THE OXFORD INSTITUTE FOR ENERGY STUDIES

August 2022

The Role of Nuclear Energy in the Global Energy Transition

Energy Transition

OIES Paper: ET14

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ISBN 978-1-78467-202-7

Preface

The continuing increase in global greenhouse gas emissions and the likelihood that targets to limit the temperature increase to 1.5^{o} above the level seen at the start of the industrial revolution will be missed has resulted in a growing focus on the development of all forms of carbon-free energy. Solar and wind power have been the main beneficiaries in the power sector, but it is becoming clear that if climate goals are to be met by 2050 then other forms of low or zero emission electricity generation must be prioritised. This has led to something of a renaissance for the nuclear industry, the development of which has been rather stagnant since the Fukushima disaster in Japan in 2011.

In this OIES paper, Anna Davidson, a Saudi Aramco fellow at the Institute and a doctoral student at St Antony's College Oxford, explores the key motivations for the development of nuclear energy in the current global energy economy. She naturally considers climate change as a key driver, but also discusses energy security and foreign relationships as other important motivating forces. She also outlines the different drivers for countries exporting nuclear technology and those importing it to generate domestic electricity, and provides important detail on the current reactors under construction, the providers of key technologies and the methodologies which various exporters use to gain a competitive position in the nuclear market place.

The paper provides a wealth of data about the current state of the nuclear industry and the potential for its growth over the next ten to twenty years, while also considering important questions about the geo-political dimensions which underpin the relationships between the exporters and importers of nuclear technology and the ties, such as financing and provision of services in the nuclear energy value chain, which bind them over multiple decades. We hope that it will prove useful to all those interested in the role of nuclear power in the energy transition and the political and economic implications of the further development of this important source of low carbon electricity.

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Contents

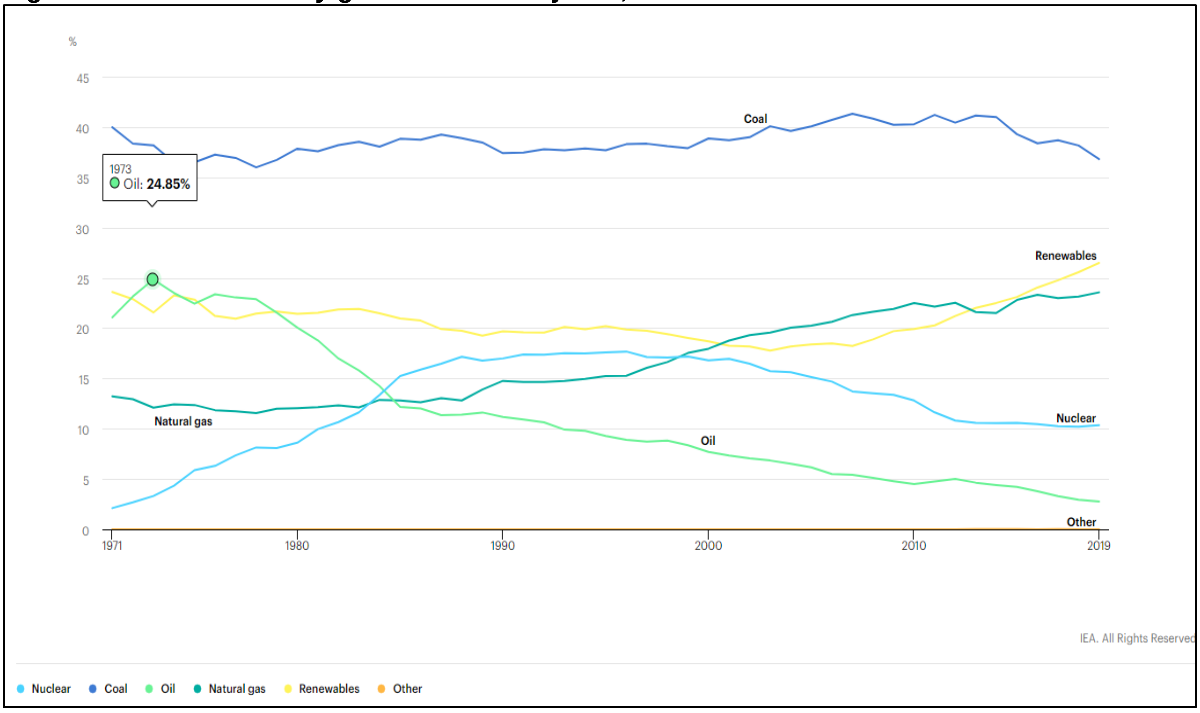
Tables

Figures

1. Introduction

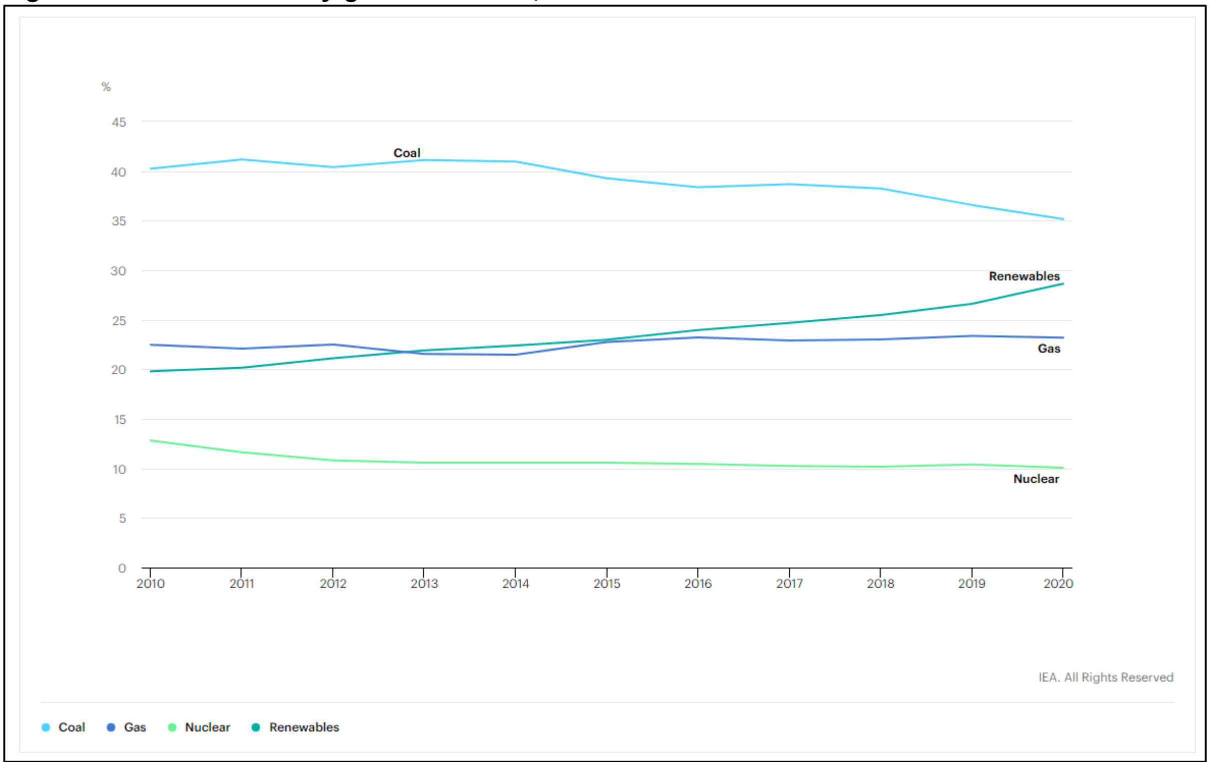
At present, countries are in the process of re-evaluating and adapting their energy systems to meet various demands on multiple fronts. The global energy transition is occuring in the context of international efforts to achieve net zero CO_2 emissions by mid-century. Thus any examination of the use of nuclear energy for electricity production as part of the global energy transition must take into account both the motivations related to climate targets as well as possible additional or alternative motivations that drive states' decisions to adopt and advance their civil nuclear technology. *Figure 1* below shows how the global energy mix for electricity generation by fuel type has changed over the last 50 years. The shares of coal and oil have declined in the past 15 years whilst natural gas has experienced a steady increase in use and renewables have sharply increased. Nuclear energy, although experiencing a dip in use after the 2011 Fukushima disaster, has remained relatively steady at about 10% of the global energy mix with about four hundred and forty nuclear reactors operating today. A snapshot of the last 10 years is provided in *Figure 2*. The nuclear share of the generation mix has remained fairly steady since 2010, with the dip early on marking decommissioned reactors going offline and not being replaced. Although a good many nuclear power plant construction projects have started in the past 10 years, they will only be reflected in the figures once the reactors are online (which can take about 10 years after initial planning and construction begins).

Figure 1: World electricity generation mix by fuel, 1971-2019[1]



[1] IEA, World electricity generation mix by fuel, 1971-2019, *IEA*, Paris https://www.iea.org/data-and-statistics/charts/world-electricity-generation-mix-by-fuel-1971-2019

Figure 2: Global electricity generation mix, 2010-2020[2]



The current energy transition, with its emphasis on renewable and sustainable energy sources, is considered the fourth since the Industrial Revolution.[3] The first transition, during the Industrial Revolution, was from wood, wind, and water to coal; the second to rising use of oil; and the third to rising use of natural gas, hydropower, and nuclear power. Nuclear power experienced a sharp decline in public confidence and usage in some countries following the 'industry wide disruption caused by the Three Mile Island accident in 1979', the 'increase in costs and a steady increase in construction duration' after the 1986 Chernobyl accident, and the demand for 'greater transparency' by nuclear programmes after the 2011 Fukushima disaster.[4] However, nuclear energy has now been reinstalled at the centre of the debate as a sustainable energy source, especially in the electricity generation sector, given its low emissions levels.[5]

This paper explores the key motivations for the development of nuclear energy in the current global energy economy. It considers climate change as a key driver, but also discusses energy security and foreign relationships as other important motivating forces. The paper also outlines the different drivers for countries exporting nuclear technology and those importing it to generate domestic electricity, and provides important detail on the current reactors under construction, the providers of key technologies and the methodologies which various exporters use to gain a competitive position in the nuclear market place.

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[2] IEA, Global electricity generation mix, 2010-2020, *IEA*, Paris. https://www.iea.org/data-and-statistics/charts/global-electricity-generation-mix-2010-2020

[3] Rudy Swennen, *China's Energy Revolution in the Context of the Global Energy Transition*, ed. Shell International B.V and The Development Research Center (DRC) of the State Council of the People's Republic of China (Cham: Springer International AG, 2020).

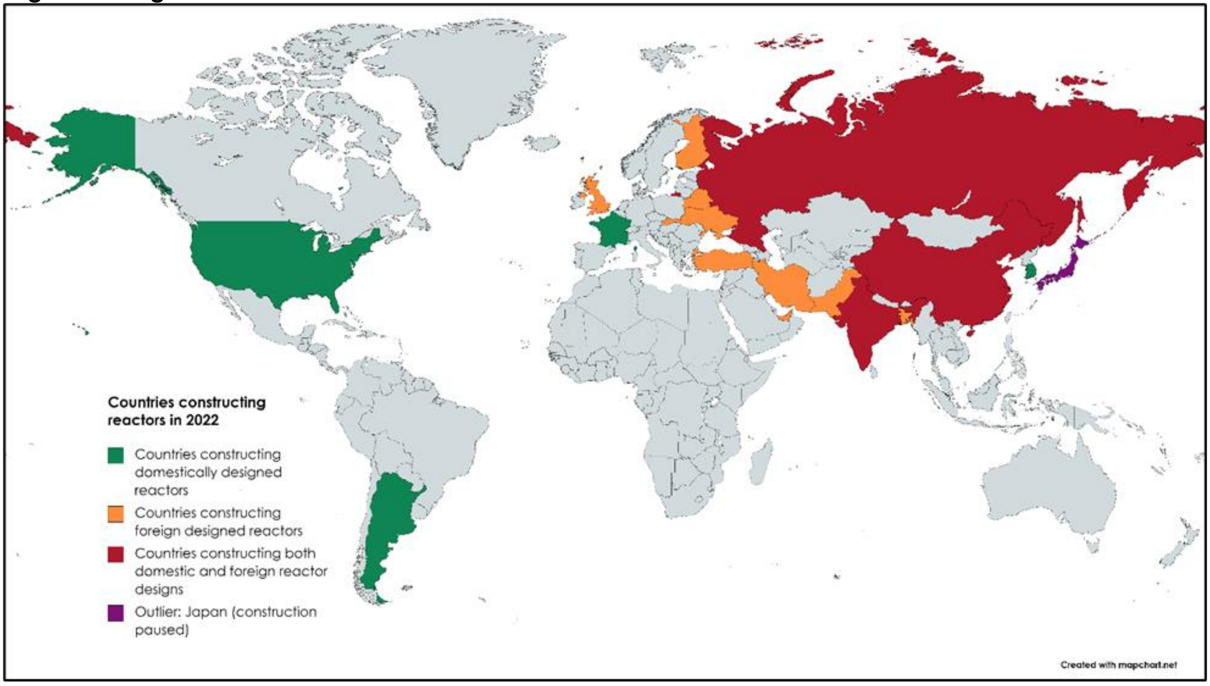
[4] Jessica R. Lovering, Arthur Yip, and Ted Nordhaus, "Historical Construction Costs of Global Nuclear Power Reactors," *Energy Policy* 91 (2016): 371–82, https://doi.org/10.1016/j.enpol.2016.01.011; Nicolas Boccard, "The Cost of Nuclear Electricity: France after Fukushima," *Energy Policy* 66 (2014): 450–61, https://doi.org/10.1016/j.enpol.2013.11.037.

[5] IEA, "World Energy Outlook 2020" (Paris, 2020); Li Chen Sim and Robin Mills, *Low Carbon Energy in the Middle East and North Africa: Panacea or Placebo?*, *International Political Economy Series*, 2021, https://doi.org/10.1007/978-3-030-59554-8_1.

2. Motivations for nuclear energy today

It is important to distinguish between the motivations of countries transitioning to nuclear for climate reasons and those transitioning or adopting nuclear for other reasons. The focus here is on countries transitioning or constructing nuclear power plants (or NPPs) and on countries which are interested in adopting nuclear energy for the first time but have not yet begun the construction process. *Figure 3* below provides a snapshot of current reactor construction worldwide.

Figure 3: A global look at current reactor construction in 2022[6]



The primary trends in motivations for nuclear energy are related to climate change, energy security, and foreign relationships. Climate change motivations are consistently to achieve lower carbon emissions or reach a net zero target by a given deadline. Energy security motivations are less consistent but include caution towards depending on imports from a foreign energy provider, depending on fossil fuels, and the desire to be in control of the electricity supply. Motivations related to foreign relationships include using the electricity generated from nuclear energy for financial export gains, gaining influence over clients, and gaining international prestige through technological advancement. Tables 1 and 2 summarise motivations for importing countries and those using their own technology.

Table 1: Motivations for nuclear energy in countries with imported reactors currently under construction[7]

	Climate Change	Energy Security	Foreign Relationship	Export	Influence	Prestige
Slovakia	x	x	x	x		
Bangladesh			x			x
Belarus		x	x	x		x
China	x	x	x	x	x	x
Finland	x	x				

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[6] Compiled by the author using the data in this report and software from mapchart.net; IAEA, "Under Construction Reactors."
[7] This table is compiled by the author. Imported here is defined by the origin of the reactor design. The data can be found in the appendix.

India	x					
Iran	x	x	x	x		
Pakistan	x	x	x			x
Turkey		x	x			x
Ukraine		x	x	x		x
United Arab Emirates	x	x				
United Kingdom	x	x				

Table 2: Motivations for nuclear energy in countries with domestic-design reactors currently under construction[8]

	Climate Change	**Energy Security**	**Foreign Relationships**	**Export**	**Influence**	**Prestige**
Argentina			x	x		x
China	x	x	x	x	x	x
France	x	x	x	x		
India	x	x	x			x
Russia	x	x	x	x	x	x
South Korea	x	x	x	x		
USA	x	x	x	x		x

Table 3 summarises which reactors have been sold to whom. Asterisks in the table indicate first-time nuclear energy countries (i.e., those who are adopting nuclear energy into their energy mix for the first time). Unless indicated, vendors are owned domestically either by the state or private enterprise. Of the fifty-five reactors currently under construction, twenty-four are being constructed by a foreign supplier (including Russia, China, South Korea, France, and Germany).

Table 3: Nuclear reactors currently under construction worldwide (2022)

Client	**Quantity of Reactors Under Construction**	**Vendor**	**Total Reactors Currently in Operation in the Country**
Argentina	1	**Nucleoeléctrica Argentina SA (NA-SA)**	3
Slovakia	2	**Rosatom (Russia)**	4
Bangladesh*	2	**Rosatom (Russia)**	0
Belarus*	1	**Rosatom (Russia)**	1
China	2 7 7 2	**Rosatom (Russia)** **CGN** **CNNC** **SPIC Huaneng**	54
Finland	1	**TVO (Finland) with Areva (France) Siemens (Germany)**	5
France	1	**EDF**	56
India	1 (FBR prototype) 3	**BHAVINI**	23

[8] This table is compiled by the author. Exported here is defined by the origin of the reactor design. The data can be found in the appendix

	4	**Nuclear Power Corporation of India** **Rosatom (Russia)**	
Iran	1	**Rosatom (Russia)**	1
Pakistan	1	**CNNC (China)**	5
Russia	3	**Rosatom**	37
South Korea	4	**KEPCO**	24
Turkey*	4	**Rosatom (Russia)**	0
Ukraine	2	**Rosatom (Russia)**	15
United Arab Emirates*	2	**KEPCO (Korea) with ENEC (UAE)**	2
United Kingdom	2	**EDF (France)**	11
USA	2	**Westinghouse**	92

2.1 Climate change

Electricity generation is considered the primary target of efforts to curb climate change because emissions from burning fossil fuels for electricity account for roughly 40% of total global emissions and they are the 'fastest growing source of CO_2 emissions over recent decades.'[9] Systemic changes in the levels of CO_2 and greenhouse gases in the earth's atmosphere represent one of the foremost challenges for the international community. The Paris Agreement saw nearly all of the world governments agree to combine efforts in limiting the increase in global temperature to two degrees centigrade. Accountability and progress towards this goal is reviewed and renewed each year at the UN Conference of the Parties (COP) in order 'to build real impetus, real change towards getting the world on track to achieve that headline target,' according to one of the UK's former COP26 Regional Ambassadors, Sir Laurie Bristow.[10] The universality of a changing climate presents an opportunity for potential cooperation between states whose interests and needs would otherwise rarely cross paths.

One of these opportunities has arisen in the acquisition and development of nuclear energy.

Nuclear energy is a core component in the international response to climate change and is regarded by nearly all countries considered in this report as a means of addressing climate-related challenges. 66% of the countries currently constructing reactors for nuclear energy express a motivation to address climate change by either adopting or expanding their nuclear energy capabilities.[11] These include the United Kingdom, the UAE, Pakistan, Iran, India, Finland, China, South Korea, and Slovakia.

In Europe, the replacement of coal as an electricity generation source is considered inevitable, although which source is most likely to replace coal is contested. Nuclear energy and renewable energy both play a role in modelling scenarios in an EU-wide coal phase-out policy.[12] Given the substantial degree of nuclear energy in its energy mix France is well positioned to replace a certain degree of nuclear energy with renewables and is among the first in the world to have reached this step in the global energy transition. Most states answer the question of how to replace oil with the environmentally friendlier option of natural gas, or how to replace all fossil fuels with either nuclear energy or renewables. France, however, starts 'from a lower base point relative to other economies who are more reliant on fossil fuel-

[9] Organisation for Economic Co-operation Development, *Nuclear Energy Today*, Second (Paris: OECD Publishing, 2013), https://ezproxy-prd.bodleian.ox.ac.uk:3355/nuclear-energy/nuclear-energy-today_9789264179233-en.
[10] Anna J. Davidson, "The UC Interview Series: Sir Laurie Bristow," The University Consortium, 2020, https://uc.web.ox.ac.uk/article/the-uc-interview-series-sir-laurie-bristow.
[11] See the Tables 1 and 2
[12] Dogan Keles and Hasan Ümitcan Yilmaz, "Decarbonisation through Coal Phase-out in Germany and Europe — Impact on Emissions, Electricity Prices and Power Production," *Energy Policy* 141, no. February (2020): 111472, https://doi.org/10.1016/j.enpol.2020.111472.

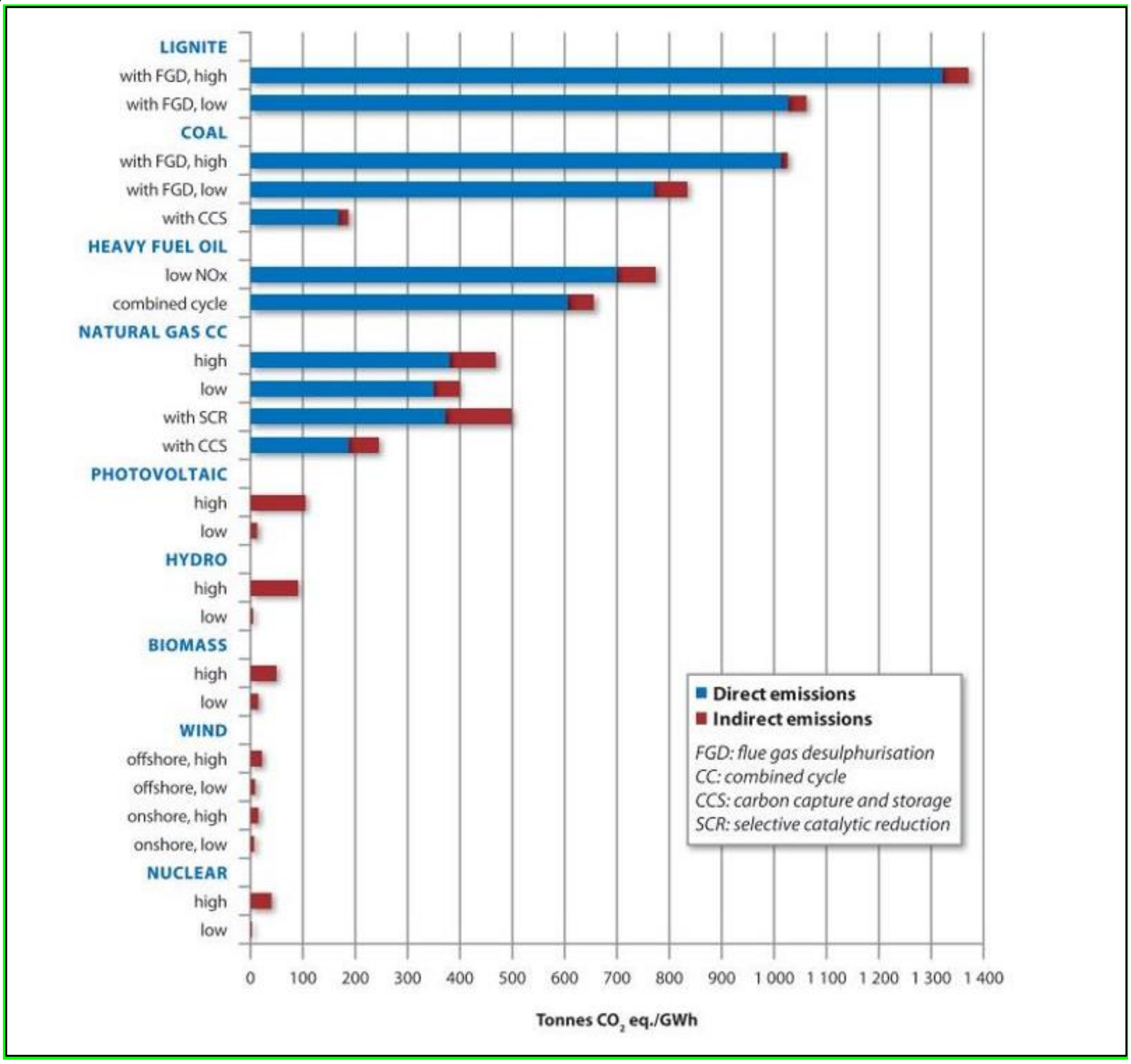
based generation' and in recent years has been looking to reduce the nuclear share of its energy mix, from 75% to 50% by 2035 by allowing ageing reactors to be decommissioned and increasing renewables.[13] However, since early 2022, French leadership has expressed a reversal in this policy by declaring a 'renaissance' in nuclear energy and a programme to construct up to 14 new reactors by 2050.[14]

Nuclear is an obvious choice for meeting clean energy goals as any emissions that do result from nuclear energy for electricity generation are related largely to the acquisition of materials (mainly concrete and steel production) for plant construction and to the mining and enrichment of uranium. The IEA's scenario on 'Net Zero by 2050' claims that '[h]ydropower and nuclear, the two largest sources of low-carbon electricity today, provide an essential foundation for transitions.'[15] Nuclear energy is the 'second-largest source of low emissions electricity' next to hydropower.[16] Nuclear energy supports other renewable energy sources by acting as a steppingstone between the shift away from fossil fuels and the time when other renewables such as wind, solar, and hydroelectric are more widely accessible and viable.[17] Some IEA scenarios for 2050 predict that almost 70% of electricity generation will come from renewable sources, and most of the remainder from nuclear.[18]

The primary factor under consideration in adopting new energy sources or expanding current energy sources is the life cycle emissions of CO_2 and carbon intensity. Carbon intensity[19] is determined by measuring the number of CO_2 grams emitted in the generation of one unit of electricity per kilowatt hour. The higher the ratio, the more carbon intensive the electricity source. Carbon intensity is defined by the OECD as 'the product of the inverse of fuel efficiency and…the input weighted emission factor.'[20] The rate of carbon intensity for nuclear is a minimum of 15-50 gCO_2/KWh, resulting from indirect emissions in the construction and operation stage as shown in *Figure 4.*[21] Recent studies comparing the carbon intensity of electricity sources estimate that 'the energy cost of constructing and operating power plants will, in 2050, be equivalent to 3–8% of electricity output for nuclear, wind and solar power, and more than 13% for other low-carbon technologies.'[22] Together, wind, solar, and nuclear are the only energy sources whose greenhouse gas emissions occur only in the construction and operation stages of their life cycles.[23] This is shown in *Figure 4* as indirect emissions.

[13] News Wires, "Macron Says Nuclear Will Remain Key Energy Source for France," *Reuters*, August 12, 2020, https://www.france24.com/en/europe/20201208-macron-says-nuclear-will-remain-key-energy-source-for-france.
[14] Angelique Chrisafis, "France to Build up to 14 New Nuclear Reactors by 2050, Says Macron," *The Guardian*, February 10, 2022, https://www.theguardian.com/world/2022/feb/10/france-to-build-up-to-14-new-nuclear-reactors-by-2050-says-macron.
[15] IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector," 2021, www.iea.org/t&c/.
[16] IEA, "World Energy Outlook 2020."
[17] Ibid.
[18] IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector."
[19] Also referred to as the 'energy cost' and 'carbon footprint' in other reports.
[20] OECD, *Energy and Climate Policy: Bending the Technological Trajectory.*, *OECD Studies on Environmental Innovation* (Paris: OECD Publishing, 2012), https://ezproxy-prd.bodleian.ox.ac.uk:2102/10.1787/9789264174573-en.
[21] Michaja Pehl et al., "Understanding Future Emissions from Low-Carbon Power Systems by Integration of Life-Cycle Assessment and Integrated Energy Modelling," *Nature Energy* 2, no. 12 (2017): 939–45, https://doi.org/10.1038/s41560-017-0032-9; Grantham Research Institute on climate change and the environment, "What Is the Role of Nuclear Power in the Energy Mix and in Reducing Greenhouse Gas Emissions?," The London School of Economics and Political Science, January 26, 2018, https://www.lse.ac.uk/granthaminstitute/explainers/role-nuclear-power-energy-mix-reducing-greenhouse-gas-emissions/.
[22] Pehl et al., "Understanding Future Emissions from Low-Carbon Power Systems by Integration of Life-Cycle Assessment and Integrated Energy Modelling."
[23] Ibid.

Figure 4: Direct and indirect greenhouse gas emissions from various electricity generation systems



Source: Organisation for Economic Co-operation Development, 2013

Nuclear energy's greenhouse gas emissions derive from the energy sources used in construction and uranium enrichment. Although hydro and biomass do not directly emit greenhouse gases, their life cycle emissions are considered substantial compared to solar, wind, and nuclear power.[24] Compared to the average twenty to twenty-five year lifespan of renewables such as wind and solar, nuclear energy is a much longer term option as a single reactor typically operates for sixty years or up to 80 years after lifetime extensionss.[25] Lifetime extensions for nuclear are 'generally cost competitive with other sources of low emissions electricity, including wind and solar PV.'[26]

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[24] Ibid.

[25] Sim and Mills, *Low Carbon Energy in the Middle East and North Africa: Panacea or Placebo?*; ROSATOM Overseas, "The VVER Today: Evolution, Design, Safety," *VVER Brochure*, n.d., http://www.rosatom.ru/en/resources/b6724a80447c36958cfface920d36ab1/brochure_the_vver_today.pdf; OECD Nuclear Energy Agency, "Uranium 2020: Resources, Production and Demand," *A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency Uranium*, 2020.

[26] IEA, "World Energy Outlook 2020."

In order to reach 2050 net zero emissions goals, a combination of technologies is necessary. Renewables must be supported to a degree by other energy sources, including nuclear energy. Other sources such as natural gas represent a temporary solution to a much wider goal of reducing global greenhouse gas emissions.[27] Although the life cycle CO_2 emissions of natural gas are comparatively less unattractive than other hydrocarbon energy sources, the presence of those emissions eliminates natural gas from consideration in some states where the long-term competition with renewables is in place. In such cases nuclear energy as a non-CO_2 emitting energy source can find a key role in the global energy transition.

The counterargument that 2050 net zero emissions goals can be reached without nuclear energy is a problem for two primary reasons. A decline in the use of nuclear energy in advanced economies would require substantial investment increases (USD ~1.6 trillion between 2018 and 2040) in renewables which would be passed on to consumers.[28] The IEA estimates that the cost of the electricity supply for advanced economies would average USD ~80 billion higher per year without lifetime extensions of current reactors and investment in new NPP construction.[29] We can observe already that many countries which currently possess NPPs have incorporated reactor lifetime extensions, and constructing new NPPs, in their strategies for achieving 2050 net zero emissions targets.[30] Secondly, NPPs are considered to be more reliable sources of dispatchable electricity generation than renewables and less subject to price volatility than fossil fuels.[31] Dispatchability relates to the long-term certainty of an electricity source to meet demand at all times.[32] This is discussed in more detail in the next section.

2.2 Energy security

In addition to the attractiveness of lower carbon intensity, nuclear energy's rise as one of the prime candidates for adjusting the electricity generation energy mix is also supported by its relative ease of access financially and geographically. Unlike other alternative energy sources, nuclear energy does not depend on wind directions or speeds, cloud cover, or haze and can operate in diverse locations so long as it is near a large water source needed for cooling.[33] One of the most attractive features of nuclear energy is the stability of its fuel supply and the consistency of power supply despite adverse weather conditions and political instability.[34] Instances of political instability interfering with energy supply have been observed in various oil and gas conflicts between suppliers, especially Russia, and clients.[35] Both the Russo-Georgian war and the disputes with Ukraine over gas transit are considered to be results of Russia's perception of energy as a strategic tool in foreign policy.[36] Conversely, although Ukraine is a country which receives the majority of its nuclear fuel supplies from Russia, the ongoing war with Russia has not disrupted the electricity generation operations of its nuclear power plants. (Chernobyl has been under military occupation but the NPP does not currently generate electricity to the grid.) At the

[27] Patrick Trent Greiner, Richard York, and Julius Alexander McGee, "Snakes in The Greenhouse: Does Increased Natural Gas Use Reduce Carbon Dioxide Emissions from Coal Consumption?," *Energy Research and Social Science* 38, no. January (2018): 53–57, https://doi.org/10.1016/j.erss.2018.02.001; Michael Levi, "Climate Consequences of Natural Gas as a Bridge Fuel," *Climatic Change* 118, no. 3–4 (2013): 609–23, https://doi.org/10.1007/s10584-012-0658-3.

[28] IEA, "Nuclear Power in a Clean Energy System" (Paris, 2019), https://doi.org/10.1787/fc5f4b7e-en. P. 5.

[29] Ibid. p. 5.

[30] Jochen Markard et al., "Destined for Decline? Examining Nuclear Energy from a Technological Innovation Systems Perspective," *Energy Research and Social Science* 67, no. August 2019 (2020): 101512, https://doi.org/10.1016/j.erss.2020.101512.

[31] IEA, "Nuclear Power in a Clean Energy System." p. 13

[32] Ibid.

[33] Ioannis N. Kessides, "Powering Africa's Sustainable Development: The Potential Role of Nuclear Energy," *Energy Policy* 74, no. S1 (2014): S57–70, https://doi.org/10.1016/j.enpol.2014.04.037.

[34] Tomoko Murakami, "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study," *Energy Reports* 7 (2021): 3428–36, https://doi.org/10.1016/j.egyr.2021.05.049.

[35] Adrian Dellecker and Thomas Gomart, eds., *Russian Energy Security and Foreign Policy*, Routledge/GARNET Series. Europe in the World ; 13 (London ; New York: Routledge, 2011).

[36] Ibid.

Zaporizhzhia NPP in Ukraine which Russian military forces now control, fighting caused a training building to be hit by a projectile, but none of the reactors on site nor personnel were harmed and no radioactive materials were released. Two of the five high-voltage off-site power transmission lines that supply electricity to the NPP were damaged. (A single line needs to be in operation to provide power, and these are separate and unrelated to the safety equipment power lines for the NPP).[37] Despite this, reactor output has only been affected by the occupation of an invading military force, when there was a brief 100 MWe reduction per reactor on 17 March caused by an onsite power line break which was promptly repaired on the same day.[38] Receiving of fuel assemblies is not a common concern for NPPs as these remain inside a reactor for 18-36 months at a time; therefore, immediate replacement fuel supplies for Ukraine's NPPs have not been necessary.[39] Ukraine has also been in the process of diversifying its sources of fuel to include Westinghouse's fuel services.[40]

As shown in the appendix, countries that emphasise the security or stability benefits of nuclear energy as a steady supply of electricity, as domestically sourced electricity, or as financially affordable, include all the countries currently constructing nuclear reactors with designs originating from foreign suppliers. This is not surprising. Energy security can be defined in many ways. Generally it is defined as 'low vulnerability of vital energy systems'.[41] However, defining the source of vulnerability is the point at which the definition becomes more nuanced. It can refer to the stability and physical security of the grid and transmission of electricity or protection of the source of energy production. Such a physical definition of energy security is especially significant for countries in wartime and in natural disaster scenarios which threaten the structural integrity of the energy system. Energy security may also be defined as the ability of a country to determine its electricity generation or, as decreased or proportional dependence on outside actors. Energy security further holds different meanings depending on the actor. A former director of the IEA, Maria van der Hoeven, once characterised energy security as, for exporting countries, about '…security of demand, for importing countries about security of supply'.[42] Thus, for energy exporting countries, energy security speaks to the resilience of the market for their specific exports, while for energy importing countries it entails a reliable external supply to purchase.

Countries using their own reactor designs which consider nuclear energy to play a role in their energy security include China, France, India, Russia, South Korea and the USA (i.e., all countries except Argentina). For China, controlling and producing key facets of its own nuclear technology supply chain are considered important in order to decrease reliance on foreign imports. At present reliance on foreign imports for its own reactor designs is decreasing, with 88% of the equipment for the Hualong One reactor design now manufactured domestically.[43] Although China's energy imports are expected to rise in the short term, it is expected to reduce its dependency on energy imports through domestic capabilities in renewable energy and nuclear power.[44] By 2030, China's share of electricity from nuclear energy in its energy mix is expected to rise from 4% at the time of writing to 10% and reach 20% by

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[37] World Nuclear Association, "Ukraine: Russia-Ukraine War and Nuclear Energy," World Nuclear Association, March 30, 2022, https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine-russia-war-and-nuclear-energy.aspx.
[38] Ibid.
[39] Chris Park and Michael Allaby, "Nuclear Fuel Cycle," in *A Dictionary of Environment and Conservation* (Oxford University Press, 2017).
[40] World Nuclear Association, "Nuclear Power in Ukraine," March 2021, https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine.aspx#:~:text=Ukraine is heavily dependent on,by buying fuel from Westinghouse.
[41] Jessica Jewell and Elina Brutschin, "The Politics of Energy Security," *The Oxford Handbook of Energy Politics*, no. May (2021): 247–74, https://doi.org/10.1093/oxfordhb/9780190861360.013.10.
[42] Ibid. This report was written as the 2022 Russian war in Ukraine was unfolding and thus does not consider any responses by governments towards imports of Russian energy supplies.
[43] Beijing Review, "Hualong One Lays the Foundation for Homegrown Nuclear Power Technology Standards," *Beijing Review*, February 11, 2021, https://www.proquest.com/magazines/hualong-one-lays-foundation-homegrown-nuclear/docview/2486403703/se-2?accountid=13042.
[44] Swennen, *China's Energy Revolution in the Context of the Global Energy Transition*.

2050.[45] South Korea[46] is also expected to at least maintain the share of nuclear energy at 30% in its energy mix with an inflection point occurring in the government's policy from phasing out nuclear energy to reviving it.[47] The shift has come with the election of Yoon Suk-yeol as president, whose views on nuclear energy are opposite to those of the previous administration's nuclear-phase out policy of cancelling construction of new reactors and allowing current ones to age without replacements.[48] Four reactors have been in construction for several years now in South Korea by the Korea Electric Power Corporation (KEPCO). They are meant to replace ageing reactors whilst increasing the share of renewables in the energy mix. Yoon's policy to restart and continue construction of these four reactors, and possibly more to come, decreases Korea's need to rely on imported electricity, including from North Korea, China, and Russia.[49]

This idea of energy security was reaffirmed in Russia's official energy strategy to 2020 to be deeply involved in the energy sector so as to protect Russia from both internal and external threats. The official Energy Strategy of Russia for the period up to 2030 considers 'energy security is one of the most important components of the national security' and that Russia will continue 'strengthening its position in the world nuclear electric energy industry.'[50] The Kursk-II NPP, which is currently seeing the construction of two new reactors is said to be of 'strategic importance' and 'will ensure the energy security of the Central Federal District' of Russia, according to Rosatom Director General Alexei Likhachev.[51] Similar sentiments are echoed by the Indian government regarding the 'mega-project' of constructing ten domestically designed Pressurised Heavy Water Reactors (PHWR) as supporting India's 'energy security and…clean energy commitments.'[52]

In the USA, the former Secretary of Energy emphasised 'energy security, economic security,…national security' as functions of the new reactors at the Vogtle NPP.[53] These reactors are set to mark the beginning of continued investment and development in nuclear technology in order to maintain American assets and expertise in nuclear enterprise and avoid international dependency.[54]

Next to the United States, France operates the most nuclear reactors for electricity generation worldwide (56 in total compared to 93 in the USA). In France, the nuclear energy industry is considered 'the cornerstone of [France's] strategic autonomy,' according to President Emmanuel Macron.[55]

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[45] Ibid.World Nuclear Association, "Nuclear Power in China," World Nuclear Association, 2021. Accessed 10 August 2021. https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx#:~:text=Generation mix%3A 4796 TWh (66,(1.4%25) biofuels %26 waste.&text=Most of mainland China's electricity,coal – 69%25 in 2019.

[46] Henceforth, Korea.

[47] David Rogers, "South Korea's New President Wants Nuclear U- Turn," Global Construction Review, 2022, https://www.globalconstructionreview.com/south-koreas-new-president-wants-nuclear-u-turn/.

[48] Joyce Lee, "South Korea's Nuclear Power at Inflection Point as Advocate Wins Presidency," 2022, https://www.reuters.com/world/asia-pacific/skoreas-nuclear-power-inflection-point-advocate-wins-presidency-2022-03-11/; Kwon Mee-yoo, "Nuclear Phase-out Plan Emerging as Key Issue in Upcoming Presidential Election," The Korea Times, 2021, https://www.koreatimes.co.kr/www/nation/2021/07/371_312722.html.

[49] Mee-yoo, "Nuclear Phase-out Plan Emerging as Key Issue in Upcoming Presidential Election."

[50] Dellecker and Gomart, *Russian Energy Security and Foreign Policy*; Ministry of Energy of the Russian Federation, *Energy Strategy of Russia for the Period up to 2030*, *… "European Market of Energy Resources:* … (Moscow, 2010), http://www.energystrategy.ru/projects/docs/ES-2030_(Eng).pdf.

[51] Nuclear Engineering International, "Rosatom Director Checks Progress at Kursk-II NPP," Nuclear Engineering International, July 27, 2021, https://www.neimagazine.com/news/newsrosatom-director-checks-progress-at-kursk-ii-npp-8936722.

[52] Government of India, "Top Nuclear Scientists of India Welcome Government's Decision to Launch Mega-Project for 10 Indigienous Nuclear Reactors" (Deparment of Atomic Energy, 2017).

[53] U.S. Department of Energy, *Secretary Perry Speaks at the Vogtle Nulcear Power Plant in Georgia* (U.S Department of Energy, 2019), https://www.youtube.com/watch?v=r5wy6hlWBCg.

[54] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020.

[55] News Wires, "Macron Says Nuclear Will Remain Key Energy Source for France."

Continued development of France's nuclear industry also balances the risk of transferring a substantial portion of the country's energy mix to renewable energy with the ageing of many of its current reactors.[56]

The countries constructing reactors with foreign designs which consider nuclear energy to play a role in their energy security include Slovakia, Belarus, China, Finland, Iran, Pakistan, Turkey, Ukraine, and the UAE.[57] The nature of nuclear energy as a domestic electricity source enabling self-sufficiency appears attractive to new nuclear states. This can be observed with Slovakia seeking to self-contain its domestic electricity supplies and Belarus reducing its reliance on gas imports with the construction of NPPs.[58] According to the latest white paper published by the Chinese State Council, China is applying its new imported nuclear reactors to strengthen the resilience of its energy sector.[59] Finland emphasises that nuclear energy will 'reduce energy import dependency' and contribute to security of the electricity supply, especially during the winter months.[60] The stability and reliability of electricity supply from nuclear energy appears also to be a key point especially, with Iran, Pakistan, Turkey, the UK, and the UAE emphasising 'reliable electricity', a 'secure' supply of electricity, security in energy supply, 'reliable…power generation', and other similar characterisations of the role of the new reactors in their respective countries.[61]

Although excluded from the data on states currently constructing reactors, it is worth noting the position of Japan. At the time of writing, Japan has restarted ten of its reactors since 2015 and is planning to resume construction of two more in the near future.[62] The distinction between restarting construction and new construction is significant because the Japanese government decided to suspend all NPP construction after the 2011 Fukushima disaster. Construction restarts began with the Ohma NPP in 2012, which is currently suspended due to ongoing review of enhanced safety measures.[63] Motivations for the decision to restart construction were linked to energy security with the Ohma NPP characterised as a 'reliable power plant that will play an instrumental role in the stable supply of electricity and the nuclear fuel cycle of Japan.'[64]

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[56] World Nuclear News, "New Nuclear Will Ensure France's Energy Security, SFEN Says," World Nuclear News, 2020, https://world-nuclear-news.org/Articles/New-nuclear-will-ensure-Frances-energy-security-SF.
[57] See Table 1.
[58] Slovenské elektrárne, "Mochovce 3 & 4 Constructiontion," Slovenské elektrárne, 2021; BelTA, "Belarus Plans to Reduce Gas Imports," *Belarusian Telegraph Agency*, October 13, 2020, https://eng.belta.by/economics/view/belarus-plans-to-reduce-gas-imports-134186-2020/; Lucia Yar, "Slovakia Ready to Launch New Nuclear Power Plant Unit," *Euractiv*, January 27, 2021, https://www.euractiv.com/section/politics/short_news/slovakia-ready-to-launch-new-nuclear-power-plant-unit/.
[59] World Nuclear News, "China Plans Clean Energy Future," World Nuclear News, 2021, https://world-nuclear-news.org/Articles/China-plans-clean-energy-future; John Kemp, "China's Five-Year Plan Focuses on Energy Security," Reuters, 2021, https://www.reuters.com/article/us-column-china-energy-kemp-idUSKBN2BB1Y1.
[60] Afry, "Finnish Energy – Low Carbon Roadmap," 2020, https://energia.fi/files/4943/Finnish_Energy_Low_carbon_roadmap_FINAL_2020-06-01.pdf; Ministry of Economic Affairs and Employment, "The Government Granted an Operating Licence to the Nuclear Power Plant Unit Olkiluoto 3," Finnish Government, 2019, https://valtioneuvosto.fi/en/-/1410877/valtioneuvosto-myonsi-kayttoluvan-olkiluoto-3-ydinvoimalaitosyksikolle.
[61] DW Akademie, "Iran Starts Building New Nuclear Reactor at Bushehr," *DW Akademie*, October 11, 2019, https://www.dw.com/en/iran-starts-building-new-nuclear-reactor-at-bushehr/a-51192986; World Nuclear News, "2021 - May - Karachi Unit 2 Inaugurated.Pdf," *World Nuclear News*, May 21, 2021, https://world-nuclear-news.org/Articles/Karachi-unit-2-inaugurated-by-Pakistan-PM; Dilara Hamit, Havva Kara Aydin, and Elena Teslova, "Turkey's Nuclear Power Plant to Produce 10% of Electricity Need," *Anadolu Agency*, March 10, 2021, https://www.aa.com.tr/en/economy/turkeys-nuclear-power-plant-to-produce-10-of-electricity-need/2171480#; World Nuclear News, "Khmelnitsky Expansion Part of European 'Renaissance', Says Energoatom Chief," *World Nuclear News*, 2021, https://world-nuclear-news.org/Articles/Khmelnitsky-expansion-part-of-European-renaissance; Emirates Nuclear Energy Corporation, "Barakah Nuclear Energy Plant," 2021, https://www.enec.gov.ae/barakah-plant/; The Committee of Public Accounts, "The Government's Decision to Support Hinkley Point C" (House of Commons, United Kingdom, 2017), https://publications.parliament.uk/pa/cm201719/cmselect/cmpubacc/393/39306.htm.
[62] World Nuclear Association, "Nuclear Power in Japan," *World Nuclear Association.* Accessed 8 August 2021. https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx
[63] IAEA, "Under Construction Reactors," Power Reactor Information System (PRIS), 2021.
[64] World Nuclear News, "Construction of Japanese Reactor to Resume," World Nuclear News, October 1, 2012, http://www.world-nuclear-news.org/NN-Construction_of_Japanese_reactor_to_resume-0110124.html.

Japan has pursued a plan to produce a demonstration fast breeder reactor by 2025 and a commercial one by 2050, which signals a substantial motivation to lead technological development and increase Japan's energy security. There is no commercial fast breeder reactor in operation today, only experimental and demonstration reactors, which means that Japan would be among the first to do so.[65] Fast breeder reactors are also guarantors of increased energy security as they reprocess uranium and essentially breed nuclear fuel, meaning 'they are ideal for fundamentally solving the problem of nuclear fuel.'[66] However, this development process has stalled over the years with the fluctuation of the price of uranium; when it is cheaper to purchase uranium than breed it, the incentive for fast breeder reactor research and development, and especially commercialisation, wavers.[67] It is worth noting that these types of reactors have demonstrated the conversion of weapons-grade plutonium and nuclear waste to electricity, reducing the proliferation and waste associated risk from nuclear energy.[68] Fast breeder reactors are therefore ideal when uranium supply is either scarce or expensive. At the time of writing, it is neither.[69]

2.3 Foreign relationships

The state's responsibility in providing electricity as a public good as well as ensuring the responsible use of nuclear energy according to international treaties makes the state inherently involved, and representative of, motivations towards the acquisition of nuclear energy. Ultimately, the state is the customer of the energy market, and the provider of electricity to the public. This means that the relationships between states are an important factor to consider in analysing the role of nuclear energy in the global energy transition. Although, establishing the influence of foreign relationships on nuclear energy decision-making is not straightforward, it can be narrowed into three primary themes: financial export gains, generating dependency, and achieving international prestige.

Financial export gains

A rather obvious motivation for developing a country's own nuclear energy capacity is the export revenue that it can generate: the export of nuclear reactor technology and the export of electricity generated by nuclear energy. In the context of financial export gains, client states tend to focus on nuclear energy for electricity export whereas vendor states and states where nuclear technology is domestically designed tend to focus on developing new reactor technology for export.

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[65] Fast breeder reactors in operation today are either experimental or demonstration, with Russia's BN fleet at commercial scale but not commercialised. For more, see World Nuclear Association, "Fast Neutron Reactors," World Nuclear Association, 2021, https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

[66] Murakami, "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study"; Thomas Davis, "Dispelling Misconceptions of Nuclear Energy Technology: How Generation IV Nuclear Reactors Could Become the Key to Achieving the Paris Agreement and the United Kingdom's Net Zero CO2 Emissions Target by 2050," *St Anne's Academic Review (STAAR)* 11, no. 1 (2019): 34–45.

[67] Murakami, "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study."

[68] Davis, "Dispelling Misconceptions of Nuclear Energy Technology: How Generation IV Nuclear Reactors Could Become the Key to Achieving the Paris Agreement and the United Kingdom's Net Zero CO2 Emissions Target by 2050"; Bruno Merk et al., "The Current Status of Partitioning & Transmutation and How to Develop a Vision for Nuclear Waste Management," *Atw-International Journal for Nuclear Power* 64, no. 5 (2019): 261–66.

[69] Murakami, "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study." Further along the route towards fast breeder reactor demonstration and experimentation are Russia (the BN series), China (CEFR and CDFR series), India (FBTR and PFBR), and Korea (primarily KALIMER and PGSFR, a demonstrative fast burner reactor instead of breeder). For more on these, see R. D. Kale, "India's Fast Reactor Programme – A Review and Critical Assessment," *Progress in Nuclear Energy* 122, no. January (2020): 103265, https://doi.org/10.1016/j.pnucene.2020.103265; IAEA, "Power Reactor Information System (PRIS)," Power Reactor Information System, 2021, https://www.iaea.org/PRIS/home.aspx; Caroline Peachey, "Chinese Reactor Design Evolution," *Nuclear Engineering International* 59, no. 717 (2014): 16–20; Murakami, "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study."

The countries looking to gain financially from exporting electricity include Slovakia, Belarus, France, Iran, and Ukraine. Slovakia is looking to become an electricity exporter to the European Union with the capacity provided by its new VVER reactors supplied by Rosatom.[70] Belarus has expressed intentions to export electricity generated from its Astravyets NPP to the Baltic States and Ukraine.[71] Iran is a unique case in that the financial export gains from the Bushehr II reactor currently under construction are meant to be achieved by freeing up oil for export.[72] Ukraine is aiming to harness the full potential of the electricity output from its nuclear energy to become an 'energy bridge' with power lines connected from the Khmelnitsky NPP to Poland and Hungary.[73] As the world's largest net electricity exporter, France is expected to continue to use some of the electricity produced from nuclear energy to export to its neighbours, notably Italy, Germany, and the United Kingdom.[74]

The countries looking to gain financially from nuclear technology exports include Argentina, China, Russia, South Korea, and the USA. All reactors are domestically designed and being constructed as demonstrations for the commercial market. Argentina's CAREM reactor is meant to enable Argentina to become the first to commercialise SMRs for the international market.[75] China is constructing a total of seventeen reactors, of the Hualong One, ACPR-1000, CAP1400, and CFR-600 designs as well as its demonstration SMR called ACP100.[76] The ACP100 is intended to resemble Argentina's CAREM, to enable the design to be suitable for the international market and to propel China to become the first to do so. The CFR-600 is a sodium-cooled, pool-type, fast-neutron Generation IV demonstration reactor. The CAP1400 is a demonstration project as well advancing Westinghouse's AP1000.[77] The ACPR-1000 is a revised version of a French design from the 1970s and 1980s (the French 900 MWe three cooling loop design (M310)) improved to the Generation III level; it is likely that this design is intended for domestic use.[78] The Hualong One design, however, is the main Chinese export reactor being deployed today (unlike the CFR-600, CAP1400, and ACP100 which are still in the demonstration and commercialisation phase).[79] The first Hualong One entered commercial service in 2021, and has reached criticality at the Karachi NPP in Pakistan. It is being considered as a suitable reactor design for NPPs in the UK, Argentina, Romania, and Iran among others.

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[70] World Nuclear News, "New Nuclear Reactor Will Make Slovakia a Power Exporter," World Nuclear News, 2021, https://www.world-nuclear-news.org/Articles/New-nuclear-reactor-will-make-Slovakia-a-power-exp.
[71] Although it has not yet been announced at time of writing whether this policy may change in light of the 2022 Russian invasion of Ukraine. BelTA, "Energy Minister: Belarus Can Export Nuclear Power Plant's Electricity If Necessary," BelTA, 2021, https://atom.belta.by/en/news_en/view/energy-minister-belarus-can-export-nuclear-power-plants-electricity-if-necessary-11273/.
[72] DW Akademie, "Iran Starts Building New Nuclear Reactor at Bushehr."
[73] World Nuclear News, "Ukraine Must Expand Nuclear Energy , Says President," 2020, https://world-nuclear-news.org/Articles/Ukraine-must-expand-nuclear-energy-says-President; World Nuclear News, "Khmelnitsky Expansion Part of European 'Renaissance', Says Energoatom Chief."
[74] World Nuclear Association, "Nuclear Power in France," World Nuclear Association, 2022, http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/France/#.Uei-jY3_E8E.
[75] Jorge Morales Pedraza, *Small Modular Reactors for Electricity Generation : An Economic and Technologically Sound Alternative* (Cham, Switzerland: Springer, 2017).
[76] Steve Thomas, "China's Nuclear Export Drive: Trojan Horse or Marshall Plan?," *Energy Policy* 101 (2017): 683–91, https://doi.org/10.1016/j.enpol.2016.09.038.
[77] International Atomic Energy Agency, "Nuclear Power Reactors in the World" (Vienna), accessed February 9, 2022, https://nucleus-new.iaea.org/sites/graphiteknowledgebase/wiki/Guide_to_Graphite/General Design and Principles of the Advanced Gas-Cooled Reactor (AGR).aspx%0Awww.open.gov.uk.hse.nsd%0Ahttp://www-ns.iaea.org/standards/.
[78] Lovering, Yip, and Nordhaus, "Historical Construction Costs of Global Nuclear Power Reactors"; World Nuclear News, "France and China to Enhance Nuclear Energy Cooperation," World Nuclear News, January 10, 2018, http://www.world-nuclear-news.org/NP-France-and-China-to-enhance-nuclear-energy-cooperation-1001185.html; World Nuclear News, "New Nuclear Will Ensure France's Energy Security, SFEN Says"; World Nuclear Association, "Nuclear Power in France"; Boccard, "The Cost of Nuclear Electricity: France after Fukushima."
[79] Beijing Review, "Hualong One Lays the Foundation for Homegrown Nuclear Power Technology Standards"; Thomas, "China's Nuclear Export Drive: Trojan Horse or Marshall Plan?"; Xiaopeng Guo and Xiaodan Guo, "Nuclear Power Development in China after the Restart of New Nuclear Construction and Approval: A System Dynamics Analysis," *Renewable and Sustainable Energy Reviews* 57, no. December 2014 (2016): 999–1007, https://doi.org/10.1016/j.rser.2015.12.190.

The Energy Strategy of Russia for the period up to 2030 outlines 'the enhancement of the Russian nuclear technologies export potential' as an 'important component' of state strategy.[80] Russia's involvement in the nuclear technology export market is well established, and its reactors currently under construction, the VVER-TOI and the BREST-300, emphasise that involvement. The VVER-TOI is a Generation III+ reactor intended to improve the already internationally competitive VVER design. The BREST-300 is a demonstration lead-cooled fast reactor (Generation IV) with a closed fuel cycle. Generation IV reactors have not yet reached the international market and the BREST-300 may support Russia's endeavour to become the first to offer this type of reactor to Rosatom clients. Conversely, the USA is a relative newcomer to the international market for nuclear reactors despite having used nuclear energy for electricity generation for decades. For this reason, the only reactors under construction in the USA are tried and tested AP-1000 designs in Vogtle, Georgia. However the recent enabling of the Export-Import Bank (Ex-Im) to offer export credit financing for the construction of reactors is a step towards a wider aim of 'exporting best-in-class nuclear energy technology'.[81] The most likely first client of American reactor exports is Poland, where discussions on the country's first nuclear power plant have been taking place since 2021.[82]

Korea is a player to keep an eye on in the international nuclear reactor market because of the expected inflection in the government's policy towards nuclear energy with the election of president Yoon Seok-youl.[83] Although Korea has only had one foreign customer for its reactor technology thus far (the Barakah NPP in UAE), the incoming government appears to be pursuing a policy of both revived nuclear energy use domestically and increased nuclear reactor export.[84] The reactor used for export is KEPCO's APR-1400, a PWR with a 1,000MW to 1,400MW capacity with a lifetime of 40 to 60 years.[85] Given recent indications, Korea will likely focus heaviest on the European market and KEPCO, the state-owned nuclear energy corporation, will pursue winning bids for NPP construction in the Czech Republic and Poland.[86]

Influence

The dynamics between suppliers, consumers, the state, and the international nuclear regulatory regime afford a greater degree of geopolitical influence to the supplier of reactors than to the supplied/consumer state. The 'deep involvement' of governments in the nuclear energy relationship is uniquely more substantial than the more commercial and enterprise relationships in mainstream forms of energy production and consumption.[87] This is because the state is responsible for ensuring proper regulation and handling of nuclear and radioactive materials, which in turn makes the state a key player and decision maker in civil nuclear relationships. Scholarship on the connection between state foreign policy

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[80] Ministry of Energy of the Russian Federation, *Energy Strategy of Russia for the Period up to 2030*.
[81] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020.
[82] U.S. Department of Energy, "U.S. Secretary Brouillette and Poland's Minister Naimski Sign Strategic Agreement on U.S. - Poland Cooperation Towards Developing Poland's Civil Nuclear Energy Program" (Washington, D.C. and Warsaw, 2020), https://www.energy.gov/articles/us-secretary-brouillette-and-poland-s-minister-naimski-sign-strategic-agreement-us-poland; Baltic Industry, "Nuclear Reactors Are to Reduce Poland's Dependence on Coal," Baltic Industry, 2021, https://bindustry.eu/nuclear-reactors-are-to-reduce-polands-dependence-on-coal/.
[83] Also known as Yoon Suk-yeol.
[84] Rogers, "South Korea's New President Wants Nuclear U- Turn"; Byun Hye-jin, "Yoon's Pledge Signals a U-Turn from Nuclear- Free Power Policy," The Korea Herald, 2022, http://www.koreaherald.com/view.php?ud=20220313000220; Mee-yoo, "Nuclear Phase-out Plan Emerging as Key Issue in Upcoming Presidential Election"; World Nuclear News, "South Korea's AP1400 Clear for European Export," World Nuclear News, 2017, https://www.world-nuclear-news.org/Articles/South-Korea-s-AP1400-clear-for-European-export.
[85] KEPCO, "APR1400," KEPCO Engineering & Construction Company Inc., 2022, https://www.kepco-enc.com/eng/contents.do?key=1533.
[86] World Nuclear News, "South Korea's AP1400 Clear for European Export"; Rogers, "South Korea's New President Wants Nuclear U- Turn."
[87] Jane Nakano, "The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China," *Center for Strategic & International Studies*, 2020, https://doi.org/10.2298/ijgi1201125m.

and the nuclear industry finds that 'foreign policy influence' and 'nuclear commercial relationships' are linked: nuclear commerce 'serves to create or maintain diplomatic, commercial, and institutional relationships.'[88] The international supply of nuclear energy *requires* governments not only to communicate but also to cooperate, innovate, and maintain the entire nuclear endeavour for years on end. This is because there are:

- accountability structures and oversight,
- regulations (both international and domestic),
- waste management
- international and regional security norms (this is significant especially in Eastern Europe due to the Chernobyl disaster),
- repayment and loan negotiations,
- personnel exchange and training, and
- the enforcement of safety standards by both states involved and by international nuclear energy associations and multilateral organisations such as IAEA.

Intergovernmental nuclear energy relations become especially conducive to enhanced cooperation when the commercial enterprises involved are state-owned, such as Rosatom. This, combined with the realisation that private sponsorship alone does not enable competition for nuclear energy in the free market, is now fuelling new exporters, such as the United States, to adjust their approach to nuclear energy technology export.[89] The argument that vendors of nuclear reactor technology sometimes attempt to create dependencies by clients is made most often against Rosatom and Chinese state-owned nuclear energy corporations. Such intentions are rarely, if ever, acknowledged by the Russian and Chinese states or the corporations which they sponsor and own but so-called 'strategic energy exports' are noted as increasingly used as instruments of foreign policy.[90] It is therefore important to explore this issue as a potential motivation for selling nuclear reactors abroad.

Because of the relationship between the nuclear industry and the state, client states tend to consider the trustworthiness of the state associated with potential vendors of nuclear reactors in determining whether or not to cooperate with those vendors. This means that the motivations of civil nuclear corporations cannot be taken at face value as being governed by profit, the market, and commercial interests and may be intertwined with either known or unknown state policy. When vendors are owned by the state, this becomes even more of an element in the client's decision-making process because the extent to which state sponsorship is connected with the foreign policies of the state is unknown. This is especially true for Rosatom and CNNC and CGN because of ownership by their respective states and the assumption that they operate as instruments of foreign policy in certain cases.[91] Therefore, the assumption that civil nuclear corporations operate according to commercial and market motivations can be clouded when the governments of client states do not have trusting or positive relationships with the governments of vendor states. Rosatom was excluded from bidding for a tender

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[88] Ibid.
[89] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020, https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring America%27s Competitive Nuclear Advantage-Blue version%5B1%5D.pdf.
[90] Simeon Djankov, "Russia's Economy under Putin : From Crony Capitalism to State Capitalism," vol. 2, 2018, https://piie.com/sites/default/files/publications/pb/pb15-18.pdf.; "Russia Leads the World at Nuclear-Reactor Exports," article, *The Economist (Online)*, n.d.
[91] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020; Thomas P. Davis, "Could Generation IV Nuclear Reactors Strengthen Russia's Growing Sphere of Influence?'," *2019 UK PONI Papers, Royal United Services Institute*, 2019; Nakano, "The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China"; Thomas, "China's Nuclear Export Drive: Trojan Horse or Marshall Plan?"

to supply a new reactor to a nuclear power plant in the Czech Republic because of the lack of trust in the Russian government following Russia's alleged involvement in the fatal explosions that occurred at an ammunition depot in the Czech Republic in 2014. The Czech government refused to cooperate with Rosatom, although it was a corporation and not a government body.[92]

Some observers of Russian energy consider that the dominant strategy of Russian energy companies is to focus on European markets 'to build new export pipelines backed by long-term contracts, in order to strengthen dependencies by locking customers into energy purchases many years into the future.'[93] Trends have been observed in Russian energy relationships that centre on positioning Russia's future as the 'single most important supplier of energy to Europe,' maintaining control of the flow of energy in Eurasia, and eventually becoming a lead energy supplier to Asia.[94] This requires fostering 'existing dependencies through downstream investment and the renegotiation of long-term contracts on energy deliveries…'[95] One concern in this respect is that contracts for NPPs constructed by Rosatom stipulate the adjustment of interest rates every few years according to changes in the cost for Russia of offering loans on the international market.[96] This concern has not materialised in civil nuclear cooperation with Rosatom thus far because the Russian government has expressed willingness to renegotiate loan agreements over time with the client states. In Belarus, for example, the loan agreement of USD $10 billion given by Rosatom for the Astravets NPP in 2011 set a 5.23% interest rate for half of the loan with the other half at the LIBOR rate for 6-month deposits in US dollars, increased by a margin of 1.83% per year, all to be paid in 30 equal 6-monthly instalments.[97] Russia has thus far been willing to negotiate restructuring the loan several times in recent years at the request of the Belarusian government, including adjusting the repayment period from 25 to 35 years, changing the fixed interest rate to 3.3% per annum, and deferring the start date of the loan repayment.[98] Similarly, the EUR €10 billion loan from the Russian state to finance Hungary's Paks II NPP has been amended by both governments a few times, including when an amended protocol on the credit use period of the loan and the repayment period signed in 2021 by Russian Prime Minister Mikhail Mishustin was later ratified as a five-year extension by the Russian State Duma at the request of the Hungarian Finance Ministry.[99]

Conversely, concerns about China's trustworthiness as a nuclear energy partner tend to centre most on the involvement that the Chinese state may hold in the critical infrastructure of its client states, for instance nuclear power plants. Such plants are considered to be critical infrastructure for several reasons including the need to anticipate and contain the unexpected, impact severity, cross border

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[92] Vusala Abbasove, "Czech Republic Excludes Rosatom from Nuclear Tender Amid Spat with Moscow," *Caspian News*, April 20, 2021, https://caspiannews.com/news-detail/czech-republic-excludes-rosatom-from-nuclear-tender-amid-spat-with-moscow-2021-4-20-30/.
[93] Andreas Wenger et al., *Energy and the Transformation of International Relations : Toward a New Producer-Consumer Framework* (Oxford: Oxford University Press for the Oxford Institute for Energy Studies, 2009).
[94] Ibid.
[95] Ibid.
[96] Kamil and Marek Menkiszak Kłysiński, "Will the Construction of a Nuclear Power Plant in Belarus Exacerbate the Country's Energy Dependence on Russia?," *OWS Commentary*, 2012, https://www.osw.waw.pl/sites/default/files/commentary_87.pdf.
[97] Nuclear Engineering International, "Russia Restructures Loan for Belarus Nuclear Power Plant," Nuclear Engineering International, 2020, https://www.neimagazine.com/news/newsrussia-restructures-loan-for-belarus-nuclear-power-plant-7994260; UAWire, "Russia Agrees to Restructure Loan Provided to Belarus for Nuclear Power Plant Construction," *UAWire*, April 20, 2020, http://www.uawire.org/russia-agrees-to-restructure-loan-provided-to-belarus-for-nuclear-power-plant-construction.
[98] Nuclear Engineering International, "Russia Restructures Loan for Belarus Nuclear Power Plant"; UAWire, "Russia Agrees to Restructure Loan Provided to Belarus for Nuclear Power Plant Construction"; Интерфакс (Interfax), "Москва Готова Реструктурировать Кредит Минску На Строительство БелАЭС (Moscow Is Ready to Restructure a Loan to Minsk for the Construction of the Belarusian NPP)," Интерфакс (Interfax), 2020, https://www.interfax.ru/business/705101.
[99] Nuclear Engineering International, "Russia Extends Loan Period for Hungary's Paks-II," Nuclear Engineering International, 2021, https://www.neimagazine.com/news/newsrussia-extends-loan-period-for-hungarys-paks-ii-8718825; Nuclear Engineering International, "Russia Amends Loan Agreement for Paks II," Nuclear Engineering International, November 30, 2021, https://www.neimagazine.com/news/newsrussia-amends-loan-agreement-for-paks-ii-9284839; World Nuclear News, "Hungary Gets Agreement to Delay Paks II Loan Repayment," World Nuclear News, April 30, 2021, https://world-nuclear-news.org/Articles/Hungary-gets-agreement-to-delay-Paks-II-loan-repay.

effects, infrastructure complexity, the need for experienced personnel, and a strict organisational structure.[100] The United States has gone so far as to place CGN on its export blacklist in 2019 because of alleged theft by the corporation of American military technology. Ultimately, China's CNNC and CGN have been significantly hindered three times in exporting reactors because of concerns related to untrustworthiness in critical infrastructure involvement by the Chinese state.

Firstly, caution has been expressed by the UK government over the purchase of China's Hualong One design for the construction of the new nuclear power plant, Bradwell B, in Essex because of 'the approach we've seen to Huawei', the Chinese company that was banned in the UK in 2020 as a 'high risk vendor'.[101] This caution is more political then technical as approval was recently given by UK regulators in the Generic Design Assessment (a voluntary but expected process for vendors to complete) that the Hualong One design is safe and suitable for deployment.[102] However, this does not necessarily mean that it will be built, because political and security concerns may prove stronger than technical suitability. It is reported that private discussions in government indicate that the Chinese desire to place one of its reactors in the UK is futile, but no decision has been officially announced.[103]

Secondly, CGN was set to build two CANDU-6 reactors at Romania's Cernavoda NPP until Romania terminated its agreement with CGN in 2020,and instead partnered with the USA to support construction.[104] According to Romania's then prime minister Ludovic Orban, partnership with CGN was 'not going to work' whilst the US Ambassador to Romania at the time referred to the partnership as an 'existential danger' which Romania no longer needed to fear by cutting off CGN.[105]

Thirdly, the Czech Republic entirely excluded both China and Russia from bidding in its tender for the construction of a new unit at its Dukovany NPP. The decision was allegedly political as, two days earlier, eighteen Russian diplomats were expelled with the announcement that the Russian state was suspected of being involved in explosions at an ammunition depot in 2014. Reasons for excluding China from the bidding process were less specific. The Czech Industry and Trade Minister Karel Havlícek claimed that 'we are all inclined to believe that China is unthinkable as a potential supplier for us in the tender.'[106] This particular obstacle is a prime example of the lack of trust between states which, when the industries are state-owned, affects international nuclear energy cooperation. At present, China's

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[100] Cristian Aurelian Popescu and Cristina Petronela Simion, "A Method for Defining Critical Infrastructures," *Energy* 42, no. 1 (2012): 32–34, https://doi.org/10.1016/j.energy.2011.09.025.
[101] Rachel Millard, "UK Seeks to Block China from Nuclear Power Role," *The Telegraph*, 2021, https://www.telegraph.co.uk/business/2021/07/26/china-role-uk-nuclear-fleet-threat/; PA Media, "Huawei: UK Bans New 5G Network Equipment from September," *The Guardian*, November 30, 2020, https://www.theguardian.com/technology/2020/nov/30/huawei-uk-bans-new-5g-network-equipment-from-september.
[102] World Nuclear News, "UK Regulators Approve China's UK HPR1000 Design," World Nuclear News, 2022, https://www.world-nuclear-news.org/Articles/UK-regulators-approve-China-s UK-HPR1000-design.
[103] The Economist, "British Regulators Have Approved a Chinese Reactor Design," *The Economist* February 1 (2022), https://www.economist.com/britain/2022/02/12/british-regulators-have-approved-a-chinese-reactor-design; Jim Pickard and Nathalie Thomas, "UK Looks to Remove China's CGN from Nuclear Power Projects," *Financial Times* (London; Edinburgh, July 2021), https://www.ft.com/content/c4a3fe02-8535-45a4-aacf-0c4fbce8409d.
[104] World Nuclear News, "Romania Restarts Approach to New Cernavoda Units: New Nuclear," World Nuclear News, 2020, https://world-nuclear-news.org/Articles/Romania-restarts-approach-to-new-Cernavoda-units; Nuclear Engineering International, "Romania Cancels China Deal on Cernavoda but Proceeds with Life Extension," Nuclear Engineering International, 2020, https://www.neimagazine.com/news/newsromania-cancels-china-deal-on-cernavoda-but-proceeds-with-life-extension-7653710; GCR Staff, "'Existential Danger ': Romania Switches from China to US for Help in Building Reactors," Global Construction Review, 2020, https://www.globalconstructionreview.com/existential-danger-romania-switches-china-us-help/.
[105] GCR Staff, "'Existential Danger ': Romania Switches from China to US for Help in Building Reactors"; Nuclear Engineering International, "Romania Cancels China Deal on Cernavoda but Proceeds with Life Extension."
[106] Abbasove, "Czech Republic Excludes Rosatom from Nuclear Tender Amid Spat with Moscow"; Nuclear Engineering International, "Czech Republic Excludes China from Dukovany Tender," Nuclear Engineering International, 2021, https://www.neimagazine.com/news/newsczech-republic-excludes-china-from-dukovany-tender-8484373.

only external construction project is through CNNC in Pakistan, with the most probable future project to be in Argentina.[107]

Prestige

States are often motivated to adopt and increase civil nuclear technologies in order to boost their international prestige, which can be gained from the levels of technological development which the country has achieved and by associating and cooperating with vendors who are considered to be advanced in nuclear energy technology.

The states currently constructing NPPs with foreign reactors which emphasise prestige include Ukraine, Turkey, Pakistan, China, Belarus, and Bangladesh. They are all constructing Russian- or Chinese-designed reactors.[108] China is building both Russian-designed and its own design reactors. Pakistan officials heralded diplomatic relations with China at the inauguration of the Karachi NPP in 2021.[109] Bangladesh emphasises cooperation with India and Russia in describing its nuclear energy endeavours.[110] Turkey aspires to enter the 'league of nuclear energy countries' and 'become among those with nuclear power' as its four reactors currently under construction by Russia's Rosatom reach their planned start-up dates.[111] It is a partnership which President Recep Tayyip Erdogan calls 'a symbol of Turkish-Russian cooperation'.[112]

Ukraine is seeking to gain a reputation as the 'energy bridge' of Europe, solidifying its claim to a status of Europeanness, and aspiring to achieve a rank among states that are 'first' in nuclear energy in Europe and globally.[113] Despite the legacy of the Chernobyl disaster it is resilient towards 'defend[ing]' the nuclear power sector and providing reliable and safe energy to Europe.[114]

The motivation to gain prestige also applies to states constructing reactors of their own design. These include Argentina, China, India, Russia, and the USA (i.e., every country currently constructing a domestic reactor design except for France). Argentina for example is looking to 'double the size of its nuclear sector' in the coming years as a 'national project,' with potential projects using China's Hualong One design and cooperation agreements for potential future purchases from Rosatom.[115] Argentina is already among the leaders in demonstrating small modular reactors (SMRs) for electricity generation with CAREM, the country's first domestically designed reactor for electricity generation, and as a research reactor and for water desalinisation.[116] According to the Argentine government, CAREM, which became the first in the world to reach the construction stage in 2014, supports Argentina's aim

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[107] It is not uncommon for suppliers of reactors to also be clients by other suppliers (i.e. Rosatom constructs NPPs in China although both China and Russia are leading suppliers of reactors worldwide). World Nuclear News, "China and Argentina Sign Nuclear Project Deal," World Nuclear News, February 2, 2022, https://www.world-nuclear-news.org/Articles/China-and-Argentina-sign-nuclear-project-deal.

[108] See appendix.

[109] Sana Jamal, "Pakistan Prime Minister Khan Inaugurates 1,100 MW Karachi Nuclear Power Plant," *Gulf News*, May 21, 2021, https://gulfnews.com/world/asia/pakistan/pakistan-prime-minister-khan-inaugurates-1100-mw-karachi-nuclear-power-plant-1.79367020.

[110] Dipanjan Roy Chaudhury, "India, Russia, Bangladesh Sign Tripartite Pact for Civil Nuclear Cooperation," *The Economic Times*, 2018, https://economictimes.indiatimes.com/news/defence/india-russia-bangladesh-sign-tripartite-pact-for-civil-nuclear-cooperation/articleshow/63127669.cms?from=mdr.

[111] Sinem Koseoglu, "Turkey's Nuclear Power Dilemma," *Al Jazeera*, 2021, https://www.aljazeera.com/news/2021/3/10/turkeys-nuclear-dilemma; Hamit, Aydin, and Teslova, "Turkey's Nuclear Power Plant to Produce 10% of Electricity Need."

[112] Koseoglu, "Turkey's Nuclear Power Dilemma."

[113] World Nuclear News, "Ukraine Must Expand Nuclear Energy , Says President."

[114] Ibid.

[115] World Nuclear News, "Argentina Reveals Its Nuclear New Build Plans," *World Nuclear News*, August 24, 2021, https://www.world-nuclear-news.org/Articles/Argentina-reveals-its-nuclear-new-build-plans; World Nuclear Association, "Nuclear Power in Argentina," World Nuclear Association, 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/argentina.aspx.

[116] World Nuclear Association, "Nuclear Power in Argentina"; World Nuclear News, "2021 - July - Nucleoelectrica Contracted.Pdf," *World Nuclear News*, 2021, https://world-nuclear-news.org/Articles/Nucleoelectrica-contracted-to-complete-CAREM-25.

towards world leadership in SMRs.[117] Similarly, Russian-designed nuclear reactors, specifically the VVER-TOIs under construction at Kursk NPP, are intended to maintain the share of nuclear in Russia's energy mix and to demonstrate their competitiveness in the global market with eventual 'serial construction' of these reactors abroad.[118]

India's home-designed nuclear reactors are 'a shining example of Make in India,' according to the Prime Minister Narendra Modi.[119] That these reactors are 'fully indigenous' is a point continuously emphasised by officials as 'a proud symbol' of India's scientific and technological excellence.[120]

In China, the Hualong One design, whose core components, including the main pump and steam generator for each Hualong One reactor are made from domestic capability, demonstrates Chinese 'homegrown' technology manufacturing.[121]

The renewal of the United States nuclear energy programme has been portrayed as a symbol of national pride and American greatness and leadership in the international community. The two AP-1000 reactors being constructed at the Vogtle NPP in Georgia will be the first to be completed in the US in the last thirty years.[122] They serve the Biden Administration's purpose of decreasing pollution from electricity, 'increasing competition in the market,' and using existing infrastructure efficiently, especially 'carbon pollution-free energy provided by existing sources like nuclear and hydropower.'[123]

3. Nuclear energy and net zero targets

At the time of writing, thirty-two countries operate nuclear power plants for electricity generation, as shown in *Figure 5* and *Figure 6.* [124] *Figure 7* shows the percentage of nuclear energy in national electricity generation mixes. In the global context, France ranks highest with 70.6% in 2020. Slovakia and Ukraine follow with 53.1% and 51.2%, respectively. Although the United States, may produce more terawatts per hour of electricity generated from nuclear energy than other countries, its nuclear share (19.7%) is lower than many other countries.

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[117] Comisión Nacional de Energía Atómica, "Reactor argentino CAREM," National Atomic Energy Commission of Argentina. Accessed 2 August 2021. https://www.argentina.gob.ar/cnea/carem

[118] Росэнергоатом Росатом, "ВВЭР-ТОИ," Росэнергоатом Росатом, 2021, https://www.rosenergoatom.ru/development/innovatsionnye-razrabotki/razrabotka-proektov-aes-s-reaktorami-novogo-pokoleniya/vver-toi/; Росэнергоатом Росатом, "Сооружение Энергоблоков В России," Росэнергоатом Росатом, 2021, https://www.rosenergoatom.ru/stations_projects/sooruzhenie-energoblokov-v-rossii/.

[119] Anil Sasi, "Explained: What Is the Significance of Kakrapar-3?," The Indian Express, 2020, https://indianexpress.com/article/explained/kakrapar-atomic-power-project-third-unit-achieves-first-criticality-india-nuclear-mission-6518946/.

[120] Ibid.; Kale, "India's Fast Reactor Programme – A Review and Critical Assessment"; Government of India, "Top Nuclear Scientists of India Welcome Government's Decision to Launch Mega-Project for 10 Indigienous Nuclear Reactors."

[121] Beijing Review, "Hualong One Lays the Foundation for Homegrown Nuclear Power Technology Standards."

[122] U.S. Department of Energy, "Vogtle," U.S. Department of Energy Loans Programs Office, 2021, https://www.energy.gov/lpo/vogtle.

[123] The White House, "Fact Sheet: The American Jobs Plan," The White House, Briefing Room, Statements and Releases, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/.

[124] It is important to note that nuclear energy is not always used solely for electricity generation or for military purposes. Applications of nuclear energy also include agricultural, medical, industrial isotope production, transport, desalinisation, and hydrogen production.[124] As the focus of this report is on nuclear energy in the global energy transition, and since the electricity sector is the primary target of the energy transition, this report considers the electricity generation role of nuclear energy and concentrates on the non-electric applications of nuclear energy only when necessary.

Figure 5: Nuclear energy for electricity generation worldwide in 2020[125]

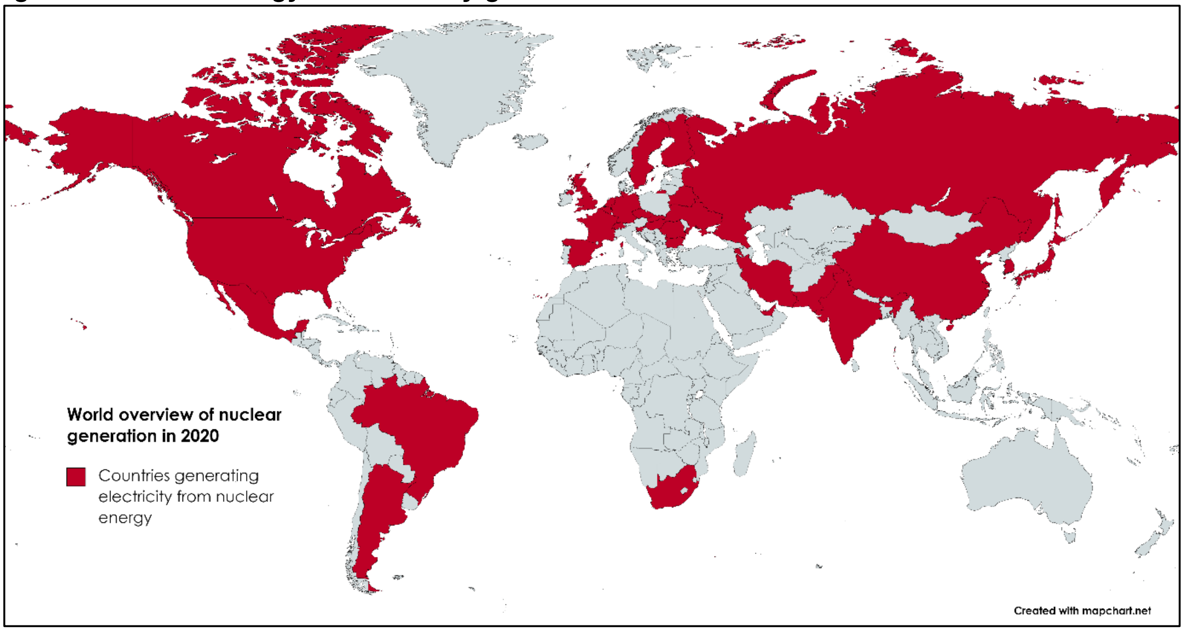
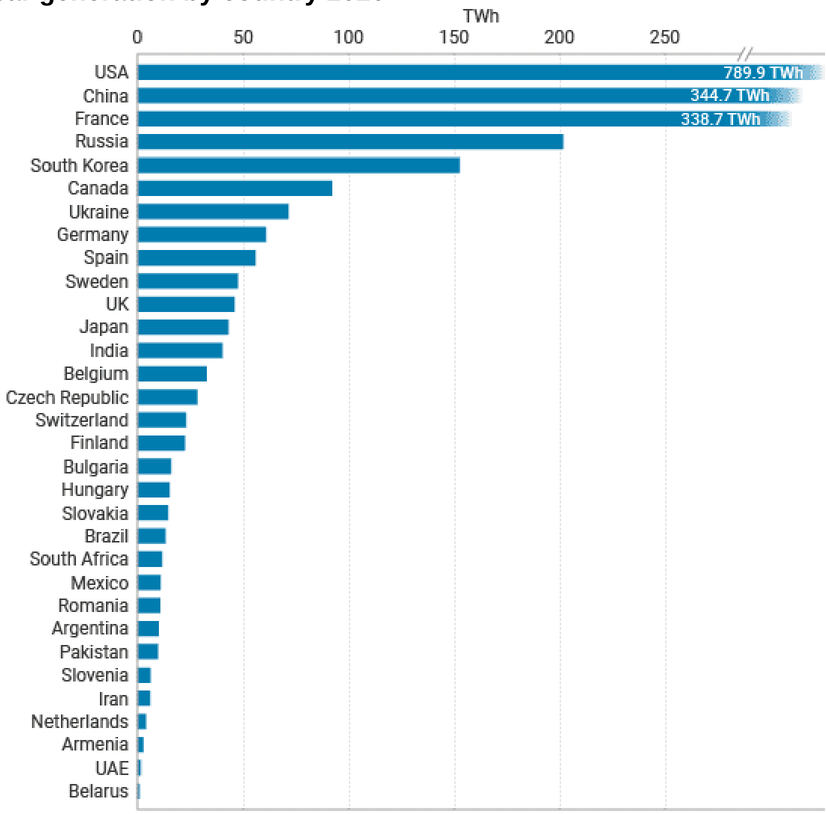


Figure 6: Nuclear generation by country 2020[126]



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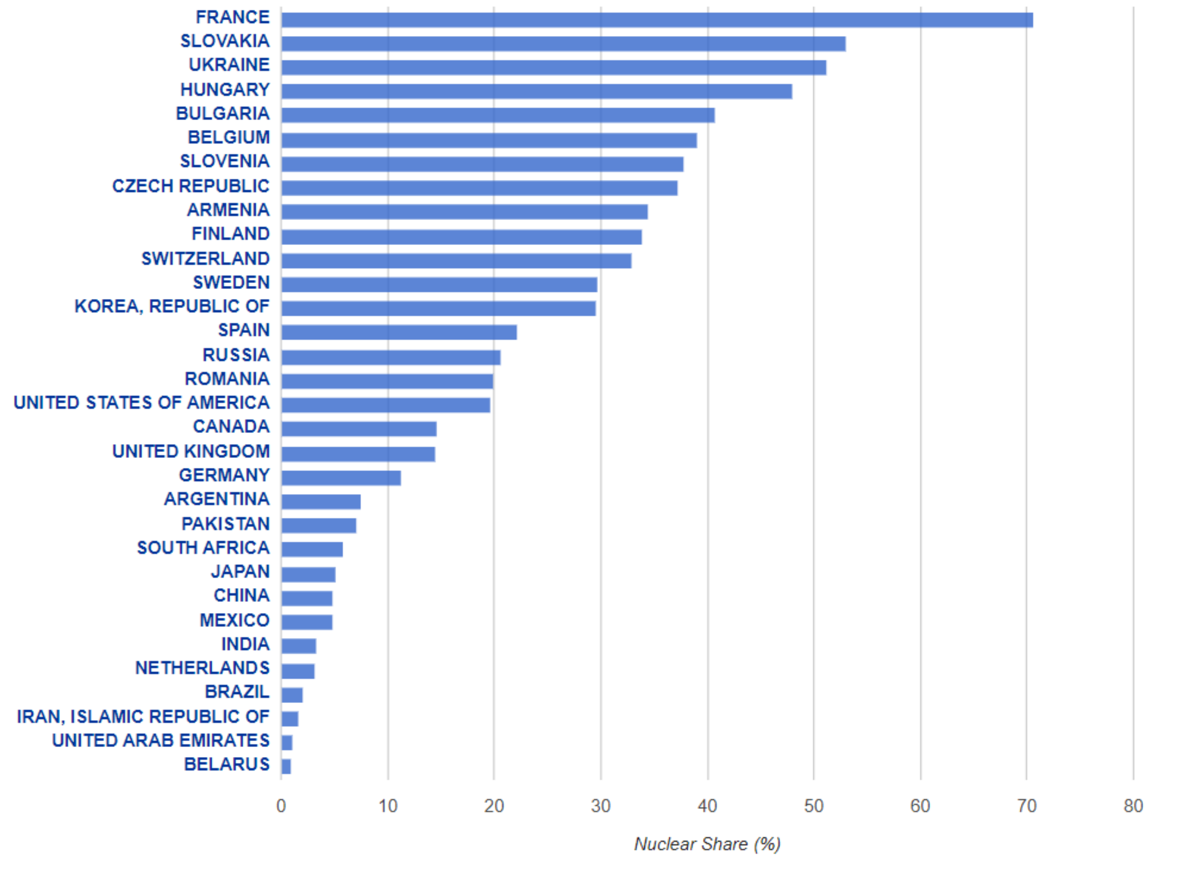
[125] Created by the author using mapchart.net with the data collected in this report.
[126] World Nuclear Association, "Nuclear Power in the World Today," World Nuclear Association, 2021, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

Figure 7: **Nuclear share of electricity generation in 2020 by country**[127]



At present, 55 reactors are under construction globally whilst 439 are currently in operation.[128] The global average age of reactors in 2019 (~32 years) reflects the increase in NPP construction during the 1970s and 1980s, the wavering of construction after the Chernobyl disaster in 1986 and again after the Fukushima Daiichi disaster in 2011.[129] After about 40 years, certain key components in a reactor need to be replaced and refurbished in order to receive renewed operating licenses towards a 50- or 60-year lifetime. Extensions vary, but typically are within the range of an additional 10 to 20 years.

According to the IEA's Outlook on Net Zero Emissions by 2050 (NZE2050), which sets out targets for achieving global net zero CO_2 emissions by this date, nuclear generation globally is expected to increase from 390.627 GWe by 36% between 2019 and 2030. In order to achieve these targets, I have calculated that approximately 235 reactors are needed in the next eight years (see Appendix). Additionally, in the UN's Intergovernmental Panel on Climate Change (IPCC) 1.5 °C Scenario, nuclear generation is forecast to increase by 60% between 2019 and 2030. This means that an additional 320 reactors, including replacement reactors for those decommissioned in this period, would need to be constructed.

Given that there are currently 55 reactors under construction globally, and assuming that they will be online by 2030 this reduces the number of new reactors that would need to be constructed and online

[127] IAEA PRIS. "Nuclear Share of Electricity Generation in 2020," IAEA Power Reactor Information System (PRIS). Accessed 23 May 2022. https://pris.iaea.org/PRIS/WorldStatistics/NuclearShareofElectricityGeneration.aspx
[128] See appendix for a global map of where these reactors are being constructed in 2022.
[129] IEA, "Nuclear Power in a Clean Energy System."

by 2030 to reach the IPCC 1.5 °C Scenario to 265. An additional 180 reactors would need to be constructed and online by 2030 in order to reach the NZE2050 Scenario (using the above assumption).

A number of reactors are already being planned, but this stage can take a few years before actual construction begins. Construction itself takes about five to ten years before a reactor goes online. This means that, although we may see a few more reactors constructed in the next eight years, both targets are very unlikely to be met by 2030. Furthermore, for countries considering or adopting nuclear energy for the first time there are a number of significant obstacles to be overcome, including the scale of investment necessary for such a major infrastructure project known for its delays, expanding construction timelines, and layers of international licensing, oversight, and coordination.[130] Although these issues are the same for everyone, the pre-existing structures, institutions, and partnerships in countries with decades of experience in operating NPPs tend to make building new nuclear facilities less challenging than for countries with little or no experience or pre-existing infrastructure who often must learn by doing. This is often the reason why investment in nuclear energy in developing economies is the responsibility of the state whilst in advanced economies, state support is balanced with private sector investment. In 2019, the IEA considered that the major delays and cost overruns of American and European NPP projects in the decade prior had 'scare[d] off' investors, with 'major design modifications' and a lack of recent industrial experience since the NPP construction wave in the 1970s causing project risks and interruptions.[131] Investment and support from the state minimises the financial risks associated with new nuclear development and reduces the need to allocate risks to potential investors, as is typically done in other energy development projects.[132]

4. Nuclear reactor providers

The most common type of reactors used today are pressurised water reactors (PWRs). The primary differences in the reactor market today are not between the reactors themselves but rather between the packages encompassing them. In a PWR the reactor core generates heat by the nuclear fission process and is cooled by high-pressured (~150-160 bar), high temperature (~275 °C) water. PWRs currently being constructed and most of those currently being used for electricity generation are considered to be Generation III and III+ reactors. To clarify, Generation I reactors were those developed in the 1950s and 1960s and are no longer developed nor in use today. Generation II reactors include those no longer being constructed but still in use, and mostly reaching their lifetime expectancies.[133] Generation IV reactors are currently under development but are not yet operating commercially.[134] They operate at higher temperatures than Generation III reactors and many are cooled by liquid sodium or lead, liquid molten salt, or gas instead of by water. For the purposes of this report, I will focus on Generation III reactors given their dominant presence in today's nuclear export market. They typically have a lifetime operating capacity of sixty years.

About thirty countries are considering purchasing or have already purchased imported reactors for the first time. (These are countries which had no prior civil nuclear power plants for electricity generation to the grid).[135] Of the twelve countries currently constructing nuclear power plants with an imported nuclear reactor design, or importing a new reactor for plants currently in operation, eight are using a Russian reactor design.[136] Finland and the United Kingdom have purchased reactors with EPR designs originating from France. The only country constructing a reactor with a Korean design is the United

[130] Ibid.
[131] Ibid.
[132] Ibid.
[133] Lifetime expectancies for some Generation II PWRs have been extended from the 40 year operational life to now 80 years with the example of US Peach Bottom units 2 and 3 (both started operation in 1974 and now will operate until 2054).
[134] These are the most widely-held definitions of the different nuclear reactor generations. However, Russia's BN-series, a fast-breeder reactor, is an outlier given that it has been in development since the 1970s and used domestically.
[135] World Nuclear Association, "Emerging Nuclear Energy Countries," World Nuclear Association, 2021, https://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx [Accessed on 26 April 2021].
[136] See the appendix.

Arab Emirates.[137] Pakistan is using China's Hualong One reactor design. Although research reactors and programmes and nuclear technology development is seen in other countries, they are excluded from this analysis because they are not provided commercially today.

Only six countries (Russia, the United States, France, Japan, China, and Korea) account for ~94% of global nuclear technology suppliers.[138] Apart from Japan they are all able to export nuclear power plants.[139]

Since the Fukushima nuclear disaster, when nuclear energy generation saw a global decline, states have begun to realise the implications of nuclear energy export for their national security strategies and economic growth. Russia and China have been exporting to global markets and developing their nuclear technology expertise for both commercial and political and strategic reasons.[140] Russian prominence in the nuclear export market is attributed to Russia's contribution to the creation of that market from 2005 onwards, prior to which there had been 'little or no market for reactors since 1990'.[141] Rosatom's low prices, financing options, and spent fuel disposal capabilities have made nuclear energy feasible for countries such as Egypt, Turkey, Vietnam, and Nigeria, whose publicly funded nuclear energy bodies had difficulty hurdling the high costs and financing for nuclear reactors.[142]

Of the countries constructing or exploring the possibility of constructing nuclear power plants, Russian and Chinese state-owned nuclear companies are leading in offering financially attractive and practically viable options.[143] Russia's Rosatom provides an unrivalled, full package supporting 'the entire nuclear fuel cycle' including construction of the plants, reactor technology, professional training, and disposal of radioactive nuclear fuel for the lifetime operation of the reactor.[144] At the time of writing, Russia leads the competition in providing offers that are attractive especially to countries with 'little experience of nuclear power…'[145] This is largely attributed to its financial, engineering, construction training, fuel supply, operation, and waste disposal and decommissioning packages offered for countries wishing to build nuclear power plants or extend the lifetime of existing reactors. Perhaps more importantly, the Russian nuclear energy industry is entirely state-owned and state-funded. This provides the Russian nuclear industry with the stability and consistent funding necessary for competing on the international market. Conversely, private nuclear ventures competing in the international market struggle to offer such attractive packages due to private investors' expectations of financial returns.[146]

This common feature of state sponsorship places Russian and Chinese nuclear energy companies at an advantage in manoeuvring and understanding the global market for nuclear reactor technologies.[147] However, compared to Russia, China lacks the decades of experience in nuclear reactor technology

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137 Although the first unit of the Barakah NPP has now been connected to the grid, the additional three Korean-designed AP-1400 units are either still under construction or not yet connected to the grid. For more see World Nuclear News, "Second Barakah Unit Starts Up," World Nuclear News, 2021, https://world-nuclear-news.org/Articles/Second-Barakah-unit-starts-up.

138 See the appendix and also Jessica Jewell, Marta Vetier, and Daniel Garcia-Cabrera, "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis," *Energy Policy* 128, no. July 2018 (2019): 838–52, https://doi.org/10.1016/j.enpol.2018.12.024.

139 Seungkook Roh, Jae Young Choi, and Soon Heung Chang, "Modeling of Nuclear Power Plant Export Competitiveness and Its Implications: The Case of Korea," *Energy* 166 (2019): 157–69, https://doi.org/10.1016/j.energy.2018.10.041.

140 B Wealer et al., "High-Priced and Dangerous: Nuclear Power Is Not an Option for The," *DIW Weekly Report* 30 (2019): 236–43, https://www.diw.de/de/diw_01.c.670590.de/publikationen/weekly_reports/2019_30/high_priced_and_dangerous_nuclear_power_is_not_an_option_for_the_climate_friendly_energy_mix.html.

141 Steve Thomas, "Russia's Nuclear Export Programme," *Energy Policy* 121, no. June (2018): 236–47, https://doi.org/10.1016/j.enpol.2018.06.036.

142 Ibid.

143 World Nuclear Association, "Emerging Nuclear Energy Countries."

144 Davis, "Could Generation IV Nuclear Reactors Strengthen Russia's Growing Sphere of Influence?'."

145 Thomas, "Russia's Nuclear Export Programme."

146 "Russia Leads the World at Nuclear-Reactor Exports." Important to note at this point is that the UK and USA have just recently begun to correct this with largescale government funding projects for private nuclear energy companies.

147 Robbie Hayunga, "Russia and China Are Expanding Nuclear Energy Exports. Can the U.S. Keep Up?," *Nuclear Energy Institute*, October 2020, https://www.nei.org/news/2020/russia-china-expanding-nuclear-exports-us-keep-up.

and innovation. Although the first reactor developed in China by the Shanghai Nuclear Engineering Research and Design Institute (SNERDI) began construction in 1985, nuclear technology development early on centred on creating Chinese versions of French reactor designs.[148] Thus, novelty and innovation in Chinese reactor designs are questionable. Unlike Rosatom, China tends to import 'a reactor design, [learns] from it and then use[s] its own and international experience and feedback to improve its own 'domestic' reactor technology.'[149]

State support means many things in the nuclear industry, among them being significant subsidies and a guaranteed source of funding.[150] State support for nuclear export programmes is considered key to achieving competitiveness in the international market, and state involvement in supporting the nuclear power industry overall has always been vital. Losses of USD $6.5 billion led to Westinghouse filing for bankruptcy in 2017. Framatome sold most of its reactor division to France's state owned nuclear corporation, EDF Energy.[151] The United States is beginning to re-expand into global markets for nuclear energy by installing and financing nuclear technology, with a recent financial boost of USD $2.5 billion by the Biden Administration to the Advanced Reactor Demonstration Program (ADRP), as well as other recent investments such as the Department of Energy's funding awards of USD $61 million to research and development of nuclear energy,.[152] It is important to bear in mind that the United States remains constrained, unlike Russia and China, in the choice of cooperation partners to those countries which are signatories of the 123 Agreements for Peaceful Cooperation.[153] The 123 Agreements restrict the proliferation of nuclear materials and ensure that the transfers of nuclear material and equipment are within the guidelines of nuclear cooperation for peaceful purposes. Forty-seven countries are signatories to the 123 Agreements.

The United States has historically been a leading developer of nuclear technology beginning with the first fully commercial PWR designed by Westinghouse in 1960.[154] Several American reactor designs have been exported since then including, in 2005. the first AP-1000 ever to be exported (to China's Sanmen NPP). However, this legacy became displaced by Russian and Chinese exports for several important reasons. The nuclear industry in the USA is owned largely by the private sector and has struggled in recent decades to remain competitive in the domestic energy market due to high up-front private capital costs of constructing NPPs. Meanwhile, state-owned nuclear power corporations in Russia and China have built multiple NPPs in recent decades funded by state-backed capital. American companies have not been able to compete with the export financing options that Russian and Chinese state-owned corporations can offer their clients. This is because, until recently, the Export-Import Bank of the United States (the agency responsible for financing and facilitating the sale of American products abroad) has only received short term reauthorisations and has been unable to offer loans of more than USD $10 million to foreign clients. The implication of this is that the American nuclear industry did not have the resources to offer enough funding for NPP projects abroad, and the short-term reauthorisations created concerns for long-term projects. However, after receiving the recent financial

[148] Thomas, "China's Nuclear Export Drive: Trojan Horse or Marshall Plan?"
[149] Peachey, "Chinese Reactor Design Evolution."
[150] Wealer et al., "High-Priced and Dangerous: Nuclear Power Is Not an Option for The."
[151] Ibid.
[152] World Nuclear News, "Congress Approves Nuclear Energy Funding for FY2021," World Nuclear News, December 23, 2020, https://world-nuclear-news.org/Articles/Congress-approves-nuclear-energy-funding-for-FY202; NEI, "Congress Continues Historic-Level Funding of Nuclear Carbon-Free Energy," NEI, December 22, 2020, https://www.nei.org/news/2020/congress-historic-funding-carbon-free-nuclear; U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020; U.S. Department of Energy, "DOE Invests $61 Million in Advanced Nuclear Energy R&D Projects Across America," U.S. Department of Energy, June 22, 2021, https://www.energy.gov/articles/doe-invests-61-million-advanced-nuclear-energy-rd-projects-across-america; World Nuclear News, "Nuclear-Supporting Infrastructure Bill Becomes US Law," World Nuclear News, November 16, 2021, https://www.world-nuclear-news.org/Articles/Nuclear-supporting-infrastructure-bill-becomes-US.
[153] National Nuclear Security Administration, "123 Agreements for Peaceful Cooperation," U.S. Department of Energy, 2021, https://www.energy.gov/nnsa/123-agreements-peaceful-cooperation.
[154] World Nuclear Association, "Outline History of Nuclear Energy," World Nuclear Association, 2020, https://world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx.

boost from Congress, the most significant development in 2020 has been the reauthorisation by Congress for the Export-Import Bank to include nuclear technology in the exports for which Ex-Im can provide financing to foreign customers.[155] Because of this reauthorisation, the United States is now involved in the Polish civil nuclear programme to reduce Poland's dependence on coal as well as reach its goal of increasing the share of renewable energy electricity generation from 13% to 23% by 2030.[156] Poland is increasingly avoiding coal as an energy source and seeking to replace it with a nuclear energy programme, and with a 23% share of its energy mix to be generated from renewables, mostly wind energy (up from 13% in 2021).[157] Under the Strategic Agreement by the United States and Poland on 'Cooperation Towards Developing Poland's Civil Nuclear Energy Program,' the U.S. will supply technology and financing options for Poland's first nuclear power plant.[158] This is the first major step by the U.S. into the global nuclear energy export market since the Fukushima nuclear disaster.

However, Russia's Rosatom remains the leader in international NPP construction and reactor export, with state ownership enabling the corporation to offer competitive financing options to prospective clients. The main reactor exported by Russia is the VVER series, designed with a service life of sixty years and currently being constructed in Belarus, India, Bangladesh, Turkey, Iran, and China.[159] Iran and India have purchased VVER-1000 Generation III reactors with a capacity of approximately 1,000 MWe each. It is the most common VVER design in operation today.[160] The VVER-1200, a Generation III+, has been purchased by Belarus, Bangladesh, Turkey, and China, and has a capacity of 1,100-1,200 MWe. VVER reactor designs have little technological difference from other PWRs on the market (the primary distinguishing factor among reactors is the package that is offered with them). Of the technical differences that do exist, Rosatom lists high-capacity pressurisers, horizontal steam generators, hexagonal fuel assemblies, and the fact that the reactor is not penetrated from the bottom.[161] Pressurisers regulate the primary cooling system for the reactor, and the VVER design allows for a large inventory of coolant. Steam generators are typically vertical in other PWR designs. The VVER's horizontal steam generators are meant to avoid issues such as denting and primary water stress-corrosion cracking.[162] The hexagonal fuel assemblies are a design trademark of VVERs as other PWR fuel assemblies are arranged in a square. However, retrofitting fuel rod assemblies is not impossible and Westinghouse has become an alternative supplier to VVER fuel assemblies to countries such as Ukraine.[163] PWR reactor pressure vessels (RPVs) are usually penetrated from the bottom head with penetration tubes, but these tubes in a VVER penetrate from the side.[164] The safety of either method is debatable as penetration from the bottom allows for tubes to benefit from gravity releasing them from the RPV in case of a core meltdown, whilst the danger of bottom penetration means that molten corium[165], which is relocated to the lower head of the RPV in a meltdown, may be discharged

[155] U.S. Congress, "Further Consolidated Appropriations Act, 2020" (2020), https://www.congress.gov/116/plaws/publ94/PLAW-116publ94.pdf.
[156] Baltic Industry, "Nuclear Reactors Are to Reduce Poland's Dependence on Coal."
[157] Ibid.; World Nuclear News, "Poland's President Hails Nuclear 'partnership' with USA," World Nuclear News, March 28, 2022, https://www.world-nuclear-news.org/Articles/Polands-president-hails-nuclear-partnership-with-U.
[158] U.S. Department of Energy, "U.S. Secretary Brouillette and Poland's Minister Naimski Sign Strategic Agreement on U.S. - Poland Cooperation Towards Developing Poland's Civil Nuclear Energy Program"; World Nuclear News, "Polish-US Civil Nuclear Agreement Enters into Force," *World Nuclear News*, March 3, 2021, https://world-nuclear-news.org/Articles/Polish-US-civil-nuclear-agreement-enters-into-forc.
[159] World Nuclear Association, "Nuclear Power in Russia," World Nuclear Association, 2021, https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx; ROSATOM Overseas, "The VVER Today: Evolution, Design, Safety."
[160] VVER-1000 is also known as AES-92 and V-412.
[161] ROSATOM Overseas, "The VVER Today: Evolution, Design, Safety."
[162] Ibid.
[163] World Nuclear News, "Energoatom Contracts Westinghouse for VVER-440 Fuel Supply," World Nuclear News, June 11, 2021, https://world-nuclear-news.org/Articles/Energoatom-contracts-Westinghouse-for-VVER-440-fue.
[164] Росэнергоатом Росатом, "ВВЭР-ТОИ."
[165] Molten corium refers to the condition of reactor core material that has been reduced to liquid form by heating. For more on this condition, see Joy L. Rempe et al., "In-Vessel Retention of Molten Corium: Lessons Learned and Outstanding Issues," *Nuclear Technology* 161, no. 3 (2008): 210–67, https://doi.org/10.13182/NT08-A3924.

into the containment environment.[166] In most PWRs, this risk is lowered by thickness of the tube and sufficient thermal margin.[167]

The primary competitive advantage of reactors on the market is less related to design and more related to the packages offered to clients. Rosatom has the ability to provide all aspects of engineering, construction, technical support of NPPs holding their reactors, front to back-end fuel cycle supply, as well as financing and loan options provided by the Russian state.[168] Rosatom calls this package its 'integrated solution' for international customers.[169] As discussed later in this report, one of the most attractive features of Rosatom's package is the option to take back spent nuclear fuel—a feature that is a major advantage to states adopting nuclear energy for the first time who would not possess the long-term storage capabilities necessary for maintaining spent nuclear fuel. Rosatom's contracts are usually based on a turnkey model, often used when the client does not hold experience in operating a nuclear reactor. This model conveys full responsibility for the NPP project, including site preparation, infrastructure, commissioning, and management, to Rosatom until the plant reaches commercial status.[170] After this point, Rosatom continues to be involved through its subsidiaries in lifetime fuel supply and waste management and in providing design expertise, advice and project design management to customers.[171] Loan repayment to Russia will ensue over this period and renegotiations of the terms and schedule are common. For example, Hungary has sought modifications to its USD $12 billion loan for two VVER-1200 reactors to delay repayment until after the reactors begin generating electricity; similarly, the Russian government agreed to restructure the loan to Belarus with an extension of the period of use, a fixed interest rate, and a deferred repayment date.[172] The cost of a Russian VVER varies depending on negotiations between parties but has been seen to range from USD $5.8 billion (India's Kudankulam NPP with type AES-92, also known as VVER-1000) to USD $13 billion (Bangladesh's Rooppur NPP with the VVER-1200 design).[173] It is important to bear in mind that the exact costs of reactors are typically kept confidential and vary from contract to contract.[174] For example, at Turkey's Akkuyu NPP, where four VVER-1200 reactors are planned to operate by 2026, Rosatom holds a 99.2% stake via its subsidiary, Akkuyu Nükleer, which is responsible for designing, constructing, maintaining, operating, and decommissioning the plant.[175] The total cost for all four reactors is estimated to reach USD $20-25 billion.[176] Conversely, Iran's Bushehr NPP provided by Rosatom and

[166] J. Jung, H. Y. Kim, and S. M. An, "Development of the Penetration Tube Failure Analysis Program in the Lower Head of the Reactor Vessel During a Severe Accident," *Nuclear Technology* 208, no. 2 (2022): 268–83, https://doi.org/10.1080/00295450.2021.1929769.
[167] Ibid.
[168] Rosatom, "Engineering and Construction," Rosatom Group, 2021, https://www.rosatom.ru/en/rosatom-group/engineering-and-construction/.
[169] Rosatom, "ROSATOM's Integrated Solution," The State Atomic Energy Coporation ROSATOM, 2022, https://www.rosatom.ru/en/integrated-offer/.
[170] IAEA, "Basic Infrastructure for a Nuclear Power Project (Tecdoc Series) No. 1513" (Vienna, 2006), https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1513_web.pdf; Nuclear Engineering International, "Russia Restructures Loan for Belarus Nuclear Power Plant."
[171] Official website of the Belarusian Nuclear Power Plant, "Spent Nuclear Fuel Management Strategy of the Belarusian NPP Approved," Department of information and public relations, Official website of the Belarusian Nuclear Power Plant, 2019, https://belaes.by/en/news/item/2485-utverzhdena-strategiya-obrashcheniya-s-otrabotavshim-yadernym-toplivom-belorusskoj-aes.html; TVEL Rosatom, "TVEL Fuel Company of Rosatom and Belarussian NPP Sign Nuclear Fuel Supply Contract," TVEL Rosatom, 2017, https://tvel.ru/en/press-center/news/?ELEMENT_ID=8176; Rosatom, "ROSATOM's Integrated Solution."
[172] Charles Digges, "Hungary Seeks to Postpone Loan Payback to Russia for Nuclear Power Plant: What Will the Final Cost Be?," Bellona, 2019, https://bellona.org/news/nuclear-issues/2019-02-hungary-seeks-to-postpone-loan-payback-to-russia-for-nuclear-power-plant-what-will-the-final-cost-be; UAWire, "Russia Agrees to Restructure Loan Provided to Belarus for Nuclear Power Plant Construction"; Nuclear Engineering International, "Russia Restructures Loan for Belarus Nuclear Power Plant."
[173] World Nuclear Association, "Nuclear Power in Russia."
[174] Ibid.
[175] World Nuclear News, "Akkuyu Construction to Be Completed by 2026, Says Project CEO," World Nuclear News, 2021, https://www.world-nuclear-news.org/Articles/Akkuyu-fully-operational-by-2026,-says-project.
[176] Ibid.; World Nuclear Association, "Nuclear Power in Russia."

equipped with a VVER-1000 reactor is reported to have cost USD $11 billion.[177] A second reactor is under construction and reportedly will cost USD $10 billion.[178]

Chinese reactor exports in the past have been based on the indigenous CNP-300 to Pakistan, but only with 300 MWe capacity, and the CAP1400 PWR based on Westinghouse's AP1000 design but made with Chinese components.[179] Today's reactor exports by China centre on promoting the Hualong One PWR with 1,150 MWe capacity. Unlike in Russia, three companies construct NPPs: the Chinese National Nuclear Corporation (CNNC), China Guangdong Nuclear (CGN), and the State Power Investment Corporation (SPIC). CNNC and CGN lead in NPP export and jointly designed the Hualong One (called HPR1000 by CGN). Two Hualong One reactors, the first to be exported, are currently under construction by CNNC at the Karachi Coastal NPP in Pakistan with an estimated cost of USD $9.6 billion.[180] At the time of writing, this is the only construction site for an NPP provided by China, with several planned and promised or under negotiation.[181] Like Rosatom, CNNC provides complete construction of NPPs and is the closest competitor to Rosatom's export capabilities. Owned by the state, CNNC reactor exports are considered to be a part of the strategic Belt and Road Initiative and enjoy financial backing which enables the corporation to offer a competitive financing option.[182] However, the competitiveness of Hualong One in the international export market has yet to fully prove itself. A major market disadvantage for Chinese companies is not being able to offer competitive export packages for reactor designs with radioactive waste and spent fuel management options as Rosatom does. Waste management by taking back spent fuel is unique to Rosatom's business model,[183] but there is as yet no fuel reprocessing facility in China capable of reprocessing spent fuel from its exported reactors. (Discussions have been in place since 2018 with France on the possibility of constructing such a facility).[184] This means that the clients must construct storage systems for long term management of spent nuclear fuel. Although interim systems are common (these are large pools which remove decay heat),[185] long term dry storage facilities are usually provided for clients of Rosatom through the repatriation of spent fuel for storage in Russia.[186] With a reactor imported from CNNC, Pakistan must design, construct, and approve its own reprocessing and storage facilities.[187]

Until recently, the United States, where nuclear energy companies are not state-owned, has not exported reactors or been involved in supplying NPPs despite being considered a leader in nuclear technology development. However, this is changing with the reauthorisation of exporting nuclear

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[177] Ali Vaez and Karim Sadjadpour, "Iran's Nuclear Odyssey: Costs and Risks" (Washington, D.C., 2013), https://carnegieendowment.org/files/iran_nuclear_odyssey.pdf.
[178] World Nuclear Association, "Nuclear Power in Iran," World Nuclear Association, 2021, http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Iran/.
[179] C.Kadak Andrew, "A Comparison of Advanced Nuclear Technologies," *Columbia SIPA*, 2017, 112, http://energypolicy.columbia.edu/sites/default/files/A Comparison of Nuclear Technologies 033017.pdf.
[180] World Nuclear Association, "Nuclear Power in China."
[181] Ibid.
[182] Nakano, "The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China"; Yan Xu, Junjie Kang, and Jiahai Yuan, "The Prospective of Nuclear Power in China," *Sustainability (Switzerland)* 10, no. 6 (2018), https://doi.org/10.3390/su10062086.
[183] Nakano, "The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China."
[184] IAEA, "Management of Spent Fuel from Nuclear Power Reactors: Learning from the Past, Enabling the Future," *IAEA Bulletin*, 2019, https://www.iaea.org/sites/default/files/bull602june20190.pdf; World Nuclear News, "France and China to Enhance Nuclear Energy Cooperation."
[185] Decay heat refers to the heat produced by decaying radioactive isotopes. For more on this, see Raymond L. Murray and Keith E. Holbert, *Nuclear Energy: An Introduction to the Concepts, Systems, and Applications of Nuclear Processes*, Eighth edi (Oxford ; Cambridge, MA, 2020); World Nuclear Association, "Safety of Nuclear Power Reactors," World Nuclear Association, 2022, http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Safety-of-Nuclear-Power-Reactors/#.UghCSj92FvA; Office for Nuclear Regulation (ONR), "Safety Assessment Principles for Nuclear Facilities," vol. Revision 1 (Office for Nuclear Regulation, 2014), https://www.onr.org.uk/saps/saps2014.pdf.
[186] Mycle Schneider and Antony Froggatt, "The World Nuclear Industry Status Report 2020" (Paris, 2020); World Nuclear Association, "Nuclear Power in Russia."
[187] Pakistan Nuclear Regulatory Authority, "Spent Nuclear Fuel Storage Facility," Pakistan Nuclear Regulatory Authority, 2021, https://www.pnra.org/pandsfacility.html.

technology by EXIM in 2019 as mentioned above.[188] American nuclear energy companies may now offer competitive loans and financing options to their clients abroad, while the US government intends to make the American nuclear industry a competitor with China and Russia in the nuclear export market.[189] As yet the United States, or American nuclear energy companies, have not secured an agreement with a foreign partner to construct an NPP or provide a reactor. Poland has yet to release a bid for vendors seeking to provide reactors and construct any NPPs, although it is likely that American companies will be involved. There have already been discussions between NuScale, a private SMR company in the USA, and Poland's KGHM on potential small modular reactors (SMRs).[190] Romania's decision to halt its agreement with China in exchange for cooperation with the US in its nuclear energy programme has led to a plan, as of November 2021, for NuScale to construct an SMR in addition to support completion of the CANDU-6 reactors at the Cernavoda NPP.[191] At the time of writing, the cost of SMR construction in either Poland or Romania has yet to be released. Such figures are usually kept confidential during negotiations and sometimes even after construction. Most recently, US company Westinghouse signed an agreement with Ukraine in November 2021 to construct five new AP1000 reactors with 1,250 MWe capacity.[192] This is the most substantial advance for American nuclear technology export in decades. Although official specifications have yet to be released project costs are expected to be USD $30 billion. It is not yet clear what additional provisions will be included in the project.

France's Framatome and EDF Energy are currently involved in constructing an Evolutionary Power Reactor (a.k.a. European Pressurised Reactor, or EPR) in Finland and two in the UK at Hinkley Point C. Like the VVER and Hualong One designs, the EPR is a PWR with a 1,750 MWe capacity (a bit more than the VVER's 1,200 MWe and the Hualong One's 1,150 MWe).[193] At present, it is estimated that Finland's EPR will cost USD ~$9.6 billion.[194] Conversely, despite being the same design, the EPR and construction at Hinkley Point C is predicted to cost USD ~$26.8 billion. However, this price tag is exceptionally high and rare, because of what is considered poor negotiating on the part of the British government with EDF Energy in 2016 about project funding.[195] Ownership of British Energy was transferred to EDF, with eight UK NPPs and a promise to construct four more, including Hinkley Point C. The guaranteed price to EDF for each unit of energy which Hinkley Point C produces was set at £92.50 per MWh, with UK taxpayers paying the difference if the wholesale price of electricity in the UK were to fall below that price.[196] Because of the inflation rate, increasing costs due to delays during the COVID-19 pandemic, and extra costs associated with the one-off construction and acquisition of supply chain capabilities and personnel training, among others have contributed to the unprecedented and unpredicted costs.[197]

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[188] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020; Ted Jones, "Congress Strengthens National Security by Boosting Nuclear Exports," Nuclear Energy Institute, 2019, https://www.nei.org/news/2019/congress-national-security-nuclear-exports.
[189] U.S. Department of Energy, "Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security," 2020.
[190] Notes from Poland, "State Firm Signs Deal with US Partner in Bid to Develop Poland's First Nuclear Power Plant," Notes from Poland, 2021, https://notesfrompoland.com/2021/09/23/state-firm-signs-deal-with-us-partner-in-bid-to-develop-polands-first-nuclear-reactor/; World Nuclear News, "Polish-US Civil Nuclear Agreement Enters into Force."
[191] World Nuclear News, "NuScale SMR Planned for Romania," World Nuclear News, 2021, https://world-nuclear-news.org/Articles/NuScale-SMR-planned-for-Romania.
[192] World Nuclear News, "Westinghouse Signs Initial Contract for Ukrainian," World Nuclear News, 2021, https://world-nuclear-news.org/Articles/Westinghouse-signs-initial-contract-for-Ukrainian.
[193] Andrew, "A Comparison of Advanced Nuclear Technologies."
[194] Nuclear Engineering International, "TVO and Areva-Siemens Reach Consensus on OL3," Nuclear Engineering International, 2021, https://www.neimagazine.com/news/newstvo-and-areva-siemens-reach-consensus-on-ol3-8757426.
[195] Holly Watt, "Hinkley Point: The 'dreadful Deal' behind the World's Most Expensive Power Plant," *The Guardian*, December 21, 2017, https://www.theguardian.com/news/2017/dec/21/hinkley-point-c-dreadful-deal-behind-worlds-most-expensive-power-plant.
[196] Ibid.
[197] Dave Harvey, "Hinkley C: Hundreds More Needed to Finish Nuclear Power Station," *BBC News*, May 25, 2021, https://www.bbc.co.uk/news/uk-england-somerset-57227918.

Korea actively markets its nuclear technology and is currently supplying two of its APR-1400 reactor designs to the United Arab Emirates. Two reactors are, at the time of writing, under construction at the Barakah NPP whilst two have already been completed there and are operating. The Barakah NPP is UAE's first and only nuclear power plant. APR-1400 reactors hold a 1,450 MWe capacity and were designed by Korea Hydro & Nuclear Power (KHNP), a subsidiary of the government-owned Korea Electric Power Corporation (KEPCO). The original contract with UAE to supply the first four reactors at the Barakah NPP as well as personnel training and support and fuel supply was set to cost USD $20.4 billion.[198] Beyond the UAE, the AP-1400 has received approval to expand into European markets.[199]

5. Conclusions

This paper is intended to highlight the importance of nuclear energy in the global energy transition debate and to aid analysis of the arguments both for and against the adoption of nuclear energy. The primary motivations for nuclear energy in the countries currently constructing nuclear power plants or purchasing reactors for electricity generation found in this report are related (one or more) to climate change, energy security, and foreign relationships, with each of these motivations holding their respective nuances.

Climate change motivations are applicable in nearly all cases, whilst energy security and foreign relationship motivations are prominent. The primary focus has been on state motivations for reactors currently under construction and identifying the differences between domestic and imported reactors for electricity generation. Further study is necessary as states continue to express interest in future research and development and engaging in the market for reactors either as vendors or clients, or in other capacities. Although some have argued that a possible motivation for adopting nuclear energy is to develop nuclear weapons capabilities, spent fuel from civil reactors does not contain weapons-grade plutonium and it is illegal for non-weapons states who have signed the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) to develop such capabilities. India, Pakistan and Israel are the only non-signatories to the NPT who hold significant unsafeguarded nuclear activities, and only India and Pakistan use nuclear energy (Israel does not have any NPPs).[200] Furthermore, both India and Pakistan have an established history of responsible civil nuclear behaviour and both of are voluntarily subjected to regular IAEA safeguards because they possess nuclear weapons.[201] Work is also needed to comparing the findings of this report with past motivations for obtaining nuclear energy capability.

In the decades ahead, it can be expected that nuclear energy for electricity generation purposes will remain a significant component of the global energy mix, with states choosing to continue or begin using nuclear energy for various reasons. The current war in Ukraine will have, and indeed already has had, an effect on how states view their energy security. This has affected governments decisions to replace oil and natural gas in their energy mix. As a result, more reliance has been placed on maintaining the current share of nuclear, accelerating the development of renewables, and accessing domestic sources

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[198] World Nuclear Association, "Nuclear Power in South Korea," World Nuclear Association, 2021, https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx; World Nuclear Association, "Nuclear Power in the United Arab Emirates," World Nuclear Association, 2021, https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-arab-emirates.aspx.

[199] World Nuclear News, "South Korea's AP1400 Clear for European Export."

[200] World Nuclear Association, "Safeguards to Prevent Nuclear Proliferation," World Nuclear Association, April 2021, http://www.world-nuclear.org/information-library/safety-and-security/non-proliferation/safeguards-to-prevent-nuclear-proliferation.aspx.

[201] Ibid.; Jeffrey S. Lantis, "Nuclear Cooperation with Non-NPT Member States? An Elite-Driven Model of Norm Contestation," *Contemporary Security Policy* 39, no. 3 (2018): 399–418, https://doi.org/10.1080/13523260.2017.1398367; T. V. Paul, Deborah Welch Larson, and William C. Wohlforth, *Status in World Politics*, *Status in World Politics*, 2014, https://doi.org/10.1017/CBO9781107444409; Nicola Leveringhaus and Kate Sullivan De Estrada, "Between Conformity and Innovation: China's and India's Quest for Status as Responsible Nuclear Powers," *Review of International Studies* 44, no. 3 (2018): 482–503, https://doi.org/10.1017/S0260210518000013; Rajesh Basrur and Kate Sullivan de Estrada, *Rising India* (London; New York: Routledge, 2017), https://doi.org/10.4324/9781315227825.

of hydrocarbons.[202] There has been an increasing call to 'rapidly reduce' the reliance on Russian natural gas imports to Europe and maximise the use of nuclear energy.[203] Therefore, it can be expected that attention towards extending the lifetimes of ageing reactors will increase in Europe in the short term and that plans to construct new NPPs will appear as long term solutions to decreasing dependence on Russian imports. At the time of writing, it is too soon to offer expectations beyond this for what exactly the crisis may mean for the role of nuclear energy and for the global energy transition as whole, but that there will be an effect is indisputable. It is on this note that the findings of this report aim to encourage another wave of analysis on a topic that could be vital for our zero-carbon future.

[202] Nathan Stirk, "Climate Change: EU Unveils Plan to End Reliance on Russian Gas," BBC News, 2022, https://www.bbc.co.uk/news/science-environment-60664799; Maev Campbell, "What Are Europe's Energy Alternatives Now That Russian Gas Is off the Cards?," Euronews, 2022, https://www.euronews.com/green/2022/03/11/europe-scrambles-to-keep-the-lights-on-as-it-sidelines-russian-gas; Nina Chestney, "Factbox: What Are Europe's Options in Case of Russian Gas Disruption?," Reuters, 2022, https://www.reuters.com/business/energy/what-are-europes-options-case-russian-gas-disruption-2022-02-15/.

[203] World Nuclear News, "Reconsider Nuclear Shutdowns to Cut Gas Imports, IEA Tells EU," World Nuclear News, March 3, 2022, https://www.world-nuclear-news.org/Articles/Reconsider-nuclear-shutdowns-to-cut-gas-imports,-I.

Appendix: Key definitions and concepts

Client states / clients: states purchasing nuclear reactor technology from a foreign corporation.

Vendor states: states with a nuclear industry, either private or state-backed, that is capable of exporting nuclear technology abroad (e.g. Russia, China, the United States, France, Korea, among others)

Vendors: corporations selling nuclear reactor technology abroad (e.g. Westinghouse, Rosatom, CGN, CNNC, among others).

Renewable energy/renewables: energy whose source is inexhaustible. This includes hydroelectricity, geothermal energy, wind energy, biomass, and solar energy.[204]

Clean energy: energy that does not emit greenhouse gases in the extraction of energy from the source. (This does not include the manufacturing process for the steel, concrete, and other material structures to build energy infrastructure. Nuclear energy is included in this definition along with renewables.[205]

IEA: International Energy Agency

IAEA: International Atomic Energy Agency

EDF: Électricité de France

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[204] This is the commonly accepted definition of renewables with my own wording applied. For similar definitions, see the following sources: https://www.edfenergy.com/for-home/energywise/renewable-energy-sources; https://dictionary.cambridge.org/dictionary/english/renewables; https://www.iea.org/fuels-and-technologies/renewables

[205] Nuclear energy is generally considered a clean source of energy, although not a renewable source of energy. See IEA, "Nuclear Power in a Clean Energy System."

Appendix: Nuclear energy and net zero targets

Below are the author's calculations of the approximate number of reactors that need to be constructed by 2030 in order for the world to be on a path to reach the NZE2050 and the IPCC 1.5 °C Scenarios. The rated electrical power outputs (GWe) of new reactor units range from 29 MWe to 1,720 MWe. Here I assume an average rated power output of 1.1 GWe for new reactors (see footnotes for more information).[206] It is also important to take into account the decommissioning of current reactors. Given that 133 reactors in operation today are more than 40 years old, it is reasonable to assume they will be decommissioned in the next decade or so. The following estimates do not include any lifetime extensions of current reactors as this is not possible to predict.

$$\boldsymbol{Commercial\ reactors\ operating\ in\ 2022 = 439\ reactors = 390.627\ GWe\ installed\ capacity}$$[207]

$$\frac{\mathbf{390.627}\ \boldsymbol{GWe}}{\mathbf{439}\ \boldsymbol{reactors}} = \mathbf{0.89}\ \boldsymbol{GWe = Average\ GWe\ installed\ capacity\ per\ reactor}$$

To calculate the additional GWe that will need to be replaced with the decommissioning of reactors that are more than 40 years old, I multiply the number of reactors (133) by today's average GWe installed capacity (0.89).

$$\mathbf{133}\ \boldsymbol{old\ reactors} * \mathbf{0.89} = \sim\mathbf{118}\ \boldsymbol{GWe\ needed\ to\ maintain\ the\ current\ average}$$

The capacities of Generation IV reactors range from above 1 GWe for Advanced Modular Reactors to up to 300 MWe for Small Modular Reactors.[208] I assume that the average GWe capacity of reactors built between now and 2030 will be 1.1 GWe. On this basis the number of reactors needed to replace the ~118 GWe that will be decommissioned would be:

$$\frac{\mathbf{118}\boldsymbol{GWe}}{\mathbf{1.1}\boldsymbol{GWe}} = \mathbf{107}\ \boldsymbol{new\ reactors\ need\ to\ replace\ ageing\ reactors}$$

NZE2050 Scenario: need 235 new reactors by 2030

According to the IEA's Outlook on Net Zero Emissions by 2050 (NZE2050), which sets out targets for achieving global net zero CO_2 emissions by this date, nuclear generation globally is expected to increase from 390.627 GWe by 36% between 2019 and 2030. In order to achieve these targets, I have calculated below that approximately 235 reactors are needed in the next eight years, as follows:

$$\mathbf{390.627}\ \boldsymbol{GWe} * \mathbf{.36} = \mathbf{140.63}\ \boldsymbol{GWe\ additional\ installed\ capacity\ by}\ \mathbf{2030}$$

Using the assumption of 1.1 GWe capacity per reactor, the estimated number of new reactors required is:

$$\left(\frac{\mathbf{140.63}\ \boldsymbol{GWe}}{\mathbf{1.1}} = \sim\mathbf{128}\ \boldsymbol{new\ reactors}\right) + \mathbf{107}\ \boldsymbol{replacement\ reactors}$$
$$= \sim\mathbf{235}\ \boldsymbol{new\ reactors\ total\ for\ NZE}\mathbf{2050}\ \boldsymbol{Scenario}$$

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[206] IAEA, "Power React. Inf. Syst."; World Nuclear Association, "Plans For New Reactors Worldwide," World Nuclear Association, 2022, https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx.

[207] At time of writing. IAEA, "Power React. Inf. Syst."

[208] Although many of them are physically smaller in size than Generation III and III+ reactors, Small Modular Reactors are defined by their output capacity according to IAEA as those with 300 MWe equivalent capacity or less.

IPCC 1.5 °C Scenario: needs 320 new reactors by 2030

Additionally, in the UN's Intergovernmental Panel on Climate Change (IPCC) 1.5 °C Scenario, nuclear generation is forecast to increase by 60% between 2019 and 2030. This means that an additional 320 reactors, including replacement reactors for those decommissioned in this period, would need to be constructed.

$$\mathbf{390.627}\ \boldsymbol{GWe} * .\mathbf{60} = \mathbf{234.38}\ \boldsymbol{GWe\ additional\ installed\ capacity\ by}\ \mathbf{2030}$$

Given that the capacity of reactors built between now and 2030 is estimated to be 1.1 GWe per reactor, the following number of new reactors are needed, including reactors needed to replace the estimated number of decommissioned reactors:

$$\left(\frac{\mathbf{234.38}\ \boldsymbol{GWe}}{\mathbf{1.1}} = \sim\mathbf{213}\ \boldsymbol{new\ reactors}\right) + \mathbf{107}\ \boldsymbol{replacement\ reactors} = \mathbf{320}\ \boldsymbol{new\ reactors\ total\ for}(\boldsymbol{IPCC})\ \mathbf{1.5}\ ^{\circ}\boldsymbol{C}\ \ \boldsymbol{Scenario}$$

Appendix: Exported nuclear power reactors under construction in 2022[209]

Country	*Location*	*Design*	*Quantity*	*Net Output Capacity*	*Origin of design — construction*
Slovakia	Mochovce NPP	VVER-440	2 reactors	440 MWe (each)	Russian design — construction jointly between Russia's Atomstroyexport and Czech and Slovak companies[210]
Bangladesh	Rooppur NPP	VVER-1200	2 reactors	1,080 MWe (each)	Russian design — Rosatom
Belarus	Astravets NPP	VVER-1200	1 reactor	1,110 MWe	Russian design — Rosatom
China	Xudabao NPP Tianwan NPP	VVER-1200	2 reactors 1 reactor	1,100 MWe (each) 1,100 MWe	Russian design — Rosatom
Finland	Olkiluoto	EPR	1 reactor	1,600 MWe	French design (Framatome and Électricité de France (EDF)) — constructed by French-German consortium Areva-Siemens
India	Kudankulam NPP	VVER-1000	4 reactors	917 MWe (each)	Russian design —Rosatom
Iran	Bushehr NPP	VVER-1000	1 reactor	915 MWe	Russian design —Rosatom
Pakistan	Karachi NPP	Hualong One (ACP1000)	1 reactor	1,014 MWe	Chinese design — China National Nuclear Corporation (CNNC)
Turkey	Akkuyu NPP	VVER-1200	4 reactors	1,114 MWe (each)	Russian design — Rosatom
Ukraine	Khmelnytskyi NPP	VVER-1000	2 reactors	1,035 MWe (each)	Russian design — construction by Energoatom (Ukrainian)
United Arab Emirates	Barakah NPP	APR-1400	2 reactors	1,345 MWe (each)	Korean design — construction by Emirates Nuclear Energy Corporation (ENEC) and design, construction and operation by Korea Electric Power Corporation (KEPCO) & consortium
United Kingdom	Hinkley Point C	EPR	2 reactors	1,630 MWe (each)	French design (EDF Energy and Framatome) — construction by EDF

209 Exported here is defined by the origin of the reactor design. The list does not included reactors that are planned for construction, only currently under construction. The table was compiled by the author using the following resources: IAEA, "Under Construction Reactors"; IAEA, "Power React. Inf. Syst."; Rosatom, "Projects," Rosatom, 2021, https://rosatom.ru/en/investors/projects/; World Nuclear Association, "Country Profiles," 2021, https://world-nuclear.org/.
210 Slovenské elektrárne, "Mochovce 3 & 4 Constructiontion."

Appendix: Motivations and the roles of exported nuclear power reactors under construction in 2021[211]

Country	*Excerpts of motivations and applications*[212]
Slovakia	• '…contributing to the EU plan of carbon neutrality by 2050'[213] • '…compensate for the capacity to…shut down…[the] Novaky lignite-burning plant…'[214] • '…become self-contained in terms of domestic electricity supplies'[215] • Export electricity generated from Slovakian reactors[216]
Bangladesh	• '…cooperation with the two countries [Russia and India] and gain from their experiences'[217] • Economic growth: 'ease the power crisis that hampers our economic activities'[218]
Belarus	• Reduce gas imports from Russia[219] • Possible electricity export[220] • '…acquire cheap energy'[221]
China	• 'exemplary project for Sino-Russian cooperation'[222] • 'create an example of global nuclear energy cooperation'[223] • Example of a 'fairer, more balanced and accessible, more open global energy management system, and offer more solutions for global energy management'[224]

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211 This table has been compiled by the author using selected excerpts characterising the main themes in official discourse. Exported here is defined by the origin of the reactor design.
212 According to the purchasing state official and elite discourse. Excluding public opinion and/or the motivations of foreign entities.
213 Yar, "Slovakia Ready to Launch New Nuclear Power Plant Unit."
214 Slovenské elektrárne, "Mochovce 3 & 4 Constructiontion."
215 Ibid.
216 World Nuclear News, "New Nuclear Reactor Will Make Slovakia a Power Exporter."
217 Chaudhury, "India, Russia, Bangladesh Sign Tripartite Pact for Civil Nuclear Cooperation."
218 BBC News, "Bangladesh Agrees Nuclear Power Deal with Russia," BBC, November 2, 2011, https://www.bbc.co.uk/news/world-asia-15552687.
219 BelTA, "Belarus Plans to Reduce Gas Imports."
220 BelTA, "Ways to Export More Belarusian Electricity to EAEU under Consideration," *Belarusian Telegraph Agency*, April 2, 2020, https://eng.belta.by/economics/view/ways-to-export-more-belarusian-electricity-to-eaeu-under-consideration-129474-2020/.
221 President of the Republic of Belarus, "Alexander Lukashenko Holds Meeting with IAEA Director General," Official Internet Portal of the President of the Republic of Belarus, 2012, http://www.president.gov.by/en/news_en/view/alexander-lukashenko-holds-meeting-with-iaea-director-general-85/.
222 Nuclear Engineering International, "Construction Begins of New Units at China's Tianwan and Xudabao NPP," *Nuclear Engineering International*, May 20, 2021, https://www.neimagazine.com/news/newsconstruction-begins-of-new-units-at-chinas-tianwan-and-xudabao-npps-8757260.
223 Ibid.
224 Ibid.

	• 'combat climate change'[225] • 'China-Russia nuclear cooperation has a great political and strategic significance. It's even more strategic than military cooperation'[226]
Finland	• Cost efficiency[227] • Security of electricity supply[228] • 'contribute to the reduction of greenhouse gas emissions'[229] • 'reduce energy import dependency' during winter months[230]
India	• Increase electricity generation capacity for domestic use[231] • 'reducing the gap in the demand and supply of energy'[232] • Climate friendly[233] • Financially attractive[234]
Iran	• 'reliable electricity'[235] • Financial and resource savings: 'saves [Iran] 11 million barrels of oil or $660 million (€599 million) per year'[236] • 'prevent the emission of more than 21 million tonnes of pollutant gasses'[237]
Pakistan	• 'risk due to climate change'[238] • 'clean, reliable and affordable power generation [to…] bring economic benefits to the country'[239] • Cooperation with China: 'China and Pakistan have been extending support to each other and cooperating in various

[225] Ibid.
[226] Chu Daye and Yang Sheng, "Xi, Putin Witness Key Nuclear Energy Project Groundbreaking; Cooperation Has Strategic Significance," *Global Times*, May 19, 2021, https://www.globaltimes.cn/page/202105/1223955.shtml.
[227] Afry, "Finnish Energy – Low Carbon Roadmap."
[228] Ibid.
[229] Ministry of Economic Affairs and Employment, "The Government Granted an Operating Licence to the Nuclear Power Plant Unit Olkiluoto 3."
[230] Ibid.
[231] Department of Atomic Energy, "Strategy for Growth of Electricity in India," Government of India, 2020, https://dae.gov.in/node/123.
[232] Ibid.
[233] Ibid.
[234] Ibid.
[235] DW Akademie, "Iran Starts Building New Nuclear Reactor at Bushehr."
[236] Ibid.; Power Engineering International, "Tehran, Moscow Begin Construction of Bushehr Nuclear Reactor," *Power Engineering International*, November 11, 2019, https://www.powerengineeringint.com/nuclear/tehran-moscow-begin-construction-of-bushehr-nuclear-reactor/.
[237] Nuclear Engineering International, "2019 - November - Work Begins.Pdf," Nuclear Engineering International, 2019, https://www.neimagazine.com/news/newswork-begins-on-unit-2-of-irans-bushehr-npp-7508058.
[238] Syed Hassan, "Pakistan's Largest Chinese-Built Nuclear Plant to Start Operating," *Reuters*, May 21, 2021, https://www.reuters.com/business/energy/pakistans-largest-chinese-built-nuclear-plant-start-operating-2021-05-21/.
[239] World Nuclear News, "2021 - May - Karachi Unit 2 Inaugurated.Pdf."

	fields including the peaceful use of nuclear energy' said at the inauguration of the Karachi NPP[240]
Turkey	• Enter the 'league of nuclear energy countries'[241] • 'symbol of Turkish-Russian cooperation'[242] • Security in energy supply[243] • Nuclear energy club? '…become among those with nuclear power in 2023…'[244]
Ukraine	• 'nuclear renaissance'[245] • Emphasis on electricity export[246] • '…be among the first [in nuclear energy], both in Europe and in the world.'[247] • Nuclear as eventual base for 'all energy in Ukraine'[248]
United Arab Emirates	• Energy mix diversification[249] • 'transition to cleaner energy sources'[250] • 'sustainable socio-economic development'[251]
United Kingdom	• 'fight against climate change' in the 'journey to net zero'[252] • 'secure' supply of electricity[253] • Financial affordability[254]

[240] Jamal, "Pakistan Prime Minister Khan Inaugurates 1,100 MW Karachi Nuclear Power Plant."
[241] Koseoglu, "Turkey's Nuclear Power Dilemma."
[242] Ibid.
[243] Hamit, Aydin, and Teslova, "Turkey's Nuclear Power Plant to Produce 10% of Electricity Need."
[244] Ibid.
[245] World Nuclear News, "Khmelnitsky Expansion Part of European 'Renaissance', Says Energoatom Chief."
[246] World Nuclear News, "Ukraine Must Expand Nuclear Energy , Says President."
[247] Ibid.
[248] Ibid.
[249] Emirates Nuclear Energy Corporation, "Barakah Nuclear Energy Plant."
[250] World Nuclear News, "UAE's First Nuclear Unit Starts Commercial Operation," *World Nuclear News*, April 6, 2021, https://world-nuclear-news.org/Articles/UAE-s-first-nuclear-unit-starts-commercial-operati.
[251] Ibid.
[252] World Nuclear News, "Hinkley Point C Delayed until at Least 2026," *World Nuclear News*, 2021, https://world-nuclear-news.org/Articles/Hinkley-Point-C-delayed-until-at-least-2026; World Nuclear News, "UK Premier Reiterates Support for Nuclear," *World Nuclear News*, July 16, 2020, https://www.world-nuclear-news.org/Articles/UK-premier-reiterates-support-for-nuclear.
[253] The Committee of Public Accounts, "The Government's Decision to Support Hinkley Point C."
[254] Ibid.; NAO, "Hinkley Point C Report," *National Audit Office*, no. June (2017), https://www.nao.org.uk/wp-content/uploads/2017/06/Hinkley-Point-summary.pdf.

Appendix: Countries constructing reactors of domestic design origin in 2022[255]

Country	***Location***	***Design***	***Quantity***	***Net Output Capacity***
Argentina	Atucha NPP[256]	CAREM-25 (SMR)	1	25 MWe
China	Shidao Bay NPP[257] Hongyanhe NPP Xiapu NPP Zhangzhou NPP Taipingling NPP San'ao NPP Changjiang NPP Changjiang NPP Fangchenggang NPP	CAP1400 ACPR-1000 CFR-600 Hualong One Hualong One Hualong One Hualong One ACP100 (SMR) Hualong One	2 1 2 2 2 2 2 1 2	1,400 MWe (each) 1,061 MWe 600 MWe (each) 1,126 MWe (each) 1,116 MWe (each) 1,117 MWe (each) 1,100 MWe (each) 125 MWe 1,000 MWe (each)
France	Flamanville NPP	EPR	1	1,630 MWe
India	Kakrapar NPP Madras NPP Rajasthan NPP	PHWR-700 PFBR IPHWR-700[258]	1 1 2	630 MWe 470 MWe 630 MWe
Russia	Kursk NPP Seversk	VVER-TOI BREST-300	2 1	1,175 MWe 300 MWe
South Korea	Shin Hanul NPP Shin Kori NPP	APR-1400 APR-1400	2 2	1,340 MWe (each) 1,340 MWe (each)
USA	Vogtle NPP	AP-1000	2	1,117 MWe (each)

[255] World Nuclear Association, "Country Profiles."
[256] CAREM is being built at an adjacent site to the Atucha nuclear power plant.
[257] Also known as Shidaowan NPP
[258] Also known as Pressurised Heavy Water Reactor (PHWR).

Appendix: Motivations and the roles of domestic design nuclear power reactors under construction in 2021[259]

Country	***Excerpts of motivations and applications***
Argentina	• Supports Argentina towards world leadership in SMRs[260] • The first SMR to reach the construction stage in 2014[261] • Enable Argentina to commercialise SMRs for the international market[262]
China	• Innovation and modernisation via nuclear power construction projects[263] • Enhance energy security and self-reliance on nuclear technology[264] • Achieve carbon neutrality[265]
France	• Maintenance of a degree of nuclear in France's energy mix as older reactors are decommissioned in good time • Support the transition to renewables
India	• Indian-ness and national pride • Ensure energy security • Meet clean energy commitments
Russia	• Maintain nuclear share in the energy mix in the 'low-carbon restructuring of Russia's energy sector.'[266] • Demonstrate VVER-TOIs for eventual export
South Korea	• '…[R]ecover the ecosystem of nuclear power generation and advance safe nuclear technologies so that they can become a core engine to drive the country'[267] • Export at least 10 NPPs abroad by 2030[268]

[259] This table has been compiled by the author using selected excerpts characterising the main themes in official discourse.
[260] Comisión Nacional de Energía Atómica, "Reactor argentino CAREM," National Atomic Energy Commission of Argentina. Accessed 2 August 2021. https://www.argentina.gob.ar/cnea/carem
[261] Ibid.
[262] Morales Pedraza, *Small Modular Reactors for Electricity Generation : An Economic and Technologically Sound Alternative*.
[263] The National People's Congress, "The 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035," The National People's Congress of China (2021). Accessed 7 August 2021. Available in Chinese online at http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm
[264] Ibid. Swennen, *China's Energy Revolution in the Context of the Global Energy Transition*; Beijing Review, "Hualong One Lays the Foundation for Homegrown Nuclear Power Technology Standards."
[265] Beijing Review, "Hualong One Lays the Foundation for Homegrown Nuclear Power Technology Standards."
[266] Vladimir Likhachev, "И Того и Другого и … Можно Без Эмоций? К Дискуссии о ВИЭ и Атомной Энергетике," *Russian International Affairs Council Analytics and Comments*, March 2021, https://russiancouncil.ru/analytics-and-comments/analytics/i-togo-i-drugogo-i-mozhno-bez-emotsiy/.
[267] Rogers, "South Korea's New President Wants Nuclear U- Turn."
[268] Ibid.

	• Reduce carbon emissions and increase energy security[269]
USA	• Begin a 'new American energy era'[270] • 'energy security, economic security,…national security'[271] • Reduce carbon emissions • 'Show the rest of the world how America leads in the energy front' and 'establish the United States as a leader in climate science, innovation, and R&D'[272]

[269] Ibid.
[270] U.S. Department of Energy, *Secretary Perry Speaks at the Vogtle Nulcear Power Plant in Georgia*.
[271] Ibid.
[272] Ibid.; The White House, "Fact Sheet: The American Jobs Plan."

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