, attracting 500 participants from 30 countries recognizing SMRs' critical role in achieving net zero by 2050, providing clean, reliable, and flexible power for electricity generation, heat production, hydrogen generation, and marine propulsion.
- A Nuclear Energy Summit is set for Brussels on 21–22 March 2024, following up the International Atomic Energy Agency's Atoms4NetZero initiative. To be co-chaired by the Agency's Director General Rafael Mariano Grossi and Belgian Prime Minister Alexander De Croo, the Summit will focus on the benefits and challenges of nuclear energy and SMR deployment, fossil fuels reduction, energy security, and economic development.

The Ministerial Declaration to Triple Nuclear Energy does not specify any intermediate targets or milestones by 2050, but commits participating countries to work together and to take domestic actions to ensure that nuclear power plants are operated in line with the highest standards of safety, security, nonproliferation, and sustainability. The declaration encourages close cooperation with international organizations, financial institutions, civil society, and academia, to share best practices and lessons learned as important elements for the successful implementation of SMRs for net zero.

Nuclear power in UK energy policy

The United Kingdom was a signatory to the Ministerial Declaration to Triple Nuclear Energy, and it recently announced ambitious plans for the biggest expansion of nuclear power in 70 years. The United Kingdom aims to provide up to quarter of the electricity supply in 2050, or 24 GW, from nuclear power, rising from 6 GW today. Various reports suggest the total investment, including both conventional reactors and SMRs, could range from £44–140 billion as of 31 December 2023.

The government expects the first SMR could be operational by the mid-2030s, and 16 SMRs could generate about 10 GW of electricity by 2050—powering 16 million homes, creating up to 40,000 high-value jobs, and creating a £250 billion export market.

In July 2023, the UK government started a funding contest to find and support the most cost-effective SMR design for the United Kingdom and accelerate the use of SMRs by the mid-2030s. Six companies were shortlisted based on their ability to deliver SMRs by the mid-2030s: EDF (Électricité de France), GE (General Electric)-Hitachi Nuclear Energy International, Holtec Britain Limited, NuScale Power, Rolls Royce SMR, and Westinghouse Electric Company UK. The next stage involves the shortlisted companies bidding for government contracts. The high-level plan is for the UK government to announce the winners in spring 2024 and award contracts by summer 2024.

The SMR contest is part of a nuclear research and development programme that will receive at least £250 million from the UK government and £300 million from industry partners over five years. Although not explicitly stated, it is assumed that the funding for the first SMR will be decided before the next election, no later than 28 January 2025, under the current parliament.The UK government has established a new financing model for nuclear projects, the Regulated Asset Base, aiming to attract private investment and reduce build costs, consumers' energy bills, and Britain's reliance on overseas developers. The funding will support the design and regulatory processes of the SMR. Beyond the potential Phase 2 funding, the UK government has also committed to providing long-term financing guarantees for the first SMR project, mitigating commercial risks for the developer and providing the winning company an opportunity to develop first-mover advantage.

Successfully deploying the first Great British Nuclear-backed SMR would establish the winning company as a leader in this emerging market, attracting further investment and potentially securing additional SMR orders. The ability to successfully deliver the project would solidify the company's credentials, providing a valuable operating reference and, quite possibly, a competitive edge in the global SMR market.

For this analysis, an LCOE (levelized cost of energy) framework was developed utilizing publicly available information from the six shortlisted SMR contestants (including reactor sizes, technology, and estimated construction costs), industry reports Nuclear Energy Agency SMR Dashboard Report[105] to assess project maturity and estimate capex scaling factors (considering differing degrees of diseconomies of scale compared to conventional reactors due to the early stage of SMRs), and information from reputable industry sources such as Lazard 2023 LCOE Plus[106], IRENA World Energy Transitions Outlook 2023[107], IRENA Renewable Power Generation Costs in 2021[108] and Bloomberg New Finance NEO 2023[109]. The framework aimed to uncover the indicative LCOE of each of the six shortlisted SMR companies, establish an average SMR indicator, and compare them. This was achieved by applying consistent premises for asset generation capacity, a 60-year asset life with supporting capex, realistic intermittency costs, and carbon pricing, thus revealing the comparative economics against other power generation technologies.

To reveal SMR's indicative comparative economic performance against other power-generation technologies, these were the main assumptions for the LCOE calculation: (1) all assets have 1,000 MW capacity; (2) all assets have an indicative capex for 60 years; (3) all technologies utilise Lazard 2023 LCOE Plus premises with adjustments for 60 years; (4) intermittency costs (nongeneration) reflect the UK average spot price for electricity for January–November 2023 at US$0.1338/kw; (5) carbon cost is based on the UK Department for Energy Security and Net Zero's premise of £84/ton or US$110/ton.

This analysis revealed some interesting results (Table 1). The base-case LCOE of SMR manufacturers with larger reactor designs and more advanced projects (GE Hitachi, Rolls-Royce, and Westinghouse) tended to be better due to more favourable

[105] Nuclear Energy Agency (2023), *The NEA Small Modular Reactor Dashboard*, https://www.oecd-nea.org/jcms/pl_73678/nea-small-modular-reactor-smr-dashboard
[106] Power, Energy & Infrastructure Group at Lazard (2023), *Lazard Levelized Cost of Energy Plus (Version 16.0)*, https://www.lazard.com/media/typdgxmm/lazards-lcoeplus-april-2023.pdf
[107] International Renewable Energy Agency (2023), *World Energy Transitions Outlook 2023*, https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023
[108] International Renewable Energy Agency (2022), *IRENA Renewable Power Generation Costs in 2021*, https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021
[109] Bloomberg New Energy Finance (2023), *New Energy Outlook 2023*, https://about.bnef.com/new-energy-outlook/

capex scaling premises with lower diseconomies of scale in relation to larger conventional nuclear reactors. SMRs, as a group, at the current development stage, are expected to have an LCOE 18–20 per cent worse than a conventional or advanced pressurized water reactor (PWR), but 10 per cent better than coal—an important economic signal with scope for further improvement of SMRs' ability to replace coal power generation. With base-case LCOEs, wind, solar and natural gas combined cycle gas turbine (CCGTs) outperform SMRs by about 40 per cent.

Table 1: Indicative 60-year LCOE including intermittency and carbon costs for 1,000 MW power generation facilities with 60-year asset life

		LCOE ($/MWh)		
Nuclear SMRs	Indicative 60 Year Capex ($ Billion)	[A] = Base Case	[B] = [A] + Intermittency Cost	[C] = [B] + Carbon Cost (b)
EDF 170 MWe PWR	7,65	**50,68**	**50,84**	**50,84**
GE Hitachi 300 MWe BWR	8,88	**52,80**	**52,96**	**52,96**
Holtec Britain 160 MWe PWR	9,39	**63,44**	**63,60**	**63,60**
NuScale 77 MWe PWR	12,26	**68,82**	**68,98**	**68,98**
Rolls-Royce 470 MWe iPWR	9,03	**48,50**	**48,66**	**48,66**
Westinghouse 300 MWe PWR	6,40	**46,93**	**47,09**	**47,09**
SMR Indicative Average	*9,19*	***54,47***	***54,63***	***54,63***
Conventional Nuclear				
PWR Base Case	4,24	**46,08**	**46,24**	**46,24**
Advanced PWR	3,24	**45,21**	**45,37**	**45,37**
Non-Nuclear Technologies				
Coal	8,50	**60,23**	**62,93**	**181,25**
Natural Gas CCGT	7,00	**35,43**	**37,22**	**94,80**
Onshore Wind	25,20	**24,67**	**35,41**	**35,41**
Offshore Wind	32,78	**42,63**	**49,32**	**49,32**
Utility-scale Photovoltaic	28,30	**30,24**	**44,57**	**44,57**

Source: Lazard (2023), Lazard 2023 Levelized Cost of Energy Plus (version 16.0), www.lazard.com/media/typdgxmm/lazards-lcoeplus-april-2023.pdf; Nuclear Energy Agency (2023), NEA SMR Dashboard Report, www.oecd-nea.org/jcms/pl_73678/nea-small-modular-reactors-smr-dashboard; International Renewable Energy Agency (2022), IRENA Renewable Power Generation Costs In 2021, www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021; International Renewable Energy Agency (2023), World Energy Transitions Outlook 2023, www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023; Bloomberg New Energy Finance (2023), New Energy Outlook 2023, https://about.bnef.com/new-energy-outlook/

Notes: Nuclear reactors: PWR = Pressurized Water Reactor, BWR = Boiling Water Reactor, iPWR = Integral Pressurized Water Reactor, Natural Gas CCGT = Natural Gas Combined Cycle Turbine
(a) Intermittency cost (non-generation) = spot price of electricity $0.1338/kw (UK average Jan-Nov 2023)
(b) Carbon price UK BEIS £84/ton = $110/ton

All 1,000 MW facilities were premised to contract sales at 90 per cent of capacity with the following capacity factors: nuclear 88 per cent, coal 58 per cent, natural gas CCGT 70 per cent, onshore wind 30 per cent, offshore wind 48 per cent, and PV solar 20 per cent. When intermittency costs were allocated, the best performing SMRs (Rolls-Royce and Westinghouse) outperformed coal by 24 per cent and were marginally better than offshore wind and equivalent to PV solar. Natural gas CCGTs and onshore wind maintained a comfortable lead.

When carbon cost was included in coal and natural gas power generation assets' LCOEs, SMRs as a group outperformed coal by 70 per cent and natural gas by 42 per cent—confirming the technical and economic viability of SMRs as an ideal replacement for fossil fuels in power generation. When comparing SMRs with other technologies, the higher cement, mineral, and metal intensity per MWh of conventional nuclear (1.5–2.5×), or onshore wind (4–8×), or offshore wind (7–15×), or PV solar (5–10×) indicates substantial 'unaccounted CO_2 cost' in renewable value chains, enabling SMR to become the optimal energy trilemma solution.

Challenges and scope for improvement

While performing relatively well on LCOE, nuclear power plants still face many challenges such as high capital costs, long construction times, an uncertain regulatory environment, limited public support, and competition from renewable sources. In addition, SMRs face the lack of technology maturity and the need for economies of scale, standardization, and development of a new supply chain.

According to an Imperial College London report,[110] the capital cost of nuclear plants represents around 80 per cent of the overall cost of nuclear power generation, and the scope and complexity of nuclear reactor plants drive delivery schedules up to 14 years, exposing the process to significant exogenous pressures impacting final capital costs. The report states that the Generic Design Assessment (GDA) process for new reactor designs in the United Kingdom takes between four and six years to complete, depending on the level of design maturity and the quality of the submissions.

The Hinkley Point C project, the United Kingdom's first new nuclear power plant in a generation, encountered significant delays and cost escalations. Originally slated for electricity generation in 2017, construction commenced in 2019 after governmental approval and signing a Contract for Difference with EDF. The project, now expected to operate in 2027, a decade behind schedule, saw capital costs soar from £16 billion (2013) to £33 billion (2024), marking a 106 per cent increase. The GDA for the European Pressurized Reactor spanned five years (2007–2012). Notably, the permitting and licensing process, comprising 36 per cent of total construction time (5 out of 14 years), contributed £9.6 billion to the £33 billion capital cost.

A report by the World Nuclear Association in 2015 suggested that the United Kingdom could benefit from adopting the following from more efficient processes in other countries:[111]

- establishing a single regulatory body for nuclear safety, security, and environmental protection;
- adopting a staged permitting approach, divided into several phases, such as site selection, design certification, construction, operation, and decommissioning;
- adopting the GDA process, where the safety, security, and environmental aspects of a reactor design are evaluated and approved independently of a specific site;
- developing and applying clear and consistent regulatory guidance and criteria, based on international standards and best practices;
- engaging and consulting with the public and stakeholders throughout the licensing or permitting process.

The United Kingdom has a well-established and internationally recognized regulatory framework for nuclear power, which involves the Office for Nuclear Regulation, the Environment Agency, and other bodies. Streamlining and expediting the regulatory and licensing process for new reactor designs involves early and continuous engagement between the regulators and the vendors, which reduces the time and cost of the GDA process. The government aims to complete the GDA process within four years.

The United Kingdom can also learn and incorporate improvements from the experiences of the following countries, whilst also being careful to recognize some of the pitfalls they have experienced.

- **France,** with a world-leading nuclear industry operating 56 reactors for over 60 years, supplying over 70 per cent of its electricity, has the highest share globally. The country boasts a centralized and integrated nuclear policy and regulatory system, along with extensive experience in nuclear power plant construction and operation. Despite achieving globally low costs and shorter construction times for its nuclear reactors, such as Flamanville 3, France has encountered recent challenges. These include issues with the ageing nuclear fleet, economic and technical challenges in extending the operational life of existing reactors, a lack of preventive maintenance and repairs, a complex electricity tariff, and political pressure for a populist energy policy, hindering necessary corrections to the tariff.
- **Canada** has a respected nuclear industry boasting over 50 years of experience, operating 19 reactors contributing 15 per cent of its electricity. The country's regulator is highly regarded for its proactive and collaborative approach to SMR regulation, engaging early with vendors and maintaining continuous dialogue with stakeholders and Indigenous communities, which has positively influenced public acceptance. Challenges persist, with cost estimates ranging from

[110] Gross, Robert, Candelise, Chiara, and Blyth, William (2015), *Understanding the Costs of Nuclear Power in the UK*, London: Imperial College Centre for Energy Policy and Technology. https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/Cost-estimates-for-nuclear-power-in-the-UK.pdf

[111] Licensing and Permitting Task Force, World Nuclear Association (2013), *Licensing and Project Development of New Nuclear Plants*. https://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/WNA_REPORT_Nuclear_Licensing.pdf

$500 million to $2 billion and unquantified benefits like remote power generation and low emissions; harmonization of federal and provincial regulations causing uncertainty for developers; and potential public concerns related to safety, waste disposal, and visual impact.

- **China**, with 57 operating reactors generating 5 per cent of its electricity, has undertaken a rapid and diversified nuclear programme with plans to triple capacity by 2030 and quadruple by 2050, backed by strong government support and investments in nuclear energy (SMRs, high-temperature gas-cooled reactors, molten salt reactors, and conventional plants). China has four SMR projects: Linglong One (125 MWe [megawatts-electric] PWR), with a three-year GDA and starting in 2025; Hainan One (200 MWe PWR), with an incomplete GDA and expected to start operation in 2026; Shidaowan One (210 MWe high-temperature gas-cooled reactor), with a four-year GDA and starting in 2024; and Wuwei One (2 MWe liquid fluoride thorium reactor), with a three-year GDA and starting 2024. However, concerns have been raised about transparency, accountability, potential shortcuts due to ambitious timelines, and centralized control, despite China's emphasis on high safety standards.

Another challenge, recognized in *Civil Nuclear: Roadmap to 2050*[112], is to 'ensure access to a secure and resilient supply of nuclear fuel for the reactors of today and tomorrow'. This involves growing domestic fuel cycle capabilities along with removing any remaining Russian fuel and uranium supply to the United Kingdom by 2030, as well as delivering UK high-assay low-enriched uranium (HALEU) enrichment and deconversion capability. HALEU is the specialized fuel essential for operating the next generation of nuclear reactors, including SMRs and advanced modular reactors. The UK government unveiled a £300 million programme to back the production of HALEU fuel pellets and rods (£210 million), the establishment of a domestic HALEU enrichment capability (£40 million), and the development of a domestic HALEU deconversion capability (£50 million).

Conclusion

Nuclear SMRs are ideal to cut CO_2 emissions, enhance grid stability supporting renewables growth with higher system intermittence, and improve energy security and affordability. SMRs are a powerful candidate to accelerate the decarbonization of hard-to-abate industrial sectors, which are estimated to emit 35–40 $MtCO_2$, or 20–25 per cent of the total UK CO_2 emissions of 168 $MtCO_2$ in 2022.

SMRs will have a strategic opportunity to demonstrate their potential in the United Kingdom, benefiting from the Great British Nuclear SMR funding competition, ambitious nuclear energy growth target, and supportive carbon price. The United Kingdom benefits by implementing an efficient energy trilemma solution, supports renewable growth, optimizes grid investments, and secures a leading position to reduce fossil fuel use.

With SMRs' increased use, their supply chain for equipment, services, and fuel will grow and become competitive. As manufacturers improve SMR project delivery and achieve manufacturing economies of scale, LCOEs will fall. Increased SMR competitiveness will open new applications in hydrogen production, district heating, water desalination, and other industrial sectors. However, for this to happen, many challenges need to be resolved, particularly the uncertain regulatory environment. The UK government's aim to complete the GDA process within four years is an important objective, and doable based on the French, Canadian, and Chinese experience. Based on the GDA process for the European Pressurized Reactor in Hinkley Point C, one year of delivery schedule reduction could have reduced £1.9 billion or 12 per cent of the original capex, ignoring the other schedule and cost increases.

[112] Department for Energy Security & Net Zero, United Kingdom Government (2024), *Civil Nuclear: Roadmap to 2050, Chapter 7, UK nuclear fuel cycle* https://assets.publishing.service.gov.uk/media/65aa96bc82fee9000d6f5f91/6.8610_DESNZ_Civil_Nuclear_Roadmap_report.pdf

WHAT'S HOLDING BACK NUCLEAR IN AMERICA?

Thomas Hochman

In the United States, the two sides of the nuclear debate are well established. The antinuclear camp, composed mostly of safetyists and conservationists, argues that the risks associated with nuclear waste and meltdown outweigh any benefits that the energy source might offer. Nuclear advocates—often an oddball coalition of conservatives and climate hawks—maintain that nuclear energy is safe, reliable, and crucial to an electric grid that increasingly relies on intermittent power generation.

These two camps—vestiges of the debates of half a century ago, when nuclear was first becoming commercially viable—are highly selective in their priorities. Now, as then, arguments over nuclear focus on safety and local environmental concerns, ignoring the many other inputs that affect energy development. This is a missed opportunity, and has led nuclear advocates and detractors alike to misunderstand the forces behind the country's dwindling atomic sector.

By now the data around nuclear safety is clear. Nuclear energy is less deadly per kWh produced than just about every other energy source, including wind and hydropower.[113] There's little doubt that nuclear power can play an important role in adding flexibility to a grid with high levels of renewable penetration. Even after years of industry decline, nuclear remains the largest source of clean power in the United States.[114]

Advocates interpret this as evidence that nuclear's problems are mostly political. As their argument goes, the greatest barriers to the nuclear renaissance are environmentalists, NIMBY ('not in my back yard') objectors, and federal regulators, particularly the Nuclear Regulatory Commission (NRC). One can understand why advocates point to these actors as the main culprits: antinuclear lobbyists such as the Sierra Club do cite safety concerns as part of their argument that 'nuclear is no solution to climate change.'[115] Environmental groups have played a role in the shuttering of some nuclear plants—most notably, the Indian Point Energy Center in New York and the last three nuclear plants in Germany. And there is no doubt that agencies such as the NRC sometimes drag their heels when permitting new projects.

But to determine whether environmentalists and regulators truly stand as the greatest threat to the American nuclear industry, one ought to consider the many recent nuclear projects that have failed to reach completion in the United States. If environmentalists and regulators really are the reason that we don't have nuclear, then their obstruction should be apparent in these cases. The evidence often turns out to be less than compelling.

In late 2023, NuScale scrapped development on its 462 MW Carbon Free Power Project in Idaho Falls. Once dubbed the future of nuclear power, the project had been tapped as the United States' first commercial small modular reactor.[116] But estimated construction costs had skyrocketed. In 2021, NuScale said it planned to deliver power at $58/MWh. By 2023, that figure had risen to $89/MWh, even with the $4 billion in federal subsidies the project planned to receive.[117] Some researchers, such as Massachusetts Institute of Technology nuclear engineer Jacopo Buongiorno, say that this was due to a particular design flaw: NuScale's reactor relied on an enormous amount of concrete at a time when concrete prices were surging globally.[118] NuScale instead attributes the price increase to broader inflationary pressures on the energy supply chain. Either way, the underlying problem was the same: NuScale dramatically underestimated construction costs and failed to deliver, even with the backing of billions of dollars in federal funds.

One would be right to pause here and ask: where was the Sierra Club? Where were the many other environmental groups who have been so roundly castigated by nuclear advocates? In NuScale's failure, at least, they were nowhere to be seen.[119]

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113 Ritchie, Hannah (2020), 'What are the safest and cleanest sources of energy?, *Our World in Data*, 10 February, https://ourworldindata.org/safest-sources-of-energy.

114 United States Department of Energy (2021), '3 reasons why nuclear is clean and sustainable,' 31 March, https://www.energy.gov/ne/articles/3-reasons-why-nuclear-clean-and-sustainable.

115 Sierra Club (n.d.), 'Nuclear free future', https://www.sierraclub.org/nuclear-free#:~:text=Nuclear%20is%20no%20solution%20to,Free%20Campaign%20Grassroots%20Network%20website.

116 Plumer, Brad, and Penn, Ivan (2023), 'U.S. bets on small nuclear reactors to help fix a huge climate problem," *New York Times*, 12 November, https://www.nytimes.com/interactive/2023/11/12/climate/nuclear-reactors-clean-energy.html.

117 Schlissel, David (2023), 'Eye-popping new cost estimates released for NuScale small modular reactor', Institute for Energy Economics and Financial Analysis, 11 January, https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor.

118 Cho, Adrian (2023), 'Deal to build pint-size nuclear reactors canceled', *Science*, 10 November,https://www.science.org/content/article/deal-build-pint-size-nuclear-reactors-canceled.

119 Environmental Progress (n.d.), 'The war on nuclear', https://environmentalprogress.org/the-war-on-nuclear; Adams, Rod (2016), 'The Sierra Club's Michael Brune offers lousy excuses about nuclear energy position', *Atomic Insights*, 16 May, https://atomicinsights.com/sierra-clubs-michael-brune-offers-lousy-excuses-nuclear-stance/; Nuclear Newswire (2021), 'Generation Atomic to Sierra Club: OK, boomer, time to rethink nuclear', 1 October, https://www.ans.org/news/article-3299/generation-atomic-to-sierra-club-ok-boomer-time-to-rethink-nuclear/.

Perhaps, then, the fault lies with the bureaucrats at the NRC. After all, the licensing process for NuScale was long: the NRC only certified NuScale's design after more than four years of deliberating.[120] Still, the NuScale small modular reactor was a first-of-a-kind reactor. First-of-a-kind projects always require a greater regulatory timeline, as the NRC is unfamiliar with the design before licensing begins and often has to update its frameworks to allow for development to continue. At the same time, US executive agencies went to enormous lengths to help NuScale navigate the permitting process. The US Department of Energy (DOE) agreed to host the NuScale project at its Idaho National Laboratory, for example, allowing NuScale to circumvent the years-long site permitting process. And the federal government played a major role in financing the company's Carbon Free Power Project, approving a $1.35 billion cost-share award for the project in 2020 and passing a $30/MWh generation subsidy in the 2022 Inflation Reduction Act.

What's more, if the American regulatory environment were uniquely hostile to new nuclear development, one should expect substantially faster permitting and construction timelines abroad. It is not at all clear that this is the case. In December, the world's first fourth-generation nuclear reactor became operational in Shandong, China, 12 years after the project was planned to begin construction. The project's long list of delays will look eerily familiar to anyone who has followed the American nuclear industry. In January 2006, China announced its intention to develop a commercial nuclear plant with small modular reactors, setting the construction start date to 2011.[121] After several years of design, licensing, and a delay due to the Fukushima meltdown, construction began almost two years behind schedule in December 2012.[122] In 2016, China installed the first reactor vessel at the project site, announcing that it expected the plant to begin commercial operation in 2017.[123] The plant was not connected to the grid until 2021, however, and did not begin operating until two years later.[124] All told, in the world's most powerful centralised economy, it took 17 years to bring a single small modular reactor online. Long nuclear delays are simply not a uniquely American issue.

Still, the NRC's role in extending NuScale's development timeline should not be ignored. As this author noted in *The New Atlantis* in 2022, throughout the safety certification process, 'NRC's … regulatory framework forced NuScale to apply for 17 exemptions, each of which required its own set of robust technical justifications.'[125] Nuclear *would* be easier to build with a more proactive regulatory body. The structure of the NRC *is* such that there is little incentive to balance the construction of new reactors against its safety considerations. But it is also increasingly clear that the NRC is not the industry's greatest problem.

Plant Vogtle's Unit 3, the United States' newest nuclear reactor, came online last year in Waynesboro, Georgia. In many ways, Vogtle represented an enormous win for the American nuclear industry. When the unit began generating electricity in July, it became the first reactor in seven years (and the second reactor in over two decades) to begin delivering energy to the American grid.[126] It serves as proof that it is still possible to build nuclear power in the United States.

From a financing perspective, however, Vogtle was an absolute disaster. Construction on Vogtle units 3 and 4 began in 2009. At the time, cost estimates for both reactors stood at $14 billion, with the expectation that the units would connect to the grid in 2016 and 2017, respectively. By 2023, construction costs had ballooned to $34 billion, with only the first unit completed.

Again, neither the NRC nor the environmental lobby appears to have been anywhere near the top of the list of Vogtle's problems. Per a report from Columbia University's Center on Global Energy Policy,

[120] United States Department of Energy (2023), 'NRC certifies first U.S. small modular reactor design', 20 January, https://www.energy.gov/ne/articles/nrc-certifies-first-us-small-modular-reactor-design.
[121] Zuoyi Zhang, Yujie Dong, Weiwei Qi, and Jun Sun (2019), "HTR-PM: making dreams come true," Nuclear Engineering International, 26 February, https://www.neimagazine.com/features/featurehtr-pm-making-dreams-come-true-7009889/.
[122] World Nuclear News (2014), 'First HTR-PM construction progresses', 4 April, https://www.world-nuclear-news.org/NN-First-CAP1400-reactor-under-construction-0404144.html.
[123] World Nuclear News (2016), 'First vessel installed in China's HTR-PM unit', 21 March, https://www.world-nuclear-news.org/nn-first-vessel-installed-in-chinas-htr-pm-unit-2103164.html.
[124] World Nuclear News (2023), 'China's demonstration HTR-PM enters commercial operation', 6 December, https://www.world-nuclear-news.org/Articles/Chinese-HTR-PM-Demo-begins-commercial-operation.
[125] Hochman, Thomas (2022), 'A nuclear renaissance?', *The New Atlantis*, https://www.thenewatlantis.com/publications/a-nuclear-renaissance.
[126] Clifford, Catherine (2023), 'America's first new nuclear reactor in nearly seven years starts operations', CNBC, 31 July, https://www.cnbc.com/2023/07/31/vogtle-unit-3-nuclear-reactor-long-delayed-starts-delivering-power.html.

> The root causes of the overages at Vogtle included: incomplete design, inadequate level of detail in the integrated project schedule, inadequate quality assurance, poor risk assessment, limited design constructability, a shortage of experienced labor, and even the COVID-19 pandemic. These problems, in turn, led to extensive rework and remediation, supply chain delivery issues for reactor modules, low individual productivity, and high levels of attrition and absenteeism in the workforce.[127]

As with NuScale, the federal government was also a leading financier of the Vogtle project. In 2010, the DOE offered $8.33 billion in loan guarantees for the construction of the two reactors.[128] In 2019, with progress sputtering, the DOE offered an additional $3.7 billion to finance continued construction. The state of Georgia also stepped up to support Vogtle's cost overruns. In early 2017, the reactor designer Westinghouse filed for bankruptcy, citing losses from the Vogtle project. With estimated costs having already risen by $5 billion, the Georgia Public Service Commission was faced with the question of whether to approve continued construction under a new electric utility or spike the project.[129] The Commission unanimously voted to allow Georgia Power to continue construction, leaving ratepayers on the hook for substantially higher electricity costs than previously estimated.[130]

It is once again true that the NRC is not blameless in all of this. Perhaps most notably, the NRC published a decision in the federal register in 2009 that required a major redesign of the Westinghouse reactor.[131] This decision came down after Westinghouse had already sold the certified design to two customers, which some commentators suggest created up to two years of delay.[132] But again, it doesn't appear that the reactor's cost overruns and delays were unique to the United States. Westinghouse also undertook a series of reactor builds in China around the same time that construction began on Vogtle. These, too, came in far over cost and behind schedule. The first pair of reactors, in Sanmen, were first expected to cost RMB 32.4 billion each.[133] The actual price ended up soaring to around RMB 50 billion.[134] And when construction began in 2008, the Sanmen reactors were expected to begin operation in 2014 and 2015. Both reactors only began operating in 2018, with the second unit almost immediately shutting down for roughly a year in response to a reactor coolant pump defect.[135]

Taken together, the recent failures of the nuclear industry both in the United States and elsewhere seem to paint a bleak picture for the future of atomic energy. With the cancellation of the NuScale project, the United States' most well-funded, highly publicized effort at building a small modular reactor fell apart before construction even began. With Vogtle, the United States' latest standard reactor reached completion, but only after bankrupting Westinghouse and overshooting cost estimates by $20 billion. Meanwhile, recent attempts to kickstart a next-generation nuclear industry internationally have ended in similar disappointment.

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[127] Bowen, Matt, Ponangi, Rama T., and Evans, Andrew (2023), 'Vogtle unit 3 has started commercial operations. What's next for the AP1000?', Columbia University School of International and Public Affairs, 31 July, https://www.energypolicy.columbia.edu/vogtle-unit-3-has-started-commercial-operations-whats-next-for-the-ap1000/.

[128] United States Department of Energy (2023), 'How the Loan Programs Office and Plant Vogtle are shaping the energy transition through nuclear technology', 28 October, https://www.energy.gov/lpo/articles/how-loan-programs-office-and-plant-vogtle-are-shaping-energy-transition-through.

[129] Hals, Tom, Yamazaki, Makiko, and Kelly, Tim (2017), 'Huge nuclear cost overruns push Toshiba's Westinghouse into bankruptcy', Reuters, 29 March, https://www.reuters.com/article/us-toshiba-accounting-board-idUSKBN17006K/.

[130] Corwin, Tom (2017), "Plant Vogtle growth wins approval, penalties from Public Service Commission," *Savannah Morning News,* 21 December, https://www.savannahnow.com/story/news/2017/12/21/plant-vogtle-growth-wins-approval-penalties-public-service-commission/13846306007/.

[131] GovInfo (2009), '74 FR 28112—consideration of aircraft impacts for new nuclear power reactors', 12 June, https://www.govinfo.gov/app/details/FR-2009-06-12/E9-13582#:~:text=%40nrc.gov.-,Summary,of%20a%20large%2C%20commercial%20aircraft.

[132] Adams, Rod (2017), 'What does Westinghouse bankruptcy mean to nuclear energy innovators?', Forbes, 31 March, https://www.forbes.com/sites/rodadams/2017/03/31/what-does-westinghouse-bankruptcy-mean-to-nuclear-energy-innovators/?sh=446d87701536.

[133] World Nuclear Association (2023), 'Nuclear power in China', https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

[134] Dalton, David (2018), 'China's Sanmen-1 becomes world's first AP1000 to begin commercial operation," *NucNet*, 21 September, https://www.nucnet.org/news/china-s-sanmen-1-becomes-world-s-first-ap1000-reactor-to-begin-commercial-operation.

[135] World Nuclear News (2018), 'First AP1000 reactor enters commercial operation', 21 September, https://www.world-nuclear-news.org/Articles/First-AP1000-reactor-enters-commercial-operation; Energy Intelligence Group (2019), 'China: Sanmen-2 restart puts CNNC out of its financial misery," 20 November, https://www.energyintel.com/0000017b-a7d9-de4c-a17b-e7db48500000.

If there is to be a future for nuclear power in America, then, nuclear advocates will have to radically update the way they talk about energy policy. Rather than ignoring the fundamental cost and timing challenges that the industry faces, advocates will have to push for nuclear on the grounds that it provides a great deal of utility that cannot be captured by simple price estimates. Indeed, nuclear power remains expensive. New nuclear is unlikely to be able to compete with clean energy on price alone. And yet there is plenty of reason for the United States to build it anyway. The value of a given energy source does not sit solely along a continuum of greatest versus least cost. Other characteristics that nuclear does possess—reliability, resistance to foreign price shocks, low carbon output—are also crucial components of American energy security. By those measures, nuclear is still vital to the American grid. But advocates must be more clear-eyed about its downsides.

Any nuclear revival in the United States will not bring about electricity 'too cheap to meter', as the Atomic Energy Commission's Lewis Strauss predicted in 1954.[136] It may, however, bring more reliability and flexibility to the American grid. But the nuclear bubble will first have to burst. Nuclear's detractors will have to accept its role in the clean energy economy; nuclear advocates will have to dispense with the fiction that nuclear energy can be a cheap replacement for the existing clean energy mix.

Lobbyists and regulators certainly aren't doing nuclear energy any favours. But to achieve a bright future for the American nuclear industry, advocates must go beyond blaming these bogeymen to tackle the real challenges the technology faces.

UNITED STATES NUCLEAR POLICY, SMALL MODULAR REACTORS, AND GLOBAL ENERGY SECURITY

Jennifer T. Gordon and Landon Derentz

After decades of policy uncertainty and economic challenges to the US nuclear energy industry (brought largely by deregulated electricity markets and cheap and abundant natural gas), global recognition is mounting that nuclear energy has a crucial role to play in both decarbonization and energy security. In the International Energy Agency's Net Zero Emissions by 2050 Scenario, 'nuclear energy plays a significant role' and almost doubles from 413 GW in 2022 to 812 GW by 2050.[137]

In contrast to the tumultuous global political landscape of recent years, US policy supporting nuclear energy has proven steadfast, bolstering a sector that needs government support to compete internationally. Not only is nuclear energy benefiting from the robust security-focused approach to the sector during the Trump administration, the centrality of climate change in all aspects of the Biden administration has further emboldened the trajectory of related policy in the country. Nuclear energy sits at the nexus between these two priorities, as it can provide energy security and accelerate global decarbonization.

In the United States, policies supporting nuclear energy have retained bipartisan support. Even at a time when political parties seem to agree on little else, Congress and consecutive administrations have advanced incentives not only to keep US nuclear energy in the game but to elevate nuclear technologies as a central pillar of national security and the energy transition. There is also a growing appreciation for the significance of nuclear energy in aiding in decarbonization beyond the power sector.

The United States and its allies are working to ensure that, globally, nuclear energy is ascendant. Also, the UN's premier climate event, held in Dubai last year—COP28—embraced nuclear in a manner unthinkable only two years before in Glasgow. The start of the 'nuclear COP' began with a commitment from more than 20 countries to triple nuclear energy capacity by 2050, and this was soon matched by a complementary industry pledge. Moreover, the climate conference boasted extensive programming on nuclear energy and in fora such as the Net Zero Nuclear Summit, hosted by the Emirates Nuclear Energy Corporation and the World Nuclear Association.

The significance of nuclear energy's inclusion at the world's premier climate conference goes far beyond rhetoric, as it begins to shape policies such as the EU's Green Taxonomy and influence ESG (environmental, social, and governance) investing frameworks to include nuclear energy (rather than placing nuclear stocks in their 'box of sin', which also includes weapons and tobacco). These measures are significant, and they represent building blocks in the effort to deploy nuclear energy at a scale large enough to lower the trajectory of global greenhouse gas emissions. While the World Bank maintains its ban on financing

[136] Terzic, Branco (2018). 'Is power ever too cheap to meter?' Atlantic Council, 3 July, https://www.atlanticcouncil.org/blogs/energysource/is-power-ever-too-cheap-to-meter/
[137] "Nuclear Power and Secure Energy Transitions," International Energy Agency, June 2022, https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions/executive-summary.

nuclear energy projects, and nuclear energy is excluded from most ESG funds (with the notable exception of Canada's green bond framework, which is a model for the rest of the world), these changes are beginning to shift global discourse on deployment of nuclear energy, starting in the United States.

United States nuclear policy

Given the polarized political climate in Washington DC in recent years, the continuity between the Trump and Biden administrations on nuclear energy policy is striking. The Trump administration saw across the finish line a number of landmark pieces of bipartisan legislation with the goal of modernizing and streamlining the development of US nuclear energy technologies. The three central pieces of legislation in this effort were the 2018 Nuclear Energy Innovation Capabilities Act; the 2019 Nuclear Energy Innovation and Modernization Act; and the Nuclear Energy Leadership Act, which passed as part of the 2020 National Defense Authorization Bill.[138]

The Trump administration also launched the Advanced Reactor Demonstration Program,139 which distributed $160 million in 2020 under a cost-sharing structure with the private sector, in order to jump-start investment into companies designing the next generation of nuclear reactors. Finally, the US Export-Import Bank received full reauthorization in 2019, and the US International Development Finance Corporation lifted its ban on nuclear project finance in 2020. All of these efforts taken together have improved the position of the US nuclear energy industry, but more work remains to be done.

Building on this progress, the Biden administration further supported the nuclear energy industry in the United States with the 2022 Inflation Reduction Act (IRA)—the administration's signature piece of energy and climate legislation. The IRA includes a production tax credit that provides 'up to $15 per megawatt-hour for the electricity produced by the plants assuming that labor and wage requirements are met'.[140] Additionally, the legislation includes tax incentives for advanced reactors and invests $700 million to develop a domestic supply chain for high-assay low-enriched uranium (HALEU) fuel, which will be required to run advanced nuclear reactors. The IRA's provisions on nuclear energy complement the $6 billion civil nuclear tax credit programme that was established through the bipartisan infrastructure law.

The IRA and the bipartisan infrastructure law recognize the existing reactor fleet (which generates only 20 per cent of electricity overall, but accounts for more than half of zero-carbon electricity generation in the United States[141]) as the best tool for realizing a zero-emissions power sector and achieving broader climate goals. However, building out a fully realized nuclear energy innovation ecosystem in the United States requires further financing and greater regulatory certainty, including by developing well-financed fuel cycle capabilities (enrichment at the front end and recycling at the back end) and streamlining the licensing process for the deployment of advanced reactors.

In 2023, the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act was passed as part of the National Defense Authorization Act, to 'enhance United States civil nuclear leadership, support the licensing of advanced nuclear technologies, strengthen the domestic nuclear energy fuel cycle and supply chain, and improve the regulation of nuclear energy'.[142] The Nuclear Fuel Security Act also passed in the National Defense Authorization Act of 2023, and it 'directs the Department of Energy to prioritize activities to increase domestic production of low-enriched uranium (LEU) for existing reactors and accelerate efforts to ensure the availability of high-assay, low-enriched uranium (HALEU) for advanced reactors'.[143]

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[138] Julia Pyper, "Trump Signs Legislation to Promote Advanced Nuclear Reactor Technology," *Green Tech Media*, October 1, 2018, https://www.greentechmedia.com/articles/read/trump-signs-legislation-to-promote-advanced-nuclear-technology; "President Trump Signs Bipartisan Nuclear Energy Legislation into Law," US Senate Committee on Environment and Public Works, January 14, 2019, https://www.epw.senate.gov/public/index.cfm/2019/1/president-trump-signs-bipartisan-nuclear-energy-legislation-into-law; "Senate Passes Nuclear Energy Leadership Act In Defense Authorization Bill," US Senate Committee on Energy and Natural Resources, July 23, 2020, https://www.energy.senate.gov/2020/7/senate-passes-nuclear-energy-leadership-act-in-defense-authorization-bill.

[139] "U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program," US Department of Energy Office of Nuclear Energy, October 13, 2020, https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor.

[140] "Inflation Reduction Act Keeps Momentum Building for Nuclear Power," US Department of Energy Office of Nuclear Energy, September 8, 2022, https://www.energy.gov/ne/articles/inflation-reduction-act-keeps-momentum-building-nuclear-power.

[141] "Electricity explained," US Energy Information Administration, last updated June 30, 2023, https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php; "Nuclear Power in the USA," World Nuclear Association, last updated January 2024, https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

[142] "Senate Passes Bipartisan Nuclear Energy Bill from Capito, Carper, Whitehouse," US Senate Committee on Environment and Public Works, July 27, 2023, https://www.epw.senate.gov/public/index.cfm/2023/7/senate-passes-bipartisan-nuclear-energy-bill-from-capito-carper-whitehouse.

[143] "Barrasso's Nuclear Fuel Amendment Overwhelmingly Passes Senate," US Senate Committee on Energy and Natural Resources, July 27, 2023, https://www.energy.senate.gov/2023/7/barrasso-s-nuclear-fuel-amendment-overwhelmingly-passes-senate.

Bipartisan support for nuclear energy demonstrated in US policy circles in recent years is ultimately crucial for the industry to succeed in domestic and international markets. This is true domestically, because the industry requires political certainty in the long term to increase from about 100 GW in 2023 to 300 GW by 2050,[144] and internationally, since the US industry's main competitors on the global stage (in terms of both geopolitical competition and market competition) are state-owned nuclear enterprises in Russia and China, countries with heavily subsidized and politically motivated nuclear energy programmes. Accordingly, US policymakers must recognize and value nuclear energy technologies for both their zero-carbon attributes (for instance, by instituting a carbon pricing method to help nuclear energy be more competitive in domestic energy markets) and their salience to national security.

Next-generation reactors

The term 'small modular reactor' (SMR) has become a catch-all for a suite of technologies that could more accurately be termed next-generation reactors. These include reactors with light-water reactor cores that take low-enriched uranium fuel (often referred to as Generation III+ reactors), reactors with newer types of cores that require HALEU fuel (referred to as Generation IV reactors), and microreactors . In practice, there is space in the reactor ecosystem for all types of next-generation reactors alongside large light-water reactors—which, it is worth mentioning, will remain a relevant part of the global energy mix given efforts to extend the lifespans of existing large light-water reactors and efforts to build new reactors (for example, in the United Arab Emirates and in Poland).

Since SMRs and microreactors have yet to be deployed globally for commercial use, assessing their comparative strengths is best achieved by contrasting them with the scale and impact of large light-water reactors. For instance, one large light-water reactor generally produces 1 GW of power, while SMRs are generally designed to produce up to 300 MW of power, and microreactors could produce up to 50 MW of power. While large light-water reactors and many SMRs are intended to provide grid-scale power (and, as previously mentioned, are a crucial component of power sector decarbonization), SMRs and microreactors also have the potential to decarbonize industries beyond the power sector.

Looking beyond the power sector, reactors can produce zero-carbon energy for use in desalination, process heat, and hydrogen production, and microreactors can help decarbonize industries like mining that currently rely on diesel fuel. Companies with energy-intense requirements are also looking at behind-the-meter applications; for example, Microsoft has signed memoranda of understanding with fission and fusion companies to provide zero-carbon energy for data centres. SMRs and microreactors also have the potential to provide zero-carbon power to military installations and remote villages from places like Alaska to island nations. In defraying costs, especially for some first-of-a-kind reactors, it may be that the US government (especially the US Department of Defense) will become the first customer and begin using SMRs or microreactors to power military installations. This could be a potentially transformative step in broader commercialization of these technologies, since experts predict an improved cost scale would make smaller reactors more economically appealing for countries (or even companies) that do not have the resources to build large light-water reactors.

In the United States, the nuclear energy industry is enjoying the tailwinds of increased public acceptance and the excitement of innovation. However, all new industries face challenges, and nuclear energy is no exception. Of the approximately 300 reactor designs that have been proposed globally,[145] many (if not most) are unlikely to be built, especially as global markets choose which designs they wish to support. Inevitably, some reactor developer companies will fail. Furthermore, the nuclear energy industry is not being developed in a vacuum; it exists within a broader context and will suffer from inflation and increased costs of materials and construction.

The decision by the Utah Associated Municipal Power Systems and NuScale in November 2023 to terminate their planned Carbon Free Power Project does not indicate trouble for the broader nuclear energy industry. Instead, it reflects the specific challenges, especially in cost and timing, faced by the project. Two major offshore wind projects were cancelled in New Jersey,[146] also in November 2023, primarily due to challenges with supply chains and high interest rates.

Most crucially, it is imperative to look at the next generation of nuclear energy technologies as a nuclear innovation ecosystem. These technologies include the reactors mentioned above, as well as advanced fuels, and enabling technologies like the versatile test reactor (VTR). In a healthy innovation ecosystem, there will be many reactor designs to meet differing on- and off-

[144] "Pathways to Commercial Liftoff: Advanced Nuclear," US Department of Energy, March 2023, https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf.

[145] "Plans For New Reactors Worldwide," World Nuclear Association, last updated January 2024, https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx.

[146] "Offshore wind project cancellations jeopardize Biden's clean energy goals," *PBS NewsHour*, Nov 4, 2023, https://www.pbs.org/newshour/nation/offshore-wind-project-cancellations-jeopardize-bidens-clean-energy-goals.

grid needs. Different reactor types will necessitate different fuel types, including HALEU for certain next-generation reactors and TRISO (tri-structural isotropic) fuel, which is used in many high-temperature reactor designs.[147]

The VTR is a crucial piece of a robust nuclear energy innovation ecosystem, because it allows reactor designers and fuel developers to continue to innovate and improve their technologies. Former US test facilities (the now-shut-down Experimental Breeder Reactor II and Hanford Fast Flux Test Facility) allowed for innovation in fuel and materials that enabled dramatic improvements in the existing reactor fleet, especially in achieving a high capacity factor. Although the United States still has test facilities (for example, the Advanced Test Reactor and the Transient Reactor Test Facility), they are ‘more than fifty years old, oversubscribed, and insufficient to test the technologies for next-generation advanced reactors’.[148] In contrast, Russia has the BOR-60 test reactor, and it is building a new fast neutron test facility the MBIR, which could be online by 2027.

Although the US Congress and the US Department of Energy recognize the need for a domestic advanced testing capability, Congress failed to reauthorize funding for the VTR project in 2022. This decision fails to recognize the role of the VTR in the broader nuclear energy innovation ecosystem and should be reversed. Although many reactors and fuels can be demonstrated and deployed without the VTR, the VTR will be necessary for these reactor types and fuels to continue to innovate and improve in subsequent generations.

Conclusion: nuclear energy and global energy security

The stakes for the nuclear energy industry led by the United States and its allies could not be higher, especially in the face of competition from state-owned nuclear energy enterprises in Russia and China, flush with state-backed financing and compelling short-term business models. Russia, for example, offers a ‘build, own, operate’ model to purchasing countries. In contrast, the United States seeks to help emerging nuclear countries build their own domestic capacity for independent nuclear energy programmes. Russia and China also offer fuel take-back and a range of other services that are not politically tenable in the United States at this time.

The United States and its allies, alternatively, are the only nuclear energy providers able to ensure that their reactor designs incorporate the highest standards of safety, security, and nonproliferation. Furthermore, buyer countries ought to welcome US efforts to build their domestic capacity for nuclear energy (which includes training a domestic workforce and establishing a local regulator) rather than importing an industry from Russia or China. Russia especially has proven itself to be an untrustworthy civil nuclear partner, as evidenced by its willingness to weaponize the Zaporizhzhia Nuclear Power Plant in Ukraine by attacking the plant and taking its workers hostage.[149] Nearly two years following Russia’s invasion of Ukraine and its occupation of the Zaporizhzhia plant, Russia has still not allowed inspectors from the International Atomic Energy Agency to access the facility.[150]

Accompanying the global recognition of the role of nuclear energy in addressing climate change must be a realization that the United States and its allies are the best suppliers of nuclear energy technologies. In order to compete in the global market, the United States and its allies must work together—especially on co-financing and on international regulatory cooperation—to offer a counterweight to Russia and China. Decarbonization and global energy security depend on these measures.

The Atlantic Council receives funding from a wide array of sources, including the Nuclear Energy Institute, the Emirates Nuclear Energy Corporation, and the Idaho National Laboratory.

[147] "Fuel Qualification Guidance for TRi-structural ISOtropic (TRISO) Fuel," US Nuclear Regulatory Commission, last updated December 7, 2023, https://www.nrc.gov/reactors/new-reactors/advanced/modernizing/rulemaking-and-guidance/fuel-qualification/triso-fuel.html.
[148] Jackie Toth and Khalil Ryan, *The Imperative of the Versatile Test Reactor for Nuclear Innovation*, Atlantic Council, April 2023, https://www.atlanticcouncil.org/wp-content/uploads/2023/04/The-imperative-of-the-Versatile-Test-Reactor-for-nuclear-innovation.pdf.
[149] James Waterhouse, "Zaporizhzhia nuclear workers: We're kept at gunpoint by Russians," *BBC News*, August 11, 2022, https://www.bbc.com/news/world-europe-62509638.
[150] Ron Popeski, "Inspectors denied access to parts of Ukraine nuclear plant -IAEA," *Reuters*, January 4, 2024, https://www.reuters.com/world/europe/iaea-says-denied-access-parts-russia-controlled-power-station-2024-01-03/.

THE ROLE OF NUCLEAR POWER IN CHINA'S ENERGY SECURITY AND LOW-CARBON ENERGY TRANSITION

Philip Andrews-Speed

China has the world's third-largest fleet of civil nuclear power reactors, after the United States and France, and the fastest growing fleet (Table 1). Since 2021, China's electricity supply from nuclear power has been greater than France's due to the technical problems that have forced reactor shutdowns in the latter country. China's rationale for investing so heavily in nuclear power was to enhance energy security, a long-term national priority. More recently, the desire to reduce carbon emissions and other forms of pollution from power generation has added impetus to the construction programme. However, nuclear power still only provides about 5 per cent of the nation's electricity supply and 2.5 per cent of total commercial primary energy consumption.

Table 1: China's civil nuclear power in a global context

Installed operable capacity		Capacity under construction		Share of power generation	
	GW (2023)		**GW (2023)**		**% (2022)**
US	95.8	**China**	**27.7**	France	62.6
France	61.4	India	6.0	Slovakia	59.2
China	**53.2**	Turkey	4.5	7 EU members	32–47
Japan	32.0	South Korea	4.0	South Korea	30.4
Russia	27.7	Egypt	3.3	Sweden	29.4
South Korea	24.5	UK	3.2	Spain	20.3
Canada	13.6	Russia	2.7	Russia	19.6
Ukraine	13.1	Japan	2.6	US	18.2
Spain	7.1	Bangladesh	2.1	UK	14.3
Sweden	6.9	Ukraine	2.1	**China**	**5.0**

Source: International Atomic Energy Agency, Power Reactor Information System, https://www.iaea.org/resources/databases/power-reactor-information-system-pris

These statistics raise the question of how soon nuclear power can make a substantial contribution to China's energy security and low-carbon ambitions.

Thirty years of nuclear power in China

The possibility of developing nuclear power was mentioned in China's first Five-Year Plan in 1953 but was then dropped as attention switched to developing an atomic bomb. A power supply crisis in 1970 brought nuclear power back onto the government's agenda, but a lack of interest from relevant agencies delayed a formal decision until 1978. Construction started in the mid-1980s, and the first commercial nuclear reactors came online in 1994. They were one 300 MW reactor (Qinshan 1), based on a Chinese design but with imported components, and two 944 GW units (Daya Bay 1 and 2), of French design.

After the country's first nuclear power plants were commissioned, a decision was made to build three more plants, each with two reactors, in order to sustain technical expertise but limit capital requirements. The reactors were, respectively, of French, Canadian, and Russian design and came online between 2002 and 2007. The domestic energy shortage experienced by China in the early 2000s triggered an acceleration of the nuclear power programme. In addition, the government was keen to explore Generation III technologies that offered greater safety and efficiency. US, French, and Russian companies were chosen to deploy their technologies in this new round of construction. Meanwhile, Chinese companies were working with their foreign counterparts to progressively indigenize designs and component manufacturing.

As a result, of the 30 reactors that started construction between 2006 and 2011, only eight were of purely foreign design. All 30 are now in operation, as are a further 12 or more reactors as of late 2023, mostly of Generation III design. These latter included the Hualong One reactor, which is of purely Chinese design and contains almost entirely domestically manufactured components. In 2011, the government suspended ongoing construction of new reactors for six months in response to the Fukushima Daiichi accident. Approvals for new reactors only recommenced 18 months after the accident, with the understanding that plans for plants in inland areas would not be considered for the foreseeable future due to the risk of polluting inland freshwater resources.

All the commercially operating units today are pressurized water reactors, a result of a decision made back in the 1970s. In recent years, China's nuclear scientists and engineers have continued to push forward with new designs, including high-temperature gas-cooled, molten salt, and fast neutron reactors, district heating reactors, floating nuclear power plants, and nuclear fusion.

Meanwhile, the country has been building its human capacity for the construction, operation, and regulation of civil nuclear power, with the cooperation of foreign governments and companies. A key task has been to enhance the capacity and credibility of the nuclear regulator, the National Nuclear Safety Administration. The International Atomic Energy Agency carried out Integrated Regulatory Review Service missions in 2010 and 2016. The reports concluded that the National Nuclear Safety Administration was 'effectively independent' from government and industry, but expressed concerns over the number and expertise of the staff to effectively regulate such a large and rapidly growing industry.

Transparency is a further concern. For example, the government and Chinese operating company were slow to provide public information on an incident at the Taishan plant (of French design) in June 2021. Nevertheless, there have been no serious incidents at any of the nation's civil nuclear reactors, according to official reports.

The outlook for nuclear power in China

With 53 GW of capacity in operation in late 2023 and another 27 GW under construction, total capacity should reach 80 GW by 2028/2029. Construction periods for each of these reactors are expected to be about five to six years. Assuming that all 48 GW of planned capacity are built, the total should reach close to 130 GW by 2035. However, this will require the government to grant approvals for the three planned plants that lie inland, a total of 10 GW across eight reactors. Beyond the planned reactors are about 180 GW of proposed reactors, half of which are considered as firm and the other half as less firm.[151]

There are many sets of projections for the future of nuclear power in China. One of the more authoritative is that published in 2022 by China's Institute of Climate Change and Sustainable Development (see Table 2).[152] Their four scenarios involve different shares of non-fossil fuel in the primary energy mix as the share of renewable and nuclear energy rises, electrification progresses, and national energy intensity declines. Three of the scenarios envisage total reactor capacity reaching 327 GW by 2050. This would require all the planned and proposed projects mentioned above to be operational by then. Moreover, construction should have yielded 10 GW of new capacity each year between 2030 and 2050. This would be a significant increase from 5 GW per year in recent years and a possible 8 GW per year between now and 2030. Ten GW per year of new reactors is also almost double the rate of completion achieved by the United States between 1970 and 1990.

[151] World Nuclear Association (2023), 'Nuclear power in China', https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

[152] Institute of Climate Change and Sustainable Development (2022), *China's Long-Term Low-Carbon Development Strategies and Pathways: Comprehensive Report*, SpringerLink, https://link.springer.com/book/10.1007/978-981-16-2524-4

Table 2: Role of nuclear power in scenarios for 2050 developed by China's Institute of Climate Change and Sustainable Development[153]

Scenario	Non-fossil fuel share in primary energy mix	Installed nuclear capacity	Nuclear power generation	Nuclear power share of power generation
Policy	36.3%	280 GW	1,907 TWh	17.3%
Reinforced policy	51.5%	327 GW	2,380 TWh	20.0%
2°C	73.2%	327 GW	2,350 TWh	17.9%
1.5°C	86.1%	327 GW	2,340 TWh	16.4%

In these scenarios, nuclear power reaches a share of between 16 per cent and 20 per cent of total power generation by 2050. Whilst China's nuclear power industry has shown that it can construct reactors relatively rapidly and at lower cost than companies in most other countries, several inter-related factors could constrain the rate of growth of the nation's fleet of nuclear reactors.

Primary among these is safety. The large scale of the construction programme will require great vigilance on behalf of the regulator and the industry. This applies not just to the construction process itself but also to the entire supply chain in terms of both the quantity of materials and components and their quality. The effective management of supply chain quality was something that the South Korean nuclear industry failed to do for several years.

A similar level of vigilance will be needed for operating reactors, as well as for the management of fuel fabrication and waste. These challenges will increase in scale and sophistication as the nation's nuclear programme expands and technology advances. This in turn will require a massive programme of education and training to staff the relevant government agencies, nuclear power companies, suppliers of key components and materials, and research institutes.

The second key concern is public opinion. Surveys carried out over the last 15 years have shown that nuclear power has the support of the majority of the public. This may have been due to the positive stance of the state media. Additional factors creating a favourable perception have included the promise of a stable and cheaper electricity supply and decreased use of fossil fuels. However, concern over the risks of nuclear power have tended to increase with proximity to a plant. Recent years have seen nuclear plant operators and local governments increasingly engaging with nearby residents before construction begins. These meetings not only provide information on the project but also emphasize economic benefits such as jobs, infrastructure, and public services. One issue that drew negative responses was the possibility of building nuclear reactors at inland locations.

Despite the track record of China's nuclear industry in managing safety and the positive perceptions of the public, a serious nuclear accident in or near China could easily disrupt the ambitious construction programme.

Implications for energy security and the low-carbon energy transition

China will likely host the world's largest fleet of civil nuclear reactors in 10 years' time at 100 GW or more. This sounds and is impressive. But one should note that what looks big in China from the outside is small in a domestic context. In the Institute of Climate Change and Sustainable Development's aggressive Reinforced Policy Scenario, with 184 GW of installed capacity, nuclear power is providing 14 per cent of electricity by 2035. By 2050, with 327 GW of capacity, this share has risen to 20 per cent, less than onshore wind at 23 per cent. So nuclear power has the potential to make a significant contribution to China's low-carbon energy transition in concert with other forms of low-carbon electricity.

[153] The Policy Scenario reflects China's 2015 Nationally Determined Contributions. The Reinforced Policy Scenario reflects a faster reduction of energy and carbon dioxide intensities. The 2ºC and 1.5ºC scenarios are based on the goal of controlling global warming to 2ºC and 1.5ºC respectively. Institute of Climate Change and Sustainable Development (2022), *China's Long-Term Low-Carbon Development Strategies and Pathways: Comprehensive Report*, SpringerLink, https://link.springer.com/book/10.1007/978-981-16-2524-4

Nuclear power has two advantages relating to energy security. In the short term, it provides reliable base load electricity, unlike solar and wind power, which are intermittent, and hydroelectricity, which is seasonal and subject to droughts. In the longer term, nuclear power requires limited imports of fuel in terms of quantity and cost, unlike natural gas. Nevertheless, China is heavily dependent on imports of uranium. The current strategy is to source one-third of uranium requirements domestically, one-third through trade imports, and one-third from overseas mining. Chinese companies now have equity joint ventures in uranium mines in several countries, including Canada, Kazakhstan, Namibia, Niger, and Uzbekistan. In addition, two facilities for reprocessing spent fuel into uranium and plutonium are under construction in Gansu Province. Once operational, these plants will enhance China’s security of supply for these fuels. Looking ahead, some designs of Generation IV reactors will not use uranium as a fuel. Nevertheless, all reactors require metals in their construction. Today’s reactors require substantial quantities of copper, nickel, and chromium, and China is highly dependent on imports for ores of these metals.

In summary, nuclear power will continue to make a growing contribution to China’s low-carbon energy transition and energy security, provided the construction programme accelerates and there are no major interruptions due to serious nuclear accidents.

THE STATUS OF NUCLEAR ENERGY IN SAUDI ARABIA: A STRATEGIC APPROACH TO ENERGY SECURITY AND SUSTAINABILITY

Noura Y. Mansouri

In a world grappling with energy security and climate change challenges, the Kingdom of Saudi Arabia is taking a transformative leap. Known for its vast oil reserves, the Kingdom is now venturing into nuclear energy, aligning with its Vision 2030, and energy diversification goals. This move not only diversifies energy sources but also enhances energy security and sustainability. By embracing nuclear energy, the Kingdom aims to position itself as a regional leader in the field while contributing to global efforts to combat climate change.

Saudi Arabia is actively pursuing a strategic shift towards sustainable energy solutions and the ambitious goal of achieving net-zero emissions by 2060. This transition includes plans to develop two nuclear reactors, aiming for a capacity between 2.2 to 3.3 GWe[154], as a part of its broader strategy to diversify and modernize its energy sector. Despite these efforts, Saudi Arabia has adopted a cautious and considered approach towards nuclear energy development. This was evident from the revision and the downsizing of its nuclear energy plans within the energy mix over time, and its recent notable absence from the pledge made at COP 28[155] by 22 nations to triple nuclear generation capacity by 2050. This illustrates the Kingdom's commitment to a methodical and reliable expansion into nuclear energy, focusing on a comprehensive evaluation of its role within the national energy mix. This careful strategy underscores Saudi Arabia's dedication to balancing sustainability goals with environmental, technical, economic, safety and security considerations.

The Saudi Atomic Energy Ecosystem

The Saudi atomic energy ecosystem today encompasses a comprehensive structure, led by the Ministry of Energy, which is responsible for the oversight and supervision of the national nuclear energy project. This includes developing strategies and policies for the nuclear energy sector, as well as managing international relations and representation in civil nuclear programs. The King Abdullah City for Atomic and Renewable Energy (KACARE) plays a crucial role in this ecosystem by conducting and coordinating nuclear-related research, developing human resources to meet the national atomic energy needs, providing technical support services, supporting long-term nuclear energy planning, and promoting the peaceful uses of nuclear science and technology.

On the commercial and business front, the Saudi Nuclear Energy Holding Company (SNE) is a fully-owned entity of KACARE. The Duwaihin Nuclear Energy Company, another entity fully owned by SNE, is involved in purchasing, constructing, operating, managing, and maintaining nuclear power plants. It also focuses on electric power generation, water desalination, and the

[154] WNA (2023) World Nuclear Association, Nuclear Fuel Report: Global Scenarios 2023-2040, London.
[155] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/120223-cop28-22-nations-pledge-to-triple-nuclear-generation-capacity-by-2050

thermal applications of nuclear energy, alongside the sale of electric energy, desalinated water, and thermal applications derived from nuclear energy, and the decommissioning of nuclear power reactors. Lastly, the Saudi procurement power company, the Principal Buyer, serves as the single buyer of electricity.

Regulation of safety, security, and safeguards within the sector is handled by a set of regulatory bodies, including the Nuclear Radiological Regulatory Commission, the National Center for Environmental Compliance, and the Water and Electricity Regulatory Authority. These organizations ensure that all nuclear energy activities within the Kingdom adhere to the highest standards of safety, security, and environmental protection.

An important aspect of Saudi Arabia's nuclear strategy is its focus on self-sufficiency in the nuclear fuel cycle. The initial assessment of uranium deposits and prospects in Saudi Arabia classifies them as inferred unconventional resources[156]. This classification indicates that while the country is in the early stages of exploring its uranium resources, these deposits are not yet considered part of the conventional uranium mining sector. The total estimated unconventional uranium resources in the country are reported to be 77,731 tonnes of uranium (tU)[157]. While the quantity is not as substantial as initially expected, ongoing exploration suggests that these inferred resources could still present new opportunities for Saudi Arabia's energy and mining sectors.

Another important aspect of Saudi Arabia's nuclear strategy is its aim to foster the growth of the mining and metals processing sector, as part of Vision 2030. This move towards mining and processing its own uranium is integral to Saudi Arabia's energy security strategy and contributes to the global nuclear fuel supply chain. Even without a profitable business model for developing this supply chain, factors like enhancing energy security, utilizing national resources, generating employment opportunities, and contributing to the creation of new industries and GDP growth provide strong justifications.

Saudi Arabia's development of a radioactive waste management programme began in 2003 with the establishment of the National Center for Radioactive Waste Management and, subsequently, the 2017 launch of the Saudi National Atomic Energy Project. The programme's foundation includes a national policy for radioactive waste management and the designation of a site for a national repository. The programme is structured around three main pillars: enhancing the waste management framework, developing the national repository, and establishing a competent repository operator with a sound business model. The programme aims to establish a sustainable, internationally compliant radioactive waste management system in Saudi Arabia.

Navigating Global Partnerships

Saudi Arabia had entered into nuclear cooperation agreements with several countries, including France, Argentina, Korea, China, Jordan, Finland, Russia, Hungary, and Egypt, marking its ambitious entry into nuclear energy development. Possible suppliers for its nuclear reactors, including Generation III+ alternatives, consist of: South Korea's KEPCO APR1400, France's Orano/EDF EPR 1650, China's Hualong One HPR1000, Russia's Rosatom VVER-1200, and the USA's Westinghouse AP1000.

However, the selection process could be influenced by various factors. South Korea's APR1400 reactors are under construction in the UAE, showcasing regional experience. The French EPR reactors, despite being under construction in Finland, France, China, and the UK, have faced delays and cost overruns. China's Hualong One reactors are being built in Pakistan, while Russia's VVER-1200 reactors are underway in Turkey and Egypt, indicating a broad geographical spread of these technologies. However, the escalation of the Russia-Ukraine conflict could potentially impact the prospects of the Russian reactor and the global nuclear supply chain will continue to be disrupted by the ongoing conflict.

A critical consideration for Saudi Arabia's nuclear ambitions is the adherence to non-proliferation standards. The USA requires Saudi Arabia to sign the Section 123 Agreement of the U.S. Atomic Energy Act, which includes the gold standard non-proliferation guidelines, to access its nuclear technology. This will impact the prospects not only of selecting the US AP1000 reactor but also of considering the Korean APR1400, which incorporates US technology. However, Saudi Arabia has expressed a desire to retain its right to uranium enrichment, leading to a reluctance to sign the agreement, reflecting the Kingdom's stance on maintaining sovereignty over its nuclear energy program's key aspects.

[156] "An Inferred Mineral Resource is that part of a Mineral Resource for which quantity and grade or quality are estimated on the basis of limited geological evidence and sampling. Geological evidence is sufficient to imply but not verify geological and grade or quality continuity" (CIM 2014, CIM Definition Standards for Mineral Resources & Mineral Reserves, pp.4).

[157] NEA (2023), Uranium 2022: Resources, Production and Demand, OECD Publishing, Paris

The selection of technology for the first two nuclear reactors in Saudi Arabia is yet to be determined. However, regardless of the chosen option, the Kingdom's decision should prioritize considerations beyond technical aspects. All reactors boast equivalent passive safety and security levels. Instead, the focus should be on evaluating bilateral and geopolitical relationships, recognizing the significance of establishing a dependable partnership that spans at least a century.

Towards Peaceful Nuclear Energy Developments

Saudi Arabia's national nuclear energy policy emphasizes transparency, safety, and reliability. In a sector where concerns about proliferation and accidents are prevalent, setting rigorous standards in these domains is vital. Such measures aim not only to safeguard the Saudi population but also to contribute to the establishment of global nuclear safety benchmarks. Furthermore, Saudi Arabia's close cooperation with the IAEA, particularly in its National Atomic Energy Project and the establishment of its first nuclear power plant, exemplifies its commitment to advancing nuclear technology and infrastructure while adhering to global safety and non-proliferation standards. Also, the Kingdom's support for the Non-Proliferation Treaty and efforts to establish a nuclear-weapon-free zone in the Middle East should be viewed as a responsible stance in a region often fraught with tensions.

Furthermore, the plan to operate a regional cooperation centre with the IAEA is a commendable initiative. It underscores Saudi Arabia's role as a regional leader, committed to building capacities in nuclear emergency preparedness and regulatory aspects. This initiative will have far-reaching impacts, enhancing regional stability and safety. The kingdom has also participated in multiple IAEA Initiatives, including: contributing $10 million to the IAEA Nuclear Security Training and Demonstration Centre development, contributing $2.5 million towards the IAEA initiative to modernize its Seibersdorf laboratories, contributing $1 million to support the IAEA's initiative for Zoonotic Diseases Integrated Action, contributing $2.5 million to the IAEA's 'Rays of Hope' initiative.

Saudi Arabia has adopted the IAEA's Milestones Approach. This approach ensures the systematic development of both 'hard' and 'soft' infrastructures, such as electrical grids, nuclear laws, and training programs. The Integrated Nuclear Infrastructure Review conducted by the IAEA acknowledged the Kingdom's significant progress, particularly in establishing a legislative framework and conducting comprehensive studies for future steps. The infrastructure issues to be considered during the different stages of development of a nuclear power program cover a range of topics:

- Government support is essential for the nuclear power programme's success, while engaging stakeholders effectively is crucial for addressing concerns, justifying the program, and enhancing public acceptance. This is demonstrated by the significant role the Saudi government plays in its atomic energy ecosystem, as discussed earlier.
- Site selection for nuclear facilities involves comprehensive studies, considering proximity to water sources, grid connections, and environmental impacts. Saudi Arabia has undertaken significant efforts in identifying suitable sites for its nuclear power plants, with a focus on minimizing environmental impacts.
- Developing robust emergency plans and ensuring nuclear security are priorities for Saudi Arabia. The Kingdom is focused on preventing, detecting, and responding to unauthorized acts related to nuclear materials and facilities, underlining its commitment to nuclear security.
- Saudi Arabia's participation in the Non-Proliferation Treaty and commitment to non-proliferation highlights its responsible approach to the nuclear fuel cycle. The Kingdom is also developing strategies for the management and disposal of radioactive waste, adhering to international safety and security standards.
- Saudi Arabia is fostering industrial involvement in its nuclear programme. This includes training engineers on nuclear reactors, developing local suppliers, and establishing joint ventures with international partners. Such initiatives are key to building a robust nuclear industry in the Kingdom.
- The procurement process for nuclear facilities in Saudi Arabia involves unique requirements and high competence levels. The Kingdom is actively working towards establishing the necessary procurement organization and skills for the ongoing acquisition of equipment and services for its nuclear facilities.

As Saudi Arabia progresses in its nuclear power programme, balancing challenges and opportunities will be crucial. Continued focus on workforce development, public engagement, and safety standards is essential for the successful integration of nuclear power into the national energy mix.

Challenges and Opportunities

The integration of nuclear power into Saudi Arabia's energy landscape presents a set of challenges and opportunities. Addressing these challenges while harnessing the opportunities is crucial for the successful implementation of the Kingdom's nuclear energy programme. We highlight five main challenges:

- *Public Perception and Education:* Public perception of nuclear energy plays a pivotal role in its acceptance and success. Saudi Arabia must engage in extensive public awareness and education campaigns to foster understanding and trust among its citizens. Providing accurate information about nuclear safety, security, and environmental stewardship is essential in dispelling misconceptions and building public support.
- *Regulatory Framework and International Compliance:* Establishing a robust regulatory framework is critical to ensure the safe and secure operation of nuclear facilities. The Nuclear and Radiological Regulatory Commission plays a central role in overseeing compliance with international treaties and conventions. Saudi Arabia's commitment to upholding the highest standards of nuclear safety and security is essential for maintaining public trust and international credibility.
- *Workforce Development and Capacity Building:* Building a skilled workforce capable of operating and maintaining nuclear facilities is a priority. Saudi Arabia is investing in education and training programs to develop expertise in nuclear science and technology. Collaboration with international partners and institutions is instrumental in this capacity-building effort, ensuring a pool of qualified professionals for the nuclear industry.
- *Environmental Considerations and Site Selection:* Site selection for nuclear facilities involves comprehensive environmental impact assessments. Saudi Arabia must carefully evaluate potential sites, considering factors such as proximity to water sources, grid connections, and environmental impacts. Minimizing the environmental footprint of nuclear power plants is essential to align with sustainability goals.
- *Nuclear Security and Emergency Planning:* Maintaining nuclear security and developing robust emergency plans are paramount. Saudi Arabia's commitment to preventing, detecting, and responding to unauthorized acts related to nuclear materials and facilities reinforces its dedication to nuclear security. Collaborative efforts with international partners and organizations enhance the nation's capabilities in this critical aspect of nuclear energy.

The integration of nuclear power into Saudi Arabia's energy landscape also represents a strategic decision with far-reaching implications. Here we highlight some of the potential benefits:

- *Energy Diversification and Grid Stability:* Nuclear energy offers a reliable source of electricity generation with the advantage of grid stability. The intermittent nature of renewable energy sources, such as solar and wind, can lead to fluctuations in power supply. Nuclear power complements these renewables by providing a stable base load of electricity, ensuring a consistent power supply even when weather conditions are unfavourable for renewables. Similar to natural gas, nuclear energy provides an alternative baseload that can effectively support renewable sources, contributing to a reliable and resilient energy grid, as well as, cost-effective and efficient electricity generation.
- *Low Greenhouse Gas Emissions:* One of the critical advantages of nuclear power is its low level of greenhouse gas emissions. Unlike fossil fuels, nuclear reactors do not produce CO_2 during electricity generation. By incorporating nuclear power, the Kingdom can significantly decrease its CO_2 emissions, contributing to global climate goals.
- *Competitive Electricity Generation Costs:* While the initial capital investment for nuclear power plants is substantial, the operational costs are relatively low. This cost-effectiveness is particularly advantageous in the long run. Saudi Arabia's investment in nuclear energy can lead to competitive electricity generation costs[158], benefitting both consumers and industries.
- *Nuclear Desalination:* Saudi Arabia faces significant challenges related to water scarcity[159], exacerbated by its arid climate. Nuclear desalination presents a sustainable solution to address the country's water needs. By integrating nuclear power

[158] WNA (2022) Economics of Nuclear Power https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx
[159] Mansouri, Noura Youssef, and Ghoniem, Ahmed F (2017) "Does Nuclear Desalination Makes Sense for Saudi Arabia?" Desalination Volume 406, 16 March 2017, Pages 37-43 https://www.sciencedirect.com/science/article/abs/pii/S0011916416308086

with desalination processes, Saudi Arabia can produce fresh water efficiently and cost-effectively. This approach not only addresses immediate water scarcity issues but also aligns with sustainable water resource management.

- *Nuclear Self-sufficiency and the Fuel Cycle:* An integral component of Saudi Arabia's nuclear strategy is achieving self-sufficiency in the nuclear fuel cycle. Exploring and utilizing these resources for fuel production enhances energy security by reducing dependence on external sources. Additionally, it contributes to the global nuclear fuel supply chain, ensuring a stable and reliable fuel source for nuclear reactors.

Conclusion

Saudi Arabia's strategic integration of nuclear energy into its energy portfolio represents a significant step towards enhancing energy security, sustainability, and economic diversification. The Kingdom is committed to achieving net-zero emissions by 2060, aligning its energy diversification goals with global sustainability objectives.

The benefits of nuclear energy, including grid stability, low greenhouse gas emissions, competitive electricity generation costs, and nuclear desalination, position it as a valuable component of Saudi Arabia's energy mix. Moreover, the pursuit of nuclear self-sufficiency through uranium resource utilization enhances energy security.

However, this journey is not without challenges. Addressing public perception, ensuring regulatory compliance, developing a skilled workforce, and managing environmental considerations are essential aspects of Saudi Arabia's nuclear energy programme. The Kingdom's commitment to these challenges, coupled with its dedication to nuclear security and emergency planning, is integral to the responsible development of nuclear power.

DOES NUCLEAR ENERGY HAVE A ROLE IN GULF COOPERATION COUNCIL COUNTRIES?

Robin Mills

In recent years, the radiance of the sun in the Gulf has outshone the power of the atom. Yet the 9.9 terawatt-hours that came from solar in Gulf Cooperation Council (GCC) countries in 2022 is less than half the 20.1 terawatt-hours from nuclear. With five of the six GCC states having net-zero carbon targets, nuclear seems to have a role—but what?

Only two of the GCC states have serious civil nuclear activity. The United Arab Emirates (UAE) began its nuclear programme in 2008, and the fourth and, for now, final reactor at the Barakah plant is starting up now, which will bring total capacity to 5.6 gigawatts (GW). Saudi Arabia’s nuclear journey has been longer and more complicated; the latest move was to receive bids in August 2023 for a 2.8 GW plant, but the deadline was extended in November following the outbreak of Israel’s conflict with Gaza. It is reported it was seeking bids from the China National Nuclear Corporation, Korea Electric Power Corporation, Rosatom of Russia,[160] and France’s EDF (Électricité de France).[161]

The other GCC states are unlikely to pursue traditional nuclear power: increasingly cheap solar power, relatively small grids in Oman and Bahrain, land constraints in Bahrain, and the availability of low-cost gas in Qatar are deterrents. Kuwait could perhaps benefit most, given its slow-moving renewable programme and its heavy use of costly oil and imported liquefied natural gas. But its investigation of nuclear power ended following Japan’s 2011 Fukushima accident, and its perennial internal political squabbles would seem likely to derail an expensive and long-running project.

The background of the UAE’s nuclear programme is worth understanding in this context. The UAE’s seminal policy paper on the use of civil nuclear power in 2008 forecast a peak electricity demand in 2020 of more than 40 GW, and estimated that available gas could cover only 20–25 GW of this.[162] Solar power at that point was expensive and immature and not plausible to install at sufficient scale; the first utility-scale solar in the UAE, just 10 megawatts, was built in 2009.

[160] J. Aguinaldo, 14 July 2023, ‘Riyadh receives Duwaiheen nuclear advisory bids’, MEED https://www.meed.com/sppc-receives-duwaiheen-nuclear-advisory-bids.
[161] J. Aguinaldo, 16 October 2023, ‘Saudi Arabia could extend nuclear bid deadline’, MEED https://www.meed.com/saudi-nuclear-bid-deadline-could-be-extended.
[162] Emirates Nuclear Energy Corporation, 2008, ‘Policy of the United Arab Emirates on the Evaluation and Potential Development of Peaceful Nuclear Energy’ https://www.enec.gov.ae/doc/uae-peaceful-nuclear-energy-policy-5722278a2952f.pdf.

As it turned out, because of the 2008–2009 financial crisis, the 2014 oil price crash, and measures to cut subsidies and improve efficiency in the interim, the actual peak demand by 2020 was about 26.5 GW. Available gas supplies, including imports, were more than adequate.

Nevertheless, having built Barakah, the UAE has capitalized on it. A mix of solar and nuclear electricity is supplied to the Abu Dhabi National Oil Company, Emirates Global Aluminium, and Emirates Steel, lowering their carbon footprint and enabling them to offer ultra-low-carbon products to selected customers. This will maintain their competitiveness as companies increasingly require low-carbon supply chains, and the EU, UK, and likely others extend carbon border tariffs. Full decarbonization of the UAE's industrial sector, targeted by 2050, would require much more zero-carbon electricity: about 41 per cent of total reductions are intended to come from electrification with solar and nuclear.[163]

The UAE has also launched highly successful solar PV programmes, with the most recent project awarded by the Dubai Electricity and Water Authority in June 2023 at 1.62 US cents per kilowatt-hour (¢/kWh) for the 1.8 GW sixth phase of the Mohammed bin Rashid solar park. The Emirates Water and Electricity Company achieved 1.32¢/kWh for the 2 GW Al Dhafra plant, which began operations in November 2023. As the recent period of solar cost inflation is overcome, prices, already among the lowest in the world, are likely to fall further.

Of course, on its own, solar PV does not provide continuous power. However, there is a relatively good match in the Gulf between demand (driven by air conditioning, it is high in the summer and in daytime and early evening) and solar output. This makes for a much more tractable problem than in northern Europe, where maximum demand in winter coincides with minimum solar output. A few hours of storage should be able to cover much of GCC night-time demand. In winter and spring, there will be a surplus of solar power.

GCC countries have been reluctant to trade much electricity either with each other or with neighbours, but they are connected via the GCC Interconnection Authority, and have links in existence or under construction to Egypt, Jordan, and Iraq—and perhaps in future the Indian subcontinent or, politics permitting, Iran. Those are other options for selling surplus power or balancing the system over a wider geographic area.

The Dubai Electricity and Water Authority has trialled lithium-ion battery storage, and the Emirates Water and Electricity Company has also tendered for a battery system. The Dubai Electricity and Water Authority's 700 megawatts concentrated solar thermal power plant, awarded in September 2017, began start-up in July 2023. Using 15 hours of molten salt storage, it can provide round-the-clock power. It was awarded at a levelized cost of 7.3¢/kWh. The Dubai Electricity and Water Authority is also building a pumped hydropower storage plant, and Saudi Arabia plans pumped hydro projects on its west coast at Magna and Baysh.

Relatively simple calculations using some realistic patterns of hourly GCC demand and solar PV output, with batteries of various types and nuclear power, suggest that nuclear struggles to justify itself as part of a lowest-cost, low-carbon power mix. This is even before including other options, such as a concentrated solar thermal power plant with storage, wind (which is being developed in the UAE only on a small scale, but for which Saudi Arabia has major expansion plans and high-quality resources in some areas), geothermal for air conditioning, gas power with carbon capture and storage, or chemical storage, particularly via hydrogen or desalinated water.

If these other options are excluded, nuclear costs are reasonable, and an absolutely zero-carbon power system is demanded, nuclear can have a role at roughly 5–10 per cent of the total capacity, the rest being solar. However, such constraints result in significantly higher system costs, which would pose problems for economic competitiveness. Indicatively, a solar PV plus battery system with a small amount of gas-fired backup might generate at about 6–7¢/kWh; reaching a completely zero-carbon system raises costs to around 12¢/kWh; adding some nuclear, at optimistic costs, takes this back to about 9–11¢/kWh. The low cost of capital in wealthy, stable GCC countries is favourable for nuclear power, but even more helpful for renewables.

As battery and solar costs continue to fall, the optimal level of nuclear power would diminish further. Nuclear power is also less flexible: once a construction project has begun, it would be costly to stop or slow it if electricity demand turns out to be less than anticipated, whereas this would be relatively easy for a solar programme given two or three years' warning.

[163] United Arab Emirates Ministry of Climate Change and Environment, 2023, 'The United Arab Emirates First Long-Term Strategy (LTS)' https://unfccc.int/sites/default/files/resource/UAE_LTLEDS.pdf, Figure 20.

Developing a full-scale nuclear industry, with all the associated regulatory requirements, has high up-front and irreducible costs, while the learning curve from building several reactors should eventually reduce costs. Therefore, if Saudi Arabia were, for example, to pursue a 'toe in the water' strategy and not go beyond the initial tender for 2.8 GW, it would incur high unit costs without acquiring a material amount of power generation, given that peak demand on Saudi Electricity Company, the main utility, is now in excess of 64 GW. A similar experience, albeit for very different reasons, has befallen Iran, where peak demand is more than 71 GW, to which its only current reactor, the 1 GW unit at Bushehr, makes a minor contribution.[164]

Therefore, for additional nuclear power to play a significant role in GCC power systems, some combination of the following would appear to be required.

First, there could be a strategic decision to pursue nuclear power—from some combination of reasons of national prestige, technological development, acquisition of expertise, optionality, building diplomatic links with suppliers, enhancing security profile, or using local mineral resources (as Saudi Arabia hopes to do with its uranium deposits; however, these are of questionable economic viability[165]). There may also be benefits in hedging against unanticipated problems with developing a system reliant mostly on solar and batteries, for example supply chain disruptions or problems in obtaining scarce raw materials.

Second, nuclear costs could fall significantly. In the UAE's case, as the existing nuclear infrastructure, regulation, and expertise have already been established, future reactors could be added at a lower cost. On the other hand, interest rates and industry costs have risen since construction of the original reactors began in July 2012. Saudi Arabia, beginning a fresh programme, is likely to face higher initial costs.

Barakah, built by the Korea Electric Power Corporation, was already notable among global newbuild programmes for being delivered without major cost overruns (as far as is publicly known) or schedule slippage. Domestic Chinese nuclear plants are built even more cheaply, but whether this could be achieved in the GCC is questionable. However, China or Russia might make a loss-leader offer as part of building relations with the GCC, especially with Saudi Arabia.[166]

Third, small modular reactors (SMRs) could be successfully used. These reactors, intended to be largely factory-built, may be cheaper and quicker to deploy. They can be sited more conveniently, so reducing grid costs. Saudi Arabia and/or the UAE may be a good place for early deployment. But a substantial order-book is necessary for developers to gain manufacturing experience and so achieve the promised cost reductions through learning-by-doing.

The Emirates Nuclear Energy Corporation has signed some memoranda of understanding to investigate SMRs with Chinese,[167] British, and American developers.[168] Saudi Arabia has engaged extensively with South Korea on the SMART reactor,[169] and with China on high-temperature gas-cooled reactors. But the US SMR sector has struggled to deliver a working product.

Fourth, reactors could be used to provide additional services: waste heat to drive desalination or district cooling, or process heat for industry. District cooling would be more suited to SMRs, since large reactors aren't likely to be adjacent to major population centres. Or, surplus nuclear at off-peak times could be used to create 'pink' hydrogen, an option which is included in the UAE's hydrogen strategy,[170] but realistically only as an adjunct, about 5 per cent of the total planned output.

So the UAE's nuclear programme, though not originally justified on climate change grounds, seems in retrospect to have worked out reasonably well. It has accelerated the economy's decarbonization at tolerable cost far beyond where it would be today based on solar power alone.

[164] R. Mills and L-C. Sim, eds., 2021 'Low Carbon Energy in the Middle East and North Africa', Palgrave Macmillan https://link.springer.com/book/10.1007/978-3-030-59554-8, p19-56.
[165] J. Tirone, 5 April 2023, 'Saudi Quest to Become a Nuclear Player is Coming Up Short', Bloomberg https://www.bloomberg.com/news/articles/2023-04-05/saudi-quest-to-become-a-nuclear-player-is-coming-up-short.
[166] J. Nakano, 7 September 2023, 'The Saudi Request for U.S. Nuclear Cooperation and Its Geopolitical Quandaries', CSIS https://www.csis.org/analysis/saudi-request-us-nuclear-cooperation-and-its-geopolitical-quandaries.
[167] L. Barrington, 7 May 2023, 'UAE signs nuclear energy cooperation agreements with China bodies' Reuters https://www.reuters.com/world/middle-east/uae-signs-nuclear-energy-cooperation-agreements-with-china-bodies-2023-05-07/.
[168] World Nuclear News, 11 December 2023, 'ENEC signs multiple SMR MoUs' https://www.world-nuclear-news.org/Articles/ENEC-signs-multiple-SMR-MoUs.
[169] Nuclear Engineering International, 13 December 2023, 'KAERI and Hyundai Engineering to promote export of SMART SMR' https://www.neimagazine.com/news/newskaeri-and-hyundai-engineering-to-promote-export-of-smart-smr-11369646.
[170] United Arab Emirates Ministry of Climate Change and Environment, 2023, 'The United Arab Emirates First Long-Term Strategy (LTS)' https://unfccc.int/sites/default/files/resource/UAE_LTLEDS.pdf.

But improvements in solar power and batteries make it much more questionable whether large additions of nuclear capacity are economically optimal either in the UAE or Saudi Arabia, or indeed in their GCC neighbours. Bringing down nuclear costs and making use of synergies with industries and users of waste heat have promise but are not straightforward. Otherwise, strategic or technological imperatives will have to bear most of the weight in justifying multi-billion-dollar, decadal commitments.

WILL RUSSIAN AND CHINESE NUCLEAR REACTOR EXPORTS ASSIST IN THE LOW-CARBON TRANSITION?

Philip Andrews-Speed

The International Energy Agency and others foresee nuclear power playing a useful, though far from transformative, role in the low-carbon energy transition. In its three scenarios, the global installed capacity of nuclear power grows from 417 GW in 2022 to 620 GW, 770 GW, or 900 GW by 2050.[171] Over the period 2022 to 2050 many of the world's currently operating civil nuclear reactors will have reached the end of their useful lives. So the amount of newly built reactors will be much greater than the numbers mentioned above imply. Countries that will or may host new reactors fall into three broad categories:

1. established nuclear power nations which have their own reactor technologies
2. established nuclear power nations that rely partly or wholly on imported reactor technologies
3. 'newcomers' that are building their first nuclear plants and rely or will rely on imported reactor technologies.

Setting aside the fact that countries can and have moved between these categories, only a relatively small number of countries possess the capacity to design and build the types of modern reactors that nations desire. They include the United States, Canada, France, Russia, China, Japan, South Korea, and possibly India. This leads to the question of which of these nations will play leading roles in building reactors for countries in categories 2 and 3.

A cursory review of the World Nuclear Association's national summaries reveals that Russia and China have been the most active over the last decade in seeking export opportunities, particularly among newcomers. Post-Soviet Russia has been the world's most ambitious exporter of civil nuclear power technology in recent years. It has 11 operating reactors in five countries and 19 more under construction in six countries. In addition, Russia has been exploring project opportunities in at least 14 other states. In contrast, China's only operating plants overseas are in Pakistan, which hosts four reactors. However, it has opened discussions with at least 12 other countries. For both Russia and China, most of their clients or potential clients are middle-income newcomer countries. Exceptions include Hungary and Finland for Russia and the United Kingdom and Argentina for China.

The United States, Canada, and France have all been significant exporters in the past, though less active recently. In the last six years, the United States has had four reactors commissioned (all in China); it is now actively seeking new export opportunities. France has had three reactors commissioned (two in China and one in Finland) and has one under construction today (in the United Kingdom). South Korea is a new exporter. It won its first contract in the United Arab Emirates, where three reactors are in operation and a fourth is under construction.

This article compares the strategies and outlook for nuclear reactor exports from Russia and China, and asks whether these countries are likely to make a major contribution to the growth of nuclear power outside their borders.

Russia's reactor exports

The Soviet Union was marginally ahead of the United States when it commissioned its first civil nuclear power reactor in 1954. Today, Russia has the world's fifth largest fleet of operable reactors at 27.7 GW; they supply about 20 per cent of the country's electricity. As of December 2021, there were 2.7 GW of new capacity under construction, 23.7 GW planned, and a further 20 GW proposed. One of the reasons for these ambitious domestic plans is that about 50 per cent of the current capacity entered commercial operation in the 1970s and 1980s and is scheduled for closure in the late 2020s and early 2030s.

As well as building nuclear reactors on its own territory, the Soviet Union also built reactors in other Warsaw Pact as well as in Finland. Post-Soviet Russia has continued to be an international vendor and has expanded the programme, broadening its geographic scope (see Table 1). Of the eight countries that host Russian reactors in operation or under construction today, only

[171] International Energy Agency (2023), *World Energy Outlook 2023*, https://origin.iea.org/reports/world-energy-outlook-2023.

Belarus and Ukraine lay in the direct orbit of the Soviet nuclear industry. The others are in wider Asia (Bangladesh, India, Iran, China, and Turkey) and North Africa (Egypt). Of these eight, four are newcomers embarking on their first nuclear power programme (Bangladesh, Belarus, Iran, and Turkey). Russia's favoured design for export in recent years has been the Generation III VVER 1000 reactor. These are operational in Ukraine, India, China, and Iran, and are under construction in India and Iran. Only Belarus hosts the more advanced VVER 1200, whilst reactors of this design are under construction in Bangladesh, China, and Turkey.

Table 1: Export sales and prospects for post-Soviet Russian nuclear power plants

Country	Plant	Status
Plants in commercial operation or under construction		
Belarus	Ostrovets 1 & 2	Commercial operation 2020, 2023
Bangladesh	Rooppur 1 & 2	Construction start 2017, 2018
China	Tianwan 1 & 2	Commercial operation 2007
	Tianwan 3 & 4	Commercial operation 2018
	Tianwan 7 & 8	Construction start 2021, 2022
	Xudabao 3 & 4	Construction start 2021, 2022
Egypt	El Dabaa 1, 2, & 3	Construction start 2022, 2022, 2023
India	Kudankulam 1 & 2	Commercial operation 2013, 2016
	Kudankulam 3, 4, 5, & 6	Construction start 2017, 2017, 2021, 2021
Iran	Bushehr 1	Commercial operation 2013
	Bushehr 2 & 3	Construction start 2019, ? imminent
Turkey	Akkuyu 1, 2, 3, & 4	Construction start 2018, 2020, 2021, 2022
Ukraine	Khmelnitski 2	Commercial operation 2005
	Rivne 4	Commercial operation 2006
Selected other plans and proposals		
Argentina		Framework agreement
Algeria		Framework agreement
Armenia	Armenia 3	Under negotiation with Russia, China, and US
Bulgaria	Belene	Project cancelled 2023
Finland	Hanhikivi 1	Project cancelled 2022
Hungary	Paks 5 & 6	Construction start due 2025
India	Kudankulam 7 & 8	Proposal
	Andra Pradesh	Proposal
Indonesia	High-temperature gas-cooled reactors	Switched to China 2016
	Floating nuclear power plants	Cooperation agreement 2015

Country	Plant	Status
Jordan	Qasr Amra 1 & 2	Project cancelled 2018
	Small modular reactors	Cooperation agreement
Nigeria		Framework agreement 2017
Slovakia	Bohunice V3	Switched to United States 2023
South Africa	Thyspunt	National strategy not decided
Turkey	Sinop 1–4	Under negotiation
Ukraine	Khmelnitski 3 & 4	Russian involvement terminated 2015
Uzbekistan		Framework agreement
Vietnam	Ninh Thuan	National nuclear programme suspended 2016

Source: World Nuclear Association (2021), 'Nuclear power in Russia', https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx;World Nuclear Association (various dates), 'Country profiles', https://world-nuclear.org/information-library/country-profiles.aspx.

In addition to these concrete projects, Russia has been trying to lay the groundwork for further exports in several other countries (see Table 1). A number of these lay in the orbit of the former Soviet Union. Of these, Bulgaria, Finland, Slovakia, and Ukraine have since removed Russia from consideration for their planned projects. Only Hungary seems determined to go ahead with new Russian reactors. The other nations are middle-income countries, most of which are newcomers; exceptions are Argentina and South Africa. In addition to the VVER 1200 and equivalent designs, Russia is also trying to export high-temperature gas-cooled reactors, small modular reactors, and floating nuclear power plants.

Although not directly related to this analysis, it is worth noting that Russia is the world's dominant supplier of nuclear fuels. In 2021 it provided 38 per cent of the world's enriched uranium, accounting for 31 per cent of the enrichment services to the European Union and 28 per cent to the United States.[172]

China's reactor exports

China has the world's third largest installed capacity of civil nuclear power at 53.3 GW (as of October 2023). Only about 10 GW of this entered into commercial operation before 2010. There are 27.2 GW under construction, with another 48.6 GW planned and another 93 GW of firm proposals (for more details on China's nuclear power programme, see the article "*The role of nuclear power in China's energy security and low-carbon energy transition"* in this issue of the *Oxford Energy Forum*).

China's export programme for nuclear reactors is much younger and less ambitious than that of Russia. The only operational Chinese reactors overseas are in Pakistan, which has been a long-term strategic partner of China; the partnership is now known as the China-Pakistan Economic Corridor. As was the case with Russia, China's engagement for future projects has involved mainly middle-income newcomer states (see Table 2). A notable exception is the United Kingdom, where the China General Nuclear Corporation is a minority shareholder in EDF's (Électricité de France's) Hinkley Point C plant. China General Nuclear has also being seeking the opportunity to build the proposed Bradwell B plant. In this context, its Hualong One design received generic design approval from the United Kingdom's Office for Nuclear Regulation in 2022. However, security and financing concerns have stalled progress on this project.

[172] Dolzikova, Darya (2023), *Atoms for Sale: Developments in Russian Nuclear Energy Exports*, Royal United Services Institute special report, https://rusi.org/explore-our-research/publications/special-resources/atoms-sale-developments-russian-nuclear-energy-exports.

Table 2: Export sales and prospects for Chinese nuclear power plants

Country	Plant	Status
Plants in commercial operation		
Pakistan	Chasma 3 & 4	Commercial operation 2016, 2017
	Karachi 2 & 3	Commercial operation 2021, 2023
Selected other plans and proposals		
Armenia	Armenia 3	Under negotiation with Russia, China, and US
Argentina	Atucha 3 (Units IV & V)	Unit IV engineering, procurement, and construction contract signed 2022
Egypt		2015
Indonesia	High-temperature gas-cooled reactors	Cooperation agreement 2016
Iran	Makran coast	Agreement 2015
Jordan	Small modular reactors	Cooperation agreement 2018
Kenya		Memorandum of understanding 2015
Romania	Cernavoda 3 & 4	Switched to United States 2020
South Africa	Thyspunt	National strategy not decided
Sudan		Framework agreement 2016
Turkey	Igneada/Sinop	Under negotiation
United Kingdom	Bradwell	Project future uncertain

Source: World Nuclear Association (2023), 'Nuclear power in China', https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx; World Nuclear Association (various dates), 'Country profiles', https://world-nuclear.org/information-library/country-profiles.aspx.

Chinese companies have also been falling out of favour in other countries. China General Nuclear was pushed aside in Romania in favour of US funding of a CANDU reactor. In Argentina, the China National Nuclear Corporation had been lined up to provide two Hualong One reactors at Atucha. An engineering, procurement, and construction contract for the first one was signed in 2022. However, the election of Javier Milei as president in November 2023 may undermine these and other arrangements with Chinese companies.

Comparison and significance of these export programmes

Exporting nuclear reactors gives the vendor significant long-term advantages, especially if the buyer is a newcomer. The opportunity to be involved in planning, institutional design, and capacity building allows the vendor government and corporations to be engaged with their host country counterparts for several years before construction even starts; and this involvement itself may follow a decade of negotiations. A construction programme of two to four reactors may take a decade or more. These reactors will have a lifetime of 40–60 years, during which they will require fuel and spare parts. Following the closure of a reactor, there will be decades of decommissioning. Setting aside a breakdown in inter-state relations, direct involvement in a new national nuclear power programme provides the vendor with a century of economic and political engagement with the host country.

These considerations are part of the context that distinguishes the Russian and Chinese reactor export programmes. Though both governments seek to use economic tools for political influence, Russia has a more limited portfolio of options at its disposal than China. Russia's key exports are fossil fuels and minerals, arms, and nuclear power technology. In contrast, China possesses a vast array of technologies and consumer goods for export, along with construction services and investment in manufacturing facilities and natural resource extraction. Many of these economic activities fall within the Belt and Road Initiative. As a result, China relies much less than Russia on nuclear reactor exports for international economic and political influence, notwithstanding the China National Nuclear Corporation's vacuous boast in 2016 that it would build 30 new reactors in Belt and Road countries by 2030.

Arising from the relative importance of nuclear exports is the difference in generosity between these two vendors. As would be expected, Russia undertakes capacity building, assists in institutional development, provides the technology, carries out construction, and participates in the operation of the plant. It provides loans under terms that are more generous than would be permitted by OECD rules. These include, variously, a wider coverage of costs, longer repayment terms, and interest rates commonly in the 3–4 per cent range that do not take account of risk.[173] In some projects, Russia takes a share of the equity and, in the case of Turkey's Akkuyu plant, it will be in full control of operation under a build-own-operate arrangement. As a final sweetener, Russia offers to take back the spent fuel for reprocessing.

In the same way, China provided Pakistan with loans at generous interest rates of just 2 per cent for the largest loans, with 20-year repayment periods. In contrast, the planned loan to Argentina was less generous, with an interest rate of 4.5 per cent.[174] Recent shifts in the way in which the Belt and Road Initiative operates suggest that China will be less generous than Russia in most of its lending for nuclear power exports.

A second key distinction arises from the current plans for their domestic nuclear power industries. While both countries will continue to build new reactors to supply their national energy needs, the planned rate of growth of China's reactor fleet is unprecedented at twice the rate of the United States' expansion in the 1970s and 1980s. This is likely to constrain the capacity of China's nuclear power companies to undertake an ambitious programme of overseas construction for many years.

Before 2022, it would have been reasonable to suggest that Russia would continue to be the leading global player in the reactor export market in the coming years. However, the war in Ukraine has dented the nation's reputation, resulting in some countries switching to other potential vendors. In addition, the war may deplete the government's ability to continue providing generous financial support for these exports. In China, the export of nuclear reactors has yet to become a high priority, with the focus likely to remain on domestic construction for the next decade or two. Individual projects may be undertaken, but probably under terms less generous than those of Russia. Further, we have already seen a reluctance among some governments to allow Chinese involvement in such critical infrastructure.

Given this background, we should not be expecting Russia and China to contribute disproportionately to the growth of nuclear power outside their national borders over the next two decades.

[173] Bowen, Matt, and Apostoaei, Alec (2022), *Comparing Government Financing of Reactor Exports: Considerations for US Policy Makers*, Columbia University Center for Global Energy Policy, https://www.energypolicy.columbia.edu/publications/comparing-government-financing-reactor-exports-considerations-us-policy-makers/.
[174] Ibid.

THE GEOPOLITICS OF NUCLEAR ENERGY: NAVIGATING THE ENERGY SECURITY DICHOTOMY

Sara Vakhshouri

The Russian invasion of Ukraine has reignited global discussions on nuclear energy's role in enhancing energy security during the transition to green energy. This geopolitical upheaval prompted countries worldwide to reassess their long-term energy strategies for enhanced security. For example, France and announced plans for the construction of new-generation reactors, while South Korea committed to increasing nuclear energy production and exporting reactors by 2030. These developments reflect a growing recognition of the importance of nuclear power in ensuring energy security. Moreover, there has been a noticeable shift in public sentiment in favour of nuclear power as a viable option for meeting energy demands without increasing carbon emissions.

Reliance on nuclear power for energy security

The large-scale generation of nuclear power presents several key challenges, notably the reliance on enrichment and conversion services. These services are essential components of the global nuclear supply chain, yet they are vulnerable and often dependent on specific sources. This dependency is a critical issue for the security and stability of nuclear power generation worldwide. The reliance on a limited number of sources for these crucial services can lead to potential supply chain disruptions and security concerns, highlighting the need for a more diversified and secure approach to sourcing these essential components.

On the other hand, nuclear power's role in achieving energy security is underscored by a multitude of factors. One of the primary advantages is its low susceptibility to fuel price volatility. Unlike fossil fuels, nuclear plants offer stable operation once the initial capital investment has been made, mitigating the impact of fluctuating energy prices.

Additionally, integrating nuclear power into the broader energy mix, alongside renewables and natural gas, significantly diversifies the energy portfolio and enhances a country's energy security and resilience by mitigating the risks linked to an excessive dependence on a single energy source. Moreover, nuclear power plants are known for their operational flexibility, which is especially valuable in balancing the variability inherent in renewable energy sources, ensuring a stable and reliable energy supply.[175]

Therefore, while nuclear power generation faces challenges related to the reliance on specific enrichment and conversion services, its contribution to energy security is undeniable.

Russia's dominance in the nuclear energy supply chain

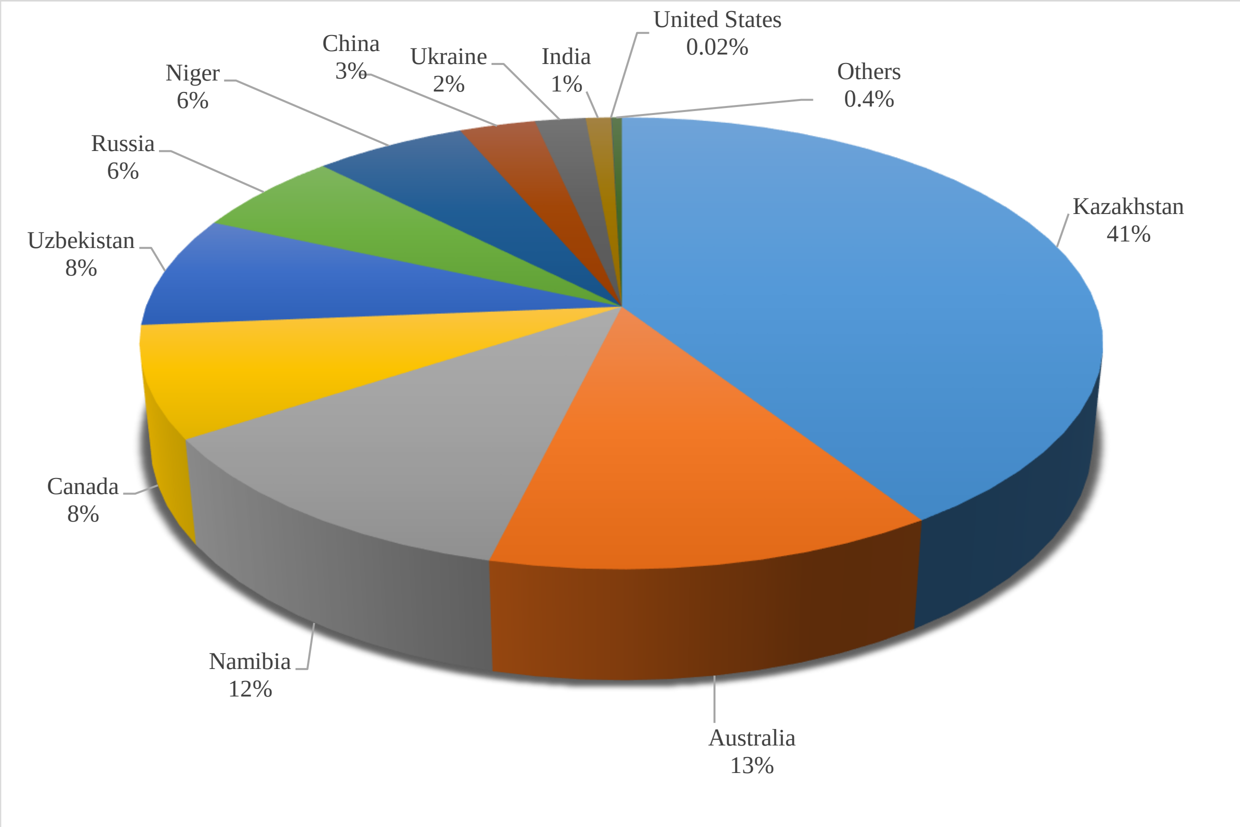
In the landscape of global nuclear energy, Russia, through its state-owned corporation Rosatom, plays a pivotal role, exerting a significant influence on uranium production and the entire nuclear fuel cycle. This influence extends from uranium mining, where Russia is a leading producer operating both open-pit and underground mines, to advanced nuclear technology capabilities.

Uranium resources

Russia stands among the top five nations globally in terms of uranium reserves, boasting an estimated 486,000 tons of uranium, accounting for approximately 8 per cent of the world's total reserves.[176] However, the nation's production of raw uranium remains relatively limited. In 2020, Russia's domestic uranium mining output constituted only about 6 per cent of global production (Figure 1).[177] Russia has made substantial investments and exerted significant influence in terms of uranium mining outside of its borders. This dominance is also clearly apparent in Rosatom's extensive global network of uranium mining activities and strategic partnerships, especially in crucial uranium-producing regions such as Kazakhstan, Uzbekistan, and Namibia, and its exploration endeavours in countries like Tanzania and Niger. These initiatives underscore Russia's dedication to securing uranium resources and upholding a substantial presence in the global uranium market.

[175] Cometto, M., et al. (2019), *The Costs of Decarbonization: System Costs with High Shares of Nuclear and Renewables* (Paris: Organisation for Economic Co-Operation and Development).
[176] Foltynova, Kristyna (2022), 'Russia's Stranglehold on the World's Nuclear Power Cycle', Radio Free Europe/Radio Liberty, 1 September.
[177] International Atomic Energy Agency and Nuclear Energy Agency (2023), *Uranium 2022: Resources, Production and Demand*, https://www.oecd-nea.org/upload/docs/application/pdf/2023-04/7634_uranium_-_resources_production_and_demand_2022.pdf.

Figure 1: World uranium production (2020)



Source: International Atomic Energy Agency and Nuclear Energy Agency (2023), *Uranium 2022: Resources, Production and Demand*, https://www.oecd-nea.org/upload/docs/application/pdf/2023-04/7634_uranium_-_resources_production_and_demand_2022.pdf.

Rosatom, currently ranked fourth worldwide in uranium production and second in mineral feedstock, heavily relies on its domestic uranium mining industry and joint ventures with foreign mining operations to maintain its raw material independence. All Russian uranium producers are affiliated with Rosatom's mining division, while non-Russian uranium mining operations are overseen by Uranium One.

Uranium One, a leading global mining firm under the Rosatom umbrella, holds a prominent position as one of the world's top five uranium producers. It manages a diverse portfolio of assets located in Tanzania, the United States, and Kazakhstan.[178]

Uranium One is also involved in major projects in Canada and exploration initiatives in Australia. The corporation's influence is further underlined by its network of supply agreements and partnerships, which guarantee stable nuclear fuel supply and enhance Rosatom's market presence.

Uranium processing and conversion

Raw, unprocessed uranium is unsuitable for use as nuclear reactor fuel. It must undergo a series of transformations, including conversion into gas, processing into uranium concentrate, and ultimately enrichment. This is an arena where Russia demonstrates exceptional expertise. In the year 2020, among the commercial conversion facilities globally, only Canada, China, France, and Russia were operational. Owing to its dominant position and control of approximately 40 per cent of the global uranium conversion infrastructure, Russia accounted for most of the world's uranium converted into gaseous form known as uranium hexafluoride.[179]

[178] Rosatom Group, Uranium mining, https://rosatom.ru/en/rosatom-group/uranium-mining/
[179] Foltynova, Kristyna (2022), 'Russia's Stranglehold on the World's Nuclear Power Cycle', Radio Free Europe/Radio Liberty, 1 September.

Uranium enrichment services

Russia's involvement in the nuclear energy supply chain encompasses the fabrication of nuclear fuel, supplying fuel assemblies and rods for various reactor types, and services related to the back end of the fuel cycle, such as spent fuel reprocessing and nuclear waste management. These capabilities are crucial for countries with limited reprocessing infrastructure. Rosatom's role in the nuclear industry is further amplified by its supply of nuclear technology, offering a range of reactor designs and comprehensive nuclear power plant projects.

Uranium enrichment capacity is concentrated among a few major players, with Russia accounting for the largest share, approximately 46 per cent.[180] This positions Russia as a significant contributor to the global supply of both uranium and uranium enrichment services. In 2020, the European Union sourced around 20 per cent of its natural uranium and 26 per cent of its enrichment services from Russia, based on the latest information.[181] Likewise, in 2021, the United States imported roughly 14 per cent of its uranium and 28 per cent of all enrichment services from Russia.[182] Rosatom covers approximately 16.3 per cent of the global nuclear fuel market, and it has maintained a perfect record of never losing a nuclear fuel supply bid over the past decade.[183]

Rosatom's global influence through supply agreements, partnerships, and uranium services

Rosatom, Russia's state nuclear corporation, has strategically established a range of supply agreements and partnerships, reinforcing its global presence in the nuclear industry.

Russia leverages the sale of nuclear technology as a strategic tool to gain influence and financial benefits in countries newly adopting nuclear power. A key factor in Russia's appeal to these nations is its comprehensive 'full package' approach. This approach not only includes the construction of nuclear power plants and provision of fuel but also extends to training local professionals, addressing safety concerns, managing scholarship programmes, and handling radioactive waste disposal.[184]

Perhaps the most persuasive aspect of Russia's strategy is its attractive financing options. These loans typically cover up to 80 per cent of the construction costs, often underpinned by government subsidies. For example, Russia has extended substantial loans of $10 billion to Egypt, $11 billion to Hungary, and $25 billion to Bangladesh, primarily for the development of nuclear power facilities.[185] Such financial arrangements make Russia's nuclear technology offerings particularly appealing to countries seeking to build their nuclear capabilities.

China's growing influence and quest for nuclear energy

China is another player with ambitions to increase its influence in the nuclear scene. China's journey into the world of nuclear power began with the establishment of its domestic uranium mining industry. China has invested in uranium mining facilities located inland in the provinces of Shaanxi and Gansu. However, a significant portion of the enriched uranium used in China's nuclear reactors is sourced from other nations. Russian company Tenex and European entity Urenco have collectively supplied at least 30 per cent of China's enriched uranium for processing, emphasizing the international dimension of China's nuclear fuel supply chain.[186]

China has also established enrichment facilities within its territory. The China National Nuclear Corporation plays a pivotal role in uranium processing, enrichment, and fabrication, with its plants located inland in regions such as Sichuan and Mongolia.

Investment in uranium reprocessing

China, with aspirations of achieving complete self-sufficiency in nuclear energy, has made significant investments in the reprocessing cycle of uranium. This process aims to recycle used uranium to generate additional energy. China's primary reprocessing plant is situated in Gansu province and has an annual production capacity of about 200 tonnes of uranium.

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[180] Ibid.
[181] Ibid.
[182] Ibid.; US Energy Information Administration (2022), 'U.S. uranium concentrate production in 2021 remained near all-time lows', *Today in Energy*, 26 July, https://www.eia.gov/todayinenergy/detail.php?id=53179.
[183] Rosatom Group, Fuel and Enrichment & Tvel Fuel Company.
[184] Foltynova, Kristyna (2022), 'Russia's Stranglehold on the World's Nuclear Power Cycle', Radio Free Europe/Radio Liberty, 1 September.
[185] Ibid.
[186] World Nuclear Association (2023), 'World Uranium Mining Production', www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx.

Furthermore, in 2018, China and France signed an agreement for the construction of a new reprocessing plant, expected to produce an estimated 800 tonnes of uranium annually. These initiatives reflect China's commitment to maximizing the utility of its uranium resources and reducing waste in the nuclear fuel cycle.[187]

According to figures from early 2023, China boasts a substantial number of nuclear processing plants, with 55 currently operational, 22 under construction, and over 70 planned. These facilities collectively produce 57 GW of energy, relying on an annual supply of 1,900 tonnes of uranium. This production capacity represents approximately 5 per cent of China's total energy use, and makes China the third-highest producer of uranium in the world, following the United States and France.[188]

Global uranium mines and diversification

To meet its growing demand for uranium, China has devised a strategic plan for diversifying its sources. This plan divides uranium procurement into thirds: one-third from domestic sources, one-third purchased internationally, and the final third obtained through foreign equity investments and joint ventures abroad.

Domestically, China's uranium resources have historically been monopolized by the state-owned China National Nuclear Corporation. In 2013, China produced an estimated 1,500 tonnes of uranium, a figure that increased to 1,700 tonnes in 2022.[189] To complement its domestic production, China has secured uranium supply agreements with top global producers. These agreements include equity investments, joint ventures, and shares in uranium mines, ensuring access to uranium production by the tonne. This multifaceted approach enables China to support its growing population's energy demands, process uranium for domestic consumption, and export surplus uranium to other countries.

A beacon of influence in Africa and Kazakhstan, the world's leading uranium producers

China has strategically intensified its uranium mining presence in Africa, with a strong focus on countries like Namibia and Niger, both emerging as pivotal uranium suppliers to China (Table 1).

Table 1: Chinese equity in uranium mines in other countries[190]

Country	Mine	Equity (%)	Start of production with Chinese equity
Niger	Azelik	37.2 CNUC + 24.8 ZXJOY	2010 but now closed
	Imouraren	CNUC share 25+, more pending	On hold
Namibia	Langer Heinrich	CNUC:25	2014
	Rössing	CNUC:68.6	2019
	Husab	CGN-URC: 100	2016
Kazakhstan	Irkol and Semizbai	CGN-URC :49	2008, 2009
	Central Mynkuduk	CGN-URC :49	2021

Source: World Nuclear Association (2023), 'China's nuclear fuel cycle', https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.

[187] IAEA Bulletin, June 2019, https://www.iaea.org/sites/default/files/bull602june20190.pdf

[188] Hung, Shih Yu (2023), 'How long will it take for China's nuclear power to replace coal?', *Forbes*, 17 May, https://www.forbes.com/sites/thebakersinstitute/2023/05/17/how-long-will-it-take-for-chinas-nuclear-power-to-replace-coal/?sh=6e4038423b1b.

[189] World Nuclear Association (2023), 'World uranium mining production', www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx.

[190] CNUC: China National Uranium Corporation (CNUC or CUC), a branch of CNNC, manages the operations of these mines. URC: China Guangdong Nuclear Uranium Resources Co Ltd (CGN-URC), a subsidiary of CGN, is tasked with overseeing CGN's fuel supply. This includes uranium exploration and mining, uranium trade, and fuel processing management for CGN. Source: https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx

In addition to equity investments in mining projects, China's uranium procurement strategy includes entering long-term supply contracts with uranium-producing nations. These contractual agreements provide a stable and predictable uranium supply for China's rapidly growing fleet of nuclear reactors, offering assurance to both China and its uranium suppliers. Furthermore, China's strategic partnership with Kazakhstan, renowned for its uranium-rich deposits, ensures a dependable uranium supply for its nuclear power plants. This partnership has not only cemented China's status as a major player in Kazakhstan's uranium sector but also has far-reaching effects on the global uranium market. China's surging demand for nuclear fuel has led to increased uranium prices, benefiting uranium-producing countries worldwide and introducing a competitive edge to the market, urging traditional uranium producers to adapt to the changing dynamics of the industry.

While China's pursuit of nuclear energy has its merits, it also raises environmental and regulatory concerns. Ensuring responsible uranium mining practices and adherence to international safety and environmental standards is crucial. China's role in the global uranium supply chain underscores the importance of robust regulations and sustainable mining practices.

Nuclear entanglements: vulnerabilities in the US nuclear industry

US President Joe Biden's ban on American imports of Russian oil and other energy products following the invasion of Ukraine did not extend to imports of uranium and nuclear fuel from Russia for US nuclear power plants. Most of the uranium procured in the United States in 2021 was sourced from overseas, with imports accounting for 95 per cent of the total, a common trend when domestic uranium production is low.[191] Kazakhstan emerged as the primary supplier of uranium to the United States in 2021, contributing 35 per cent of its total uranium purchases, followed by Canada with 15 per cent and Australia with 14 per cent.

In 2021, a significant portion of the processed uranium for use in US power plants was sourced from abroad. Only 19 per cent of the separative work units (SWU, a measure of uranium enrichment capability) originated within the United States, while a substantial 81 per cent was procured from other countries. Among these, Russia was the largest external provider, contributing 28 per cent of the SWU. Russia was followed by the United Kingdom at 17 per cent, Germany at 13 per cent, and the Netherlands at 11 per cent.[192]

In 2022, the share of SWU originating from the United States increased to 27 per cent. Russia's supply share reduced to 24 per cent, with Germany at 12 per cent, the United Kingdom at 11 per cent, and the Netherlands at 9 per cent (Table 2).[193] One of the industry sources has indicated that it may take over a decade for them to produce quantities comparable to Rosatom.[194]

[191] US Energy Information Administration (2023), 'U.S. uranium concentrate production in 2021 remained near all-time lows', *Today in Energy*, 26 July, https://www.eia.gov/todayinenergy/detail.php?id=53179.
[192] Ibid.
[193] US Energy Information Administration (2023), *2022 Uranium Marketing Annual Report*, https://www.eia.gov/uranium/marketing/.
[194]The industry source is The company operating the Ohio nuclear plant. Source: Bearak, M. (2023), 'The U.S. Is paying billions to Russia's nuclear agency. Here's why', *New York Times,* June 14, https://www.nytimes.com/2023/06/14/climate/enriched-uranium-nuclear-russia-ohio.html.

Table 2: Purchases of enrichment services for US civilian nuclear power reactors (number of SWU)[195]

thousand separative work units (SWU)

Country of enrichment service (SWU-origin)	2018	2019	2020	2021	2022
China	W	W	W	W	W
France	0	W	W	W	W
Germany	1,444	1,238	1,175	1,825	1,763
Netherlands	2,864	1,367	1,885	1,583	1,303
Russia	3,473	3,087	3,220	3,953	3,409
United Kingdom	1,544	1,262	1,218	2,366	1,593
Europe[196]	W	W	W	W	W
Other[197]	W	W	W	W	W
Non-US total	**10,034**	**7,992**	**10,012**	**11,481**	**10,301**
United States	4,979	5,289	4,132	2,736	3,876
Total	**15,013**	**13,281**	**14,144**	**14,217**	**14,176**
Average price (US$ per SWU)	115.42	109.54	99.51	99.54	101.03

Note: W = data withheld to avoid disclosure of individual company data.

Russia's export of nuclear fuel to the United States has been a pivotal element of their nuclear cooperation, significantly bolstering the US energy sector. This cooperation has extended beyond the notable Uranium One deal, with Russia's provision of nuclear fuel playing a crucial role in diversifying and stabilizing the American nuclear fuel supply.

Therefore, the United States' dependency on Russia for nuclear materials, particularly in terms of uranium processing and the provision of SWU, presents a complex challenge. This reliance, with a significant percentage of SWU sourced from Russia, highlights a strategic vulnerability in the US nuclear supply chain. It underscores the need for diversification of supply sources and the development of domestic capabilities in uranium enrichment. Addressing this dependency is crucial for ensuring national energy security, maintaining the integrity of the nuclear power industry, and upholding the principles of nuclear nonproliferation. As the geopolitical landscape evolves, it becomes increasingly important for the United States to reassess and strengthen its nuclear supply strategies to reduce reliance on foreign sources, particularly from geopolitical rivals, and to safeguard its long-term energy independence and security.

Conclusion

Russia's strategic significance in the nuclear sector cannot be overstated. As a dominant player in uranium mining and fuel processing, Russia has positioned itself as a crucial supplier in the global nuclear fuel cycle. Its extensive control over uranium conversion facilities, uranium enrichment services, and nuclear fuel supply chains grants it substantial influence over the nuclear energy landscape.

China's remarkable transformation from a newcomer to a formidable player in uranium mining and the global supply chain underscores its long-term vision and strategic investments. As China continues to expand its nuclear capacity and influence, it

[195] Source: US Energy Information Administration (2023), *2022 Uranium Marketing Annual Report*, Table 16, https://www.eia.gov/uranium/marketing/table16.php.
[196] Specific country in Europe was not reported.
[197] Specific country was not reported.

will significantly impact the global uranium market, prompting a need to balance clean energy aspirations with responsible resource management.

To encapsulate the multifaceted dynamics of nuclear energy geopolitics, it is imperative to acknowledge nuclear energy's dual role—a critical component and a challenge to global energy security. Navigating this intricate landscape necessitates careful consideration of strategic investments and diplomatic efforts aimed at mitigating risks while harnessing the advantages of nuclear energy for a sustainable and secure energy future.

As the world grapples with these complexities, it is vital for the United States, the European Union, and other nations to prioritize diversifying their nuclear supply chains, investing in domestic nuclear capabilities and engaging in diplomatic dialogues that promote transparency, nonproliferation, and responsible nuclear energy practices. Only through a combination of strategic foresight and international cooperation can the world effectively address the challenges and opportunities presented by nuclear energy geopolitics, ultimately safeguarding energy security in an ever-evolving geopolitical landscape.

THE INTERSECTING REALMS OF NUCLEAR INDUSTRY AND MEDICINE: GEOPOLITICAL DYNAMICS IN THE MEDICAL ISOTOPES SUPPLY CHAIN[198]

Sara Vakhshouri

Radioisotopes, naturally decaying atoms with significant applications across various fields, are intrinsically linked to the broader field of nuclear energy. These isotopes, essential in modern medicine, are mostly produced in nuclear reactors—the same facilities that are central to the production of nuclear energy.

Their role in medical diagnostics and therapy is crucial, marking an indelible impact on healthcare. With over 40 million nuclear medicine procedures conducted annually and a steady 5 per cent increase in demand for radioisotopes, the interdependence of nuclear medicine and the nuclear industry becomes increasingly significant.[199] This connection reveals a symbiotic relationship where advancements in nuclear energy significantly influence the production and availability of medical isotopes.

This interplay between nuclear industry and medical isotopes, when viewed in the context of global geopolitics, particularly the role of Russia and the dependency of the West, paints a complex yet intriguing picture. In this dynamic landscape, the stable and reliable supply of medical isotopes is not just a technical challenge but also a matter of geopolitical foresight.

The prevalence and utility of nuclear medicine

In developed nations, the prevalence of diagnostic nuclear medicine is considerable. Approximately one in every 50 individuals undergoes these procedures each year. Therapeutic applications, while less frequent, account for a substantial proportion of these interventions. The essence of nuclear medicine is its proficient use of radiation to explore and diagnose conditions within specific organs, allowing for rapid and accurate assessments. Technetium-99 (Tc-99m) exemplifies this utility, with around 40 million procedures globally each year, dominating both nuclear medicine procedures and diagnostic scans.[200]

Nuclear medicine originated in the 1950s, with physicians initially using Iodine-131 for thyroid-related diagnoses and treatments. Currently, the United States performs over 20 million nuclear medicine procedures annually, while Europe contributes approximately 10 million, a portion of which are therapeutic. The use of radiopharmaceuticals for diagnostics is growing rapidly, surpassing an annual increase of 10 per cent.[201]

Russia's role in global medical isotope production

Russia is a central figure in the global production and innovation of medical isotopes. Reactors generate about 80 per cent of radioisotopes, and cyclotrons account for the remainder.[202] Under the aegis of Rosatom, Russia's presence in this sector is

[198] The author wishes to express gratitude to her research intern at the Institute of World Politics, Viktor Kiss, for his invaluable assistance in navigating Russian language sources.
[199] World Nuclear Association (2023), 'Radioisotopes in medicine', https://world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/radioisotopes-in-medicine.aspx.
[200] Ibid.
[201] Ibid.
[202] A cyclotron is a type of particle accelerator that is essential in the production of certain radioisotopes used in nuclear medicine. Unlike nuclear reactors, which produce a broad range of isotopes, cyclotrons are used to produce specific types of radioisotopes by bombarding target materials with high-energy particles. These isotopes are often used in positron emission tomography scans and other diagnostic imaging techniques. Cyclotrons are instrumental in creating short-lived isotopes like fluorine-18 and carbon-11, which decay rapidly and are thus suitable for medical applications that require quick imaging processes.

notable. Its network includes the Research Institute of Physics and Chemistry, Institute of Reactor Materials, Research Institute of Atomic Reactors, Mayak, and Rosenergoatom, collectively underscoring its extensive role in isotope production. Approximately 30 per cent of the world's reactor fleet for isotope production is situated in Russia, underscoring its critical role in the global market.[203]

Rosatom produces a wide array of nuclear medicine products, including Molybdenum-99, Iodine -131, Iodine -125, Luletium Lu-177, Strontium-89, Actinium-225, and radiopharmaceuticals like Iodine -131, Strontium-153, and Gallium-67. They also manufacture generators for short-lived isotopes such as Technetium-99m and Rhenium-188, widely used in diagnostics and therapy in fields like oncology and cardiology.204

Notable among Rosatom's products are Ytterbium-176 and Lutetium-176, key in cancer treatment. Russia's production of Lutetium-177, crucial in cancer therapy, is especially significant, with over 95 per cent of the starting material sourced domestically. Russia also excels in the production of cyclotron radiopharmaceuticals. Short-lived radionuclides like Fluorine-18, Carbon-11, and Iodine-123 are vital in diagnostic imaging, enhancing oncology, neurology, and cardiology procedures. This production is led by institutions such as the Radium Institute and the Center for High-Tech Diagnostics.205

The global isotope market, valued at $6.4 billion in 2021, is expected to double by 2030. This growth is propelled by the increasing significance of therapeutic radiopharmaceuticals, despite the high costs and lengthy durations of clinical trials. Russia remains a leader in this expanding sector.

Russia's advancements in isotope production extend to logistics. The company V/O Izotop ensures efficient distribution of isotopes, particularly those with short half-lives, to about 180 clinics nationwide, including specialized transport for remote areas.[206]

The GMP plant in Obninsk marks a significant enhancement in Russia's medical isotope production capabilities.[207] Adhering to international standards, this facility will process raw isotopes into final medical products, strengthening Russia's capacity to meet growing domestic and international demands.

The Atom Mirny facility, under development by Rosatom Healthcare, is a key advancement.[208] This plant will serve as a central hub for converting raw isotopes into refined radiopharmaceuticals, aligning with Russia's goal of achieving self-sufficiency in high-tech medical products and maintaining its global market leadership.

Rosatom prioritizes the production of highly enriched stable isotopes, with its group's portfolio featuring over 200 such isotopes. As the sole industry operator, JSC Isotope plays a crucial role as the primary supplier of the entire range of isotope products produced by Rosatom's enterprises. These products are distributed to the international market, showcasing Rosatom's global influence. The company's extensive network includes partnerships with over 100 foreign organizations across 30 countries and collaboration with 600 institutions within Russia.[209] This extensive reach underlines Rosatom's substantial contribution to the availability of isotopes worldwide, emphasizing its significant role in the global isotope market.

Vulnerability of isotope supply chains in the United States

The United States faces significant challenges regarding the supply of essential medical and industrial isotopes due to its dependency on foreign sources, particularly Russia. This reliance has become a point of concern, especially given the geopolitical landscape. US vulnerability in this regard was starkly highlighted after the decommissioning of the last commercially operated research reactor producing fission-based medical isotopes in the mid-1990s. This event, coupled with the closure of the stable isotope production facility at Oak Ridge National Laboratory in the late 1990s, significantly increased US dependence on foreign isotope supplies, especially for those used as target materials in radioisotope production.

[203] Изотопы исцеления, https://atomvestnik.ru/2022/03/29/izotopy-iscelenija/.
[204] https://rosatom-centralasia.com/en/rosatom-group/r-d/isotopes/.
[205] https://rosatom-centralasia.com/en/rosatom-group/r-d/isotopes/; Изотопы исцеления, https://atomvestnik.ru/2022/03/29/izotopy-iscelenija/.
[206] Изотопы исцеления, https://atomvestnik.ru/2022/03/29/izotopy-iscelenija/. V/O Izotop is a subsidiary of Rosatom, the state nuclear energy corporation of Russia. It specializes in the production and distribution of isotopes for a variety of applications, primarily in the medical field. V/O Izotop plays a crucial role in ensuring the supply and logistics of medical isotopes, not only within Russia but also internationally. It coordinates the distribution of these isotopes to medical facilities, ensuring their timely and safe delivery, which is particularly important for isotopes with short half-lives used in diagnostic imaging and cancer treatment.
[207] Ibid.
[208] Ibid.
[209] https://rosatom-centralasia.com/en/rosatom-group/r-d/isotopes/.

This dependency became acutely evident during times of crisis. For instance, the aftermath of the 9/11 attacks and the early days of the Covid-19 pandemic, when commercial flights into the United States were disrupted, severely impacted the supply of many radioisotopes from abroad.210 These events underscored the nation's heavy reliance on foreign sources for critical isotopes.

Over 40 vital isotopes, used in the United States for both medical and industrial applications, are primarily supplied by Russian companies. Rosatom and its affiliates are pivotal in supplying these isotopes to the United States, not only as raw materials but also as finished products. The United States also relies on Russian sources for specialized devices used in nuclear medicine cameras, which are crucial for accurately measuring medical isotopes. Russia is the primary global provider of isotopes like gadolinium-153 (Gd-153) and has a significant share in the supply of cobalt-57 (Co-57).211

The United States' substantial dependence on foreign sources, notably Russia, for essential medical and industrial isotopes (Tables 1 and 2) underscores the vulnerability of its supply chains. This situation necessitates urgent attention to ensure a stable and secure supply of isotopes for various critical applications, including in healthcare and industry. In response, the United States and Canada are actively exploring ways to enhance local isotope production. One approach is repurposing existing nuclear power reactors as neutron sources for isotope production. In Canada, this is already being done using Canada Deuterium Uranium (CANDU) reactors for specific medical isotope production.[212] While these efforts are promising for bolstering local isotope supply, they may not fully address the immediate challenges posed by global events like the Russian invasion of Ukraine and potential sanctions against Russian suppliers. The possibility of imposing sanctions on Rosatom or its subsidiaries could significantly impact the supply of crucial medical and industrial isotopes, giving Russia considerable leverage in this vital sector.

Table 1: Key medical isotopes imported to the United States, mainly from Russia (highlighted isotopes are single-sourced from Russia)

Isotope	Stable?	Use
Actinium-225 (Ac-225)		Cancer treatment
Cobalt-56 (Co-56)		Calibration standard
Cobalt-57 (Co-57)		Medical imaging
Cobalt-60 (Co-60)		Cancer treatment and medical product sterilization
Cesium-137 (Cs- 137)		Cancer treatment, thickness gauging, flow detection
Cadmium-112 (Cd-112)	Stable	Target material for Indium-111 production
Erbium-168 (Er-168)	Stable	Production of Erbium-169 used for radiation synovectomy
Gadolinium-153 (Ga-153)		Medical imaging quality control source
Germanium-68 (Ge-68)		PET (positron emission tomography) imaging, cancer treatments
Iodine-131 (I-131)		Therapy for hyperthyroidism and thyroid cancer
Manganese-54 (Mn-54)		Calibration standard
Nickel-64 (Ni-64)	Stable	Target material for Copper-64 production used for cancer diagnosis
Palladium-103 (Pd-103)		Treatment for prostate cancer

[210] Peterson, Andrea (2022), 'Isotope supply chain at risk from war in Ukraine', *FYI: Science Policy News* (American Institute of Physics), July 15, https://ww2.aip.org/fyi/2022/isotope-supply-chain-risk-war-ukraine.
[211] US Senate Hearing 117-SY20, Michael Guastella, executive director of the Council on Radionuclides and Radiopharmaceuticals, 22 June 2022. https://www.congress.gov/117/meeting/house/114944/witnesses/HHRG-117-SY20-Wstate-GuastellaM-20220622.pdf
[212] U.S. mulls sanctions on Russian atomic energy company Rosatom - U.S. official, Steve Holland and Kanishka Singha, Reuters. https://www.reuters.com/world/europe/us-weighs-sanctions-russian-nuclear-power-supplier-rosatom-bloomberg-2022-03-09/.

Isotope	Stable?	Use
Rubidium-85 (Rb-85)		Cancer treatment, target for Strontium-82
Ruthenium-106 (Ru-106)		Brachytherapy for treatment of ocular melanoma
Thallium-203 (Tl-203)	Stable	Target material for Thallium-201 production used in heart imaging
Tin-112 (Sn-112)	Stable	Cancer diagnosis of brain, liver, kidney tumours
Molybdenum-98 (Mo-98)	Stable	Target material for Molybdenum-99 production
Molybdenum-100 (Mo-100)	Stable	Target material for Molybdenum-99 production
Rhenium-185 (Re-185)	Stable	Production of Rhenium-186 used in cancer treatment
Samarium-152 (Sm-152)	Stable	Production of Samarium-153 used in cancer treatment
Strontium-90 (Sr-90)		Cancer treatment
Uranium-235 (U-235)		Research reactor fuel and irradiation targets for Molybdenum-99 production
Ytterbium-176 (Yb-176)	Stable	Production of non-carrier-added lutetium-177 for cancer treatment
Yttrium-88 (Y-88)		Medical diagnostics, LEDs
Xenon-124 (Xe-124)	Stable	Production of Iodine-123 and Iodine-125 radioisotopes for imaging and cancer treatment
Xenon-133 (Xe-133)		Production of Xenon-133 for evaluation of pulmonary function and lung imaging
Zinc-67 (Zn-67)	Stable	Target material for Gadolinium-67 and Copper-67 production
Zinc-68 (Zn-68)	Stable	Target material for Gadolinium-67 and Copper-67 production

Source: US Senate Hearing 117-SY20, Michael Guastella, executive director of the Council on Radionuclides and Radiopharmaceuticals, 22 June 2022.[213]

Table 2: Key industrial isotopes imported to the United States, mainly from Russia (highlighted isotopes are single-sourced from Russia)

Isotope	Stable?	Use
Americium-241 (Am-241)		Oil/gas exploration
Barium-133 (Ba-133)		Oil/gas exploration
Barium-132 (Ba-132)	Stable	Target material to US Department of Energy for Barium-133 production
Cadmium-109 (Cd-109)		Metal analysis/lead in paint
Cerium-139 (Ce-139)		Metal production
Helium-3 (H-3)		Oceanic transient tracer, fuel for nuclear fusion reactions
Iridium-192 (Ir-192) disks		Industrial radiography

[213] US Senate Hearing 117-SY20, Michael Guastella, executive director of the Council on Radionuclides and Radiopharmaceuticals, 22 June 2022. https://www.congress.gov/117/meeting/house/114944/witnesses/HHRG-117-SY20-Wstate-GuastellaM-20220622.pdf

Isotope	Stable?	Use
Krypton-85 (Kr-85)		Radioactive tracer, arc discharge lamps, exit signs
Polonium-210 (Po-210)		Static remover
Selenium-75 (Se-75)		Industrial radiography
Tellurium-122 (Te-122)	Stable	Target material for Iodine-122 gamma imaging
Xenon-124 (Xe-124)	Stable	Instrumentation for radiation detection

Source: US Senate Hearing 117-SY20, Michael Guastella, executive director of the Council on Radionuclides and Radiopharmaceuticals, 22 June 2022.[214]

Conclusion

This exploration into the evolving landscapes of nuclear medicine and radioisotope production has illuminated the intricate intersection between nuclear industry and medical isotopes. The symbiosis of these fields is evident: advancements in nuclear industry directly influence the production and availability of medical isotopes. This relationship underscores the significance of nuclear reactors and cyclotrons, not only in energy generation but also in their critical role in medical diagnostics and treatments.

Russia's prominence in this domain is undeniable. As a leading producer of a wide range of medical isotopes, its influence extends far beyond its borders, affecting global supply chains and market dynamics. Rosatom, with its expansive portfolio and international reach, plays a pivotal role in fulfilling the global demand for medical isotopes, enabling Russia to orchestrate a significant portion of the world's supply.

On the other side of this geopolitical equation lies the vulnerability and dependence of the West, particularly the United States. US reliance on foreign sources, notably Russian, for essential medical and industrial isotopes, has been a recurring concern. This dependence is not just a matter of convenience but a critical aspect of healthcare infrastructure that has been brought into sharp focus during times of crisis, such as the 9/11 aftermath and the Covid-19 pandemic. The potential ramifications of geopolitical tensions, especially with Russia, highlight the urgent need for diversified and secure isotope supply chains.

Ensuring a stable and reliable supply of medical isotopes is not just a matter of scientific and industrial capability but also of geopolitical foresight and cooperation. As the field of nuclear medicine continues to evolve, understanding and addressing these interdependencies will be crucial for maintaining the health and well-being of populations worldwide.

[214] Ibid.

CONTRIBUTORS TO THIS ISSUE

Wade Allison, Emeritus Professor of Physics and Fellow of Keble College, University of Oxford, UK

Philip Andrews-Speed, Senior Research Fellow, Oxford Institute for Energy Studies

Robert J. Budnitz, Lawrence Berkeley National Laboratory, Berkeley, California USA (retired)

Neil Chapman, Chapman Consulting, Ireland

Landon Derentz, Senior Director of the Atlantic Council Global Energy Center

Bassam Fattouh, Director, Oxford Institute for Energy Studies and editor of the Oxford Energy Forum

Francesca Ferrazza, Head of Magnetic Fusion Initiatives Eni S.p.A, Italy

Edoardo Fiorentini, Head of Magnetic Fusion Initiatives Development Eni S.p.A, Italy

Jennifer T. Gordon, Director of the Nuclear Energy Policy Initiative at the Atlantic Council Global Energy Center

Olli Heinonen, Stimson Center, Washington DC USA

James Henderson, Distinguished Research Fellow, Oxford Institute for Energy Studies

Thomas Hochman, Research Associate at the Foundation for American Innovation. His writing has appeared in The Hill, American Affairs, and National Review

Tomas Kåberger, Chalmers University of Technology

Szymon Kardaś, PhD, senior policy fellow on energy within the European Power programme of the European Council on Foreign Relations, based in ECFR's Warsaw Office

Jan Horst Keppler, Senior Economic Advisor in the Division of Nuclear Technology Development and Economics (NTE) at the OECD Nuclear Energy Agency (NEA)

Jake Kinghorn-Mills, MCM Environmental, UK

Giacomo Luciani, Scientific Advisor, Master in International Energy, PSIA - Paris School of International Affairs

Noura Y. Mansouri, Fellow, King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia

Davide Martulli, Magnetic Fusion Initiatives Development Eni S.p.A, Italy

Charles McCombie, McCombie Consulting, Switzerland

Robin Mills, CEO, Qamar Energy, Non-Resident Fellow at the Columbia Center on Global Energy Policy and Research Associate, Oxford Institute for Energy Studies

Anita Nilsson, AN & Associates, Uppsala, Sweden

Lars J. Nilsson, Lund University

H-Holger Rogner, International Institute for Applied System Analysis (IIASA), Austria

Lars Schernikau, independent energy economist, commodity trader, entrepreneur, and author based in Switzerland and Singapore, details www.unpopular-truth.com

Adnan Shihab-Eldin, Senior Visiting Research Fellow, Oxford Institute for Energy Studies (OIES), and former Director General (retired), the Kuwait Foundation for the Advancement of Sciences (KFAS), Kuwait

Claudio H. Steuer, Director, SyEnergy Consulting (Brazil), and Faculty Member, International Human Resources Development Corporation (USA)

Sara Vakhshouri, Founder and President of SVB Energy International and SVB Green Access, Senior Fellow at Oxford Institute for Energy Studies, Professor and Chair of the Canter for Energy Security and Energy Diplomacy at the Institute of World Politics and co-editor of this issue

Tomáš Vlček, Department of International Relations and European Studies, Faculty of Social Studies, Masaryk University, Czech Republic

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THE OXFORD INSTITUTE FOR ENERGY STUDIES

57 Woodstock Road | Oxford | OX2 6FA

Direct Line: +44 (0)1865 889136
Reception: +44 (0)1865 311377
Fax: +44 (0)1865 310527

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