Nuclear Innovation: China's Strategy

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The United States and France have the world's largest nuclear power fleets; Russia sells more nuclear power stations than any other country. China is catching up; it has the largest number of nuclear power plants (NPPs) built and the most NPPs under construction in the past three decades. Major powers are competing for a piece of the global market of large size Generation-III/III+ (Gen-III/III+) nuclear power reactors; they are competing in developing advanced nuclear technologies, especially small modular reactors (SMRs) with mature as well as advanced technologies. They are in a race to get their models of SMRs to the market, as part of the global competition for new energy technologies in the global transition to low-carbon energy. So far, China has been behind the global majors in GEN-III/III+ reactors and indeed missed the first wave of NPP expansion in the 21st century. It, nonetheless, is in lead in the SMR development with one model in operation and one under construction, ahead of all except Russia.

While competition in energy innovation helps shape the transformation from fossil-based to low-carbon energy systems, it is far from being a zero-sum race. Development of advanced nuclear technologies involves cooperation/collaboration and competition for several reasons: (a) nuclear energy development has always been a global enterprise with innovation taking place through technology transfers, localisation, and upgrading among firms and across borders; (b) nuclear technology development tends to be evolutionary rather than revolutionary, in contrast to other sectors where scientific breakthroughs can disrupt old markets and create new ones overnight; and (c) nuclear energy innovation is embedded in very large, complex, and capital-intensive systems; their journey from initial ideas to impact in the market place is much longer and costlier. High-risks, intensive costs, and long-lead times necessitate both cooperation and competition among researchers, entrepreneurs, firms, and governments. Cooperation and competition exhibit themselves in different fashions in staged, yet overlapping, processes: research, development, demonstration, production, and deployment.[1]

This paper examines the development of two technologies – large-size Gen-III/III+ light water pressurised nuclear reactor (PWR) technology and SMRs with mature and advanced nuclear technologies – to explain how China is engaging in nuclear innovation and why the strategies differed in the two types of technologies. It concludes that in China, more resources are devoted to developing new technologies, than upgrading the ones developed more than half a century ago, to compete for global market shares in the post 2020 era. The discussion is at the intersection of two parallel issues: one is about technologies the world needs for sustainable development and climate change mitigation, and the other is about competition over technology innovation. Over both issues, there is a great degree of anxiety over China 'getting ahead' of the US and Europe even though the general proposition of the zero-sum energy innovation has never been appropriate.[2] To examine how innovation takes place and the strategies a country adopts in various stages of energy innovation can help understand when countries can cooperate and how they can compete. After all, as economic power and influence are flowing away from fossil fuels, new sources of power emerge that are anchored in a

[1] Kelly Sims Gallagher, John P Holdren and Ambuj D Sagar, 'Energy-Technology Innovation,' *Annual Review of Environment and Resources*, 2006, 31:193-237; Richard K Lester and David M Hart, Unlocking Energy Innovation, MIT, 2012; United States Government Accountability Office, 'Nuclear Reactors" Status and Challenges in Developing and Deployment of New Commercial Concepts,' GAO, July 2015; Jim Skea, et al, *Energy Innovation for the Twenty-First Century*, Edward Elgar, 2019.

[2] Stephen J Kline and Nathan Rosenberg, 'An Overview of Innovation,' in *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, edited by Raugh Landau and Nathan Rosenberg, Washington, DC: National Academies Press, 1986, pp. 275-306.

raft of technologies, among which are advanced nuclear technologies.[3] The competition, that does not exclude cooperation, is over how to take the commanding height in the 21st century energy transformation that is already reshaping the global nuclear energy industry, the balance of high-value manufacturing capacities and international trade.

Nuclear power is divisive; not all countries decide to include it in their energy mix, nor do all those with NPPs in operation and/or under construction have active research programs on advanced nuclear technologies. A few major countries, China included, do. For this paper, therefore, it matters less whether advanced nuclear technologies turn out to be pipedreams or saviours of climate change than how countries engage in nuclear technology innovation. This analysis provides one example of the way in which China is engaging in energy technology innovation, in line with those on renewable technologies.[4] What makes the nuclear energy development different from other energy sectors is that it is highly regulated, not only by domestic and regional rules, but also by international organisations, International Atomic Energy Agency (IAEA) in particular. Any country wishing to develop a nuclear energy program needs to be approved by the IAEA; any reactor to be sold and built in another country needs to get licensed by the national regulatory agency and/or the IAEA; and any new reactor developed goes through the technology and safety review processes at the IAEA.

The three sections of this paper discuss: climate change and nuclear energy to explain why countries include nuclear power in their energy mix, and the development of Gen-III/III+ reactor technologies, and small modular reactor technologies to highlight why China missed out the global market competition so far and is determined not to do so again.

Nuclear Energy and Climate Change

International organisations, from IEA, IAEA, IMF, World Bank to many others, have provided volumes of studies, showing that in 2020-2050, more than 780 million people will need access to electricity, yet electricity production and consumption are accounting for more than half of the GHG emission globally. To meet rising demand for modern energy, total electricity generation will grow from 26,800 TWh in 2020 to over 50,000 TWh in 2050. Meanwhile, to achieve the Paris Agreement of limiting global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels, the current total solar and wind capacities would need to be quadrupled, an equivalent to adding 630GW solar and 390 GW wind each and every year in 2020-2030. By 2050, two-thirds of electricity would have to come from wind, solar, hydro, bioenergy, geothermal and other low- or zero-carbon sources of energy. Life cycle analyses of electricity generation technologies show that nuclear power is among the least carbon intensive of all technologies, on a par with hydro and wind power. Along with variable renewables nuclear power remains a key option for deep decarbonisation of more difficult liquified energy consumption in industrial processing, travelling in air, seas and roads, and building heating, 'Without nuclear investment, achieving a sustainable energy system will be much harder,' declared IEA and IAEA jointly.

As of 31 December 2020, among 442 reactors in operation in 32 countries, 94 were in the US, 56 in France and 50 in China; and among 52 NPPs under construction, 13 were in China, 7 in India and 4 in South Korea. The 442 NPPs with a total generation capacity of 392.6 GW and generated 2553.2 terawatt-hour (TWh) electricity in 2020, accounting for

[3] IRENA, *A New World: The Geopolitics of Energy Transformation*, 2019; IRENA, Geopolitics of the Energy Transformation: The Hydrogen Factor, 2022.

[4] Kelley Sims Gallagher, *The Globalisation of Clean Energy Technology: Lessons from China*, MIT Press, 2014; Gregory F Nemet, *How Solar Energy Became Cheap*, Earthscan from Routledge, 2019.

about 10% of total electricity generation, and nearly a third of world's low carbon electricity generation – indeed the largest source of carbon-free electricity generation. The average 10% of electricity from nuclear power plants however is not distributed evenly.

Top 10 nuclear producing countries (2020):

Country	Nuclear Capacity (GWe)	Nuclear generation (TWh)	Nuclear power as % of electricity	GDP (2020) US$ trillion
USA	91.5	790	19.7	20.9
France	61.4	380	70.6	2.63
China	50.8	366	4.9	14.7
Japan	31.7	43	5.1	5.06
Russia	28.6	216	20.6	1.48
South Korea	23.1	152	29.6	1.64
Canada	13.6	93	14.6	1.64
Spain	7.1	56	22.2	1.28
India	6.9	40	3.3	2.66
UK	6.8	46	14.5	2.76

Sources: information on installed nuclear capacity, electricity generation from NPPs and the share of the total electricity generation is from IAEA (https://pris.iaea.org/pris/), while the GDP in current US$ is from the world Bank (https://data.worldbank.org/indicator/NY.GDP.MKTP.CD).

On the demand side, as of the end of 2020, a total of 28 countries expressed interest in nuclear power and are considering, planning, or actively working to include it into their energy mix. Among them, ten to twelve embarking countries plan to operate NPPs by 2030-2035.

Country status	Number	Countries
First NPP under construction	4	Bangladesh, Belarus, Turkey, UAE
First NPP contract under negotiation, or signed	2	Egypt, Poland
Decision made, preparing infrastructure	6	Jordan, Kenya, Saudi Arabia, Indonesia, Vietnam (deferred), Lithuania (deferred)
Active preparation with no final decision	8	Ghana, Kazakhstan, Malaysia, Morocco, Nigeria, Philippines, Sudan, Uzbekistan
Considering nuclear power program	8	Albania, Algeria, Chile, Croatia, Thailand, Tunisia, Uganda, Uruguay

Source: IARE, 'International Status and Prospects for Nuclear Power 2021,' 16 July 2021.

Every energy technology (e.g., coal, oil, gas, wind, solar and other renewables) has its ardent supporters and knowledgeable advocates, as well as equally passionate opponents and expert adversaries. Nuclear energy is particularly divisive. Nuclear technology represents human progress for some; it is feared by many. There are widespread anxieties about radiation that is not seen or felt, about the problem of nuclear-weapons proliferation, stemming from an uneasy suspicion that a strong connection may exist between civilian nuclear energy and nuclear armaments than is willingly admitted, and increasingly about crowding out renewable sources of energy. Some countries that have developed nuclear power plants may want to phase out their nuclear power, while others who lack indigenous natural resources, and face rising electricity demand, high volatility of energy imports, and increasing pressure from climate change, believe nuclear is an option.

For the proponents: nuclear power is one of the low-carbon energy sources and NPPs produce virtually no GHG emissions or air pollutants during their operation and only very low emissions over their full life cycle; they deliver reliable and affordable electricity to support economic and social development; and death from nuclear electricity generation is a fraction of that using other energy sources. In 2013, climatologist Pushker Kharecha and James Hansen calculated the use of nuclear power between 1971 and 2009 prevented the deaths of 1.84 million people, thanks to its air-pollution benefits, and other studies identify deaths from energy production due to pollution and accidents, (2014, per TWh): brown coal (33), coal (24.5), oil (18), biomass (4.5), gas (3), nuclear (0.07), wind (0.04), hydro (0.02), solar (0.02), and biofuels (0.01).[5] In comparison with renewables, nuclear power is compact, with 90% and over utilisation rate rather than 30% and lower for solar and wind power.

Land usage for most renewable sources of electricity generation remains a main impediment for their expansion:

Overview of land use intensity relating to electricity generation

Primary energy source		Land use intensity (m^2/MWh)				
		US data	US data	EU data	UNEP	Typical
Nuclear		0.1	0.1	1.0		0.1
Natural gas		1.0	0.3	0.1	0.2	0.2
Coal	Underground	0.6	0.2	0.2		0.2
	Open cast	8.2	0.2	0.4	15.0	5.0
Renewables	Wind	1.3	1.0	0.7	0.3	1.0
	Geothermal	5.1		2.5	0.3	2.5
	Hydro (large dams)	16.9	4.1	3.5	3.3	10
	Solar PV	15.0	0.3	8.7	13.0	10
	Solar (concentrated)	19.3		7.8	14.0	15
	Biomass (from crops)	810	13	450		500

Source: United Nations Convention to Combat Desertification and International Renewable Energy Agency, 'Global Land Outlook Working Paper: Energy and Land Use,' September 2017, p.8.

Nuclear industry produces large economic multiplier effect, producing 25% more employment per unit of electricity than wind power and workers in the nuclear sector earn one-third more than those in the renewable energy industry.[6] Many other studies also show nuclear power, as an abundant, low-carbon source of base-load power, can make it easier, faster, and cheaper to mitigate global climate change and air pollution.[7]

For some nuclear opponents, NPPs have their inherent danger and risk for societies in their operation and waste management. For some nuclear sceptics, nuclear development takes time and capital, and is constrained by a country's economic conditions, comprehensive capacities and politics, and thereby it would be a waste resources to develop nuclear power as the cost of other low-carbon energy sources are either already adequate or will soon become

[5] Pushker A Kharecha and James E Hansen, 'Prevented Mortality and Greenhouse Gas Emission from Historical and Projected Nuclear Power,' *Environmental Science and Technology*, 2013, 47:4889-4895.
[6] IAEA, 'International Status and Prospects for Nuclear Power 2021,' 16 July 2021.
[7] James H Williams, et al, 'The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050,' *Science*, 2012, 335:53-59.

so. For some diehard nuclear opponents, there is no distinction between military and civilian nuclear technologies, even though they are widely used in medicine, agriculture, and other fields, and nuclear power equal nuclear proliferation and nuclear bombs.

Opposition to nuclear power is real and it can affect policies, as seen in Austria, for instance, where a national referendum held in 1978 with a slightly over 50% of the votes banned nuclear power plants in the country when it had just completed the construction of its very first NPP before it went to operation, or in Germany where the decision was made to phase out nuclear power by 2022 before they reached their lifetime in the aftermath of the Fukushima accident. Public attitudes matter a great deal in nuclear development. Public opinion towards nuclear power, however, is also shaped by how government 'frames' the issue.[8] In recent years, some, such as the Netherlands, changed their policy on nuclear because of the urgency of climate change.[9] The newly elected president in South Korea reversed the nuclear phase-out policy of his predecessor because of the potential of export markets, and, more importantly, because the nuclear energy industry is a successful story in Korean development, representing the country's comprehensive R&D and manufacturing capacities. In the United States, one argument behind the bipartisan support for investing in nuclear energy program is that: 'If we do not, then China and Russia will fill that void;' and when 'America has lost its competitive global position as the world leader in nuclear energy, [it] threatens American energy security, narrows or eliminated foreign policy options and erodes American international influence to set strong non-proliferation, safety, and security standards.'[10]

In the past two decades, China has invested heavily in nuclear energy to a large extent because of the convergence between energy development and industrial upgrading and innovation. Innovation propels nuclear power on a new trajectory with development of advanced nuclear reactor technologies. The more recent government climate change policies are also behind investment in and research on advanced nuclear energy in China. The combination of the two has shifted the narrative of nuclear development in the first decade of the century when inland nuclear development did cause concerns in some quarters of the society.[11] The focuses are on how to move up the industrial value chain, and how to make advanced nuclear technologies work in mitigating climate change. To achieve carbon peak by 2030 and carbon neutrality by 2060 in China is not a trivial challenge and nuclear energy has to be among an array of energy technologies to be developed and deployed in China, while new nuclear technologies need to be developed to alleviate public anxieties over building nuclear power plants in the neighbourhood, to meet the ambitious deep decarbonisation goals, and to manage the more difficult challenges of deep decarbonisation, such as replacing burning coal for heating and for industrial processing or replacing petroleum products for travelling. This means the proportion of nuclear power in total electricity generation would need to increase from the current 4.9% to 10-15%. In sum, industrial upgrading (or moving up the value-chain in manufacturing industries) and climate change are the joint forces behind nuclear energy development in China and in some other countries too.

Large GEN-III/III+ Light Water Reactors

Globally, some 89.5% of operational nuclear power capacity comprised light water moderated and cooled reactor

[8] Framing is such an important issue. See Anthea Roberts and Nicolas Lamp, *Six Faces of Globalisation*, Harvard University Press, 2021.
[9] 'Nuclear Energy: A Geopolitical spectre,' *Sustainability Times*, 22 December 2021.
[10] US Department of Energy, 'Restoring America's Competitive Nuclear Energy Agenda,' 2020, p.6; David K Gattie and Joshua NK Massey, 'Twenty-First-Century U.S, Nuclear Power,' *Strategic Studies Quarterly*, Fall 2020:121-42; Daniel B Poneman, 'The Case for American Nuclear Leadership,' *Bulletin of the Atomic Scientist*, 2017, 73(1):44-47.
[11] Xu Yi-chong, 'The Struggle for Safe Nuclear Expansion in China,' *Energy Policy*, 2014, 78: 21-29.

types. The US pioneered light water pressurised reactor technology (PWR) that still dominates the global market. The nuclear industry in the US in recent years has been caught up by latecomers in France, South Korea, and recently China, that have developed their own models of Gen-III PWRs reactors, competing with the American one at global markets.

As of 2022, only five models of GEN-III/III+ PWR are in operation and under construction. Except the one from Russia, all derived from the PWR technologies in the US through technology transfer and localisation and the upgrading of the transferred technology. In the 1990s, France and Germany joined forces to develop GEN-III reactors based on their PWR technology initially transferred from the US. South Korea started with turnkey projects in the 1990s with a long-term goal of developing its own technology via technology transfer, localisation and upgrading. By the end of the century, South Korea had not only built a successful nuclear industry, but also had developed its own model of reactor and manufacturing capacities to compete on global markets. China started with turnkey projects in the 1980s-1990s too. The long-term plan was to develop its own technologies through importing, learning, absorbing, and adapting foreign technologies. It was predicted that it would take at least two decades for the Chinese nuclear industry to develop the capacity to design, build and operate its own nuclear reactors. A major difference between the three latecomers was that there was a close network of players in France and South Korea – government agencies in charge of policy making, regulatory agencies, national research institutions, utility companies, and associated manufacturing firms, while in China, bitter infights and occasionally hostile rivalries among bureaucracies, nuclear operators, utility companies, equipment makers and province constantly undermined the implementation of whatever broad policies and strategies the government might have envisioned.

Design	Vendor	Country	Type	In operation	Under construction
AP 1000	Westinghouse	USA	PWR	4 (China)	2 (USA)
VVER-1200	Rosatom	Russia	PWR	5 (Russia, Belarus)	5 (Russia, Belarus, Bangladesh, Turkey)
APR 1400	KHNP	S Korea	PWR	3 (S Korea, UAE)	7 (S Korea, UAE)
EPR	EDF (Framatome)	France	PWR	3 (China, Finland)	3 (France, UK)
HPR 1000	CNNC & CGN	China	PWR	2 (China)	7 (China)

In 2003-04 the government reversed the policy of the previous government and decided to speed up nuclear energy development and in so doing to provide opportunities for the industry to develop its competitiveness and to move up in the global value chain. The strategy was to import the most advanced nuclear reactor technology available – GENIII/III+ advanced nuclear reactors – with conditions of technology transfers from international vendors so that the industry could learn and upgrade its technology. The two major nuclear companies – China National Nuclear Corporation (CNNC) and China General Nuclear Corp (previously China Guangdong Nuclear Corp, CGN) – supported government's decision to invest in nuclear expansion while strongly opposed to importing more foreign reactors as China had already hosted reactors from Canada, France, and Russia and had already development their own brands of reactors.

After more than two years of negotiations, in 2007, Westinghouse won the contract to build 2 units of AP-1000 in China with a complete technology transfer to China, while EDF took on 34% of the stakes to build two units of EPR. The construction of AP-1000 from Westinghouse and EPR from Areva started in 2009. As first-of-a-kind projects, they both encountered enormous technical challenges, serious budget overruns and project delays. The project delays opened the opportunity for the Chinese nuclear energy industry to develop its own reactor models. CNNC and CGN were 'asked' by the government to combine their resources (financial and human) and merge their own models of reactors and upgrade them into one Gen-III+ model of reactors for export markets in 2013. Despite their strong resistance, CNNC and CGN reluctantly agreed to work together and did manage to work out a joint Gen-III reactor, HPR-1000 (Hualong One) that went through IAEA safety review process in 2015.

Nuclear energy development is highly regulated not only by domestic rules and laws, but also by rules and laws elsewhere as a condition of technology transfer and industry integration. In early 2000s, IAEA developed a specific three-step procedure to help embarking countries prepare and plan for their nuclear energy program. The process would take 10 to 15 years for a country to start planning for a nuclear program to the actual construction of a power plant. One major component of this process is to establish a regulatory regime that is not only about nuclear fuel production, transport, and usage, but also about the necessary human capital, regulatory institutions, and rules on construction and operations of NPPs. Indeed, adopting nuclear safety regulations and creating compatible institutions must take place before a nuclear energy program could even start. This was the case in China – China joined IAEA in 1984, years before it started negotiating with Britain, France, and Hong Kong for its very first NPP project. With the help of IAEA and the US Nuclear Regulatory Commission (NRC), China immediately adopted its nuclear safety regulation, that was literally a carbon-copy of the one in the United States. When CNNC and CGN joined forces to design one Gen-III reactor, their designs aimed to meet European utility requirements (EUR) and US Utility Requirement Documents (URD) and went through design and safety reviews of IAEA. After a new reactor design is developed, the vendor often seeks to get the new design certified in EU or/and the US.

Seeking approvals at EU and the US agencies and at IAEA is particularly important for China for several reasons: (a) even though its nuclear industry has maintained a good safety record and never had major accident, as a latecomer China faces a reputation challenge – that is, its products, whichever models of reactors might be, have not developed a global reputation yet; (b) China, despite its nuclear development and a large fleet of NPPs, does not have one comprehensive atomic energy law. The nuclear safety law was adopted by the National People's Congress in 2018, but not the atomic energy law, whose drafting process started in 1984. Not being able to pass an Atomic Energy Law provides an interesting and important insight by itself into Chinese politics.[12] This absence makes it absolutely necessary for the Chinese companies to seek approval elsewhere. For most countries, turnkey project remains the preferred way for its nuclear development – an international vendor aligns with its sub-contractors, sells and installs a nuclear reactor and all associated facilities, and in some cases operates the NPP for some years before transferring it to the host country. It is also responsible for training skilled workers, nuclear operators, and regulators. International vendors take this very seriously as an accident anywhere in the world has serious adversary repercussions on the entire industry. HPR-1000 was initially designed for export markets and getting certified at the IAEA was critical for its

[12] In essence, the inability to enact an atomic energy law was due to the bureaucratic conflicts over who should have what responsibility over nuclear industry, or in other words, the issue whether nuclear energy is nuclear or energy has never been settled. The old State Commission for Science, Technology and Industry for National Defence (an equivalent to Defence Advanced Research Projects Agency of the DOD in the US) has been reorganised and placed under the Ministry of Industry and Information Technology (MIIT), but it maintains quite independent and has a closer tie with Ministry of defence than with NDRC. After they were incorporated, CNNC and CGN are supervised and regulated by their nominal owner as other large state-owned corporations – the State-owned Assets Supervision and Administration Commission – while their investment and pricing are regulated by NDRC, and standards are regulated by MIIT. All these ministries are under the State Council, but they could not agree who should be responsible for what. David Lampton discussed this issue very briefly in his book, *Following the Leader* (University of California Press, 2014).

potential international buyers.

International vendors have been competing for a share of global markets and all have the back-up of their government, with finance as well as diplomacy. There are only 5 or 6 models of reactors for embarking countries to choose. In addition to the above listed five PWR models, the CANDU reactor of Canada is another option that is not PWR; several countries have already imported CANDU reactors that include Argentina, China, and South Korea. In the past two decades, Russia has an advantage in selling VVER reactors because they were cheaper than the other four models. Russia has also offered fuel-packages (fuel supplies and spent-fuel buy-backs) – very few countries can. The French Areva also has the capacity to provide nuclear fuel and reprocess spent fuel, but EPR is the most expensive GEN-III reactor of the five. APR 1400 from South Korea is economically competitive, but its sales would need to get approval from the US because Section 123 of the U.S. Atomic Energy Act requires the conclusion of a peaceful nuclear cooperation agreement for significant transfers of nuclear materials and equipment to a third party. This was the condition when South Korea won the bid to build four units of APR 1400 in UAE in 2009.[13] Russia, in addition to fuel-supplies and spent-fuel buybacks, also enjoys the advantage of its close diplomatic relations with Belarus, Bangladesh, India, Turkey, and others. In all these places, the American, French, Japanese and Korean vendors had put their bids in, but lost to Russia.

In the nuclear industry, the general principle is that no new model of reactor is exported until it is built and starts commercial operation domestically. This is because the high risk and high uncertainty with the first-of-a-kind project, and costs for such projects, without exception are much higher than expected, as seen in the EPR in Finland (construction started in 2003 and the estimated cost of €3.5 and ended up with over €11 billion). This is another reason China missed the first wave of international bidding for NPPs in the past two decades. The construction of the first HPR 1000 did not start until late 2015 – way too late to catch the first wave of international biddings for NPP projects. In sum, even though CNNC and CGN wanted to 'go global,' they simply did not a brand of technology to export.

More importantly, the State Council encouraged the Chinese nuclear industry to 'go global' as a way to compel the industry to improve its productivity and competitiveness, and to build its comprehensive high value manufacturing capacities, rather than exporting its excess capacity, as seen in other energy sectors (thermal, hydro, or even renewables). Being able to compete globally on high-value equipment manufacturing was part and parcel of the government policy of the 21st century – to move up the global supply chain with innovative manufacturing.[14]

On average, 45% of a NPP project investment goes to procurement on equipment. A typical Gen-III NPP requires, for instance: 61,000 tonnes of steel, 4,00 tonnes of forgings, 200 pumps, 5,000+ valves, 210 km piping, 2,000 km cabling, and 50,000 welding seams – all of them need to be 'nuclear-grade' – higher than normal and industrial grade. According to the World Nuclear Association, 'for very large Generation III+ reactors, production of the pressure vessel requires, or is best undertaken by, forging presses of about 14-15,000 tonnes capacity which accept hot steel ingots of 500-600 tonnes.'[15] These are not common and the very heavy forging capacity in operation in the first decade of the 21st century was only in Japan, France, and Russia. When China decided to introduce Westinghouse AP 1000 in 2006,

[13] This is a sensitive issue in South Korea as there has always been opposition to the condition imposed by the US on its nuclear development. The debate over 'nuclear sovereignty' was always entangled with the military alliance with the US, even though South Korea has built a very capable and competitive civilian nuclear industry. Its manufacturing firms have been the sub-contractors to provide nuclear core vessels, steam engines and other equipment in several countries.

[14] See the discussion in Jonas Nahm, *Collaborative Advantage*, Oxford University Press, 2021, especially Chapter 5, 'China's Specialisation in Innovative Manufacturing.'

[15] World Nuclear Association, 'The World Nuclear Supply Chain,' 11 March 2014.

none of the equipment manufacturers in China, Dongfang, Shanghai and Harbin Electric, China First Heavy Industries and China National Erzhong Group, was sufficiently competitive to be the sub-constructors. Westinghouse brought in South Korea's Doosan to supply reactor pressure vessels and steam generators, Italy's Ansaldo to provide containment vessel design and fabrication, and two American subcontractors to supply reactor coolant pumps and squib valves. These high-value manufacturing capacities were what the government encouraged the Chinese manufacturers to develop, as stated cleared in the National Medium- and Long-term Program for Science and Technology Development (2006-2020), and in Made in China 2025. The nuclear industry is one piece of a broader economic strategy set in the early 2000s – the convergence of energy development and industrial upgrading.

In the midst of media-hyped reports that nuclear export was part of the Belt and Road Initiatives, many in the nuclear energy industry in China asked whether its reactor technology was ready for export. Questions asked and debated in China were: what to export – capital, equipment, technology, or brand name – and in which ways could NPPs be exported – through joint ventures with other international vendors as in Hinkley Point C project with EDF, or with local companies to export equipment as arranged initially in Argentina? In the case of Argentina, for instance, CNNC initially agreed with the Argentinian counterpart to build a NPP with a CANDU reactor – that is, to use Canadian reactor technology, CNNC was hoping to help build a domestic equipment industry in nuclear energy. This was because both China and Argentina had already CANDU reactors in operation and China had developed its capacity to build and operate CANDU reactors. This was what agreed back in 2006 after the Argentinian government decided to resume its nuclear program. A decade later, the government decided to build a nuclear power plan with GEN-III PWR reactor. This led to the agreement signed by both countries in 2022 on the HPR 1000. It is too early to tell whether and when the project will start, even though huge resource had already been invested in.

In UK, when CGN joined hands with EDF to take on the Hinkley Point C project, it was a clear case of 'exporting' capital – the Cameron government decided to re-start its nuclear program but did not commit any public finance; EDF had its EPR reactor, but its nuclear division was at the brink of bankrupt. CGN took on 35% of the stake of the project and was hoping to use it as a steppingstone to get into the UK and European markets, eventually with its HPR 1000 reactors at the Sizewell site. The cooperation between CGN and EDF goes back to the 1980s when the very first NPP was built at Daya Bay in Guangdong. In sum, 'going out' strategy in the nuclear energy sector worked quite differently from other mature sectors where the Chinese companies had not only built excess capacities but also had their comparative advantage. Finally, in both Argentina and the UK, the investment in NPPs was regulated by national and/or regional regulatory agencies. That is, every step needs to be approved, for instance, by national regulators, regional regulators (in the EU case) and by IAEA. Indeed, it took over a decade for CGN to get HPR 1000 recognised and certified in EU (2020) and in the UK (2022).

In sum, to compete for a piece of global nuclear energy market, first and foremost, China's nuclear industry would need to have a product to compete. The HPR 1000 model of reactor did not complete its safety review from IAEA until late 2014 and the construction of the first HPR 1000 in China did not start until late 2015. Transitioning from 'fast follower to 'global leader' in Gen-III.III+ nuclear reactor technologies is extremely difficult. Second, even with a product to sell, competition among international vendors was fierce. American Westinghouse, French Areva, Japanese Toshiba and Mitsubishi put in their bids globally, but never won a single deal except in China. Government financial support is only one contributor; fuel supply and spent-fuel buy-backs help. Diplomatic relationships with the host country are particularly important. While managing public opinion, or local public opposition was not part of the negotiation for international vendors, no government could ignore it.

Small Modular Reactors (SMRs) with Mature Technology

While missing out on the competition in large Gen-III/III+ reactor markets, the nuclear industry in China nonetheless has its eye for the future market – 'our focus is not on today, but on tomorrow's market,' stated the head of the nuclear association in China in 2015 and repeated by the heads of CNNC, CGN and the China Power Investment Corp (CPI), one of the three companies that were licensed to own and operate NPPs at the time. China as a latecomer in nuclear industry, is behind in large size reactor technology. It has been investing heavily in nuclear technology for the future market. Small modular reactors (SMRs) are among them. There include both SMRs with mature PWR technology, and those with advanced nuclear technologies that will not be deployable until after 2030-35. For the Chinese nuclear industry, there is a belief that finally it is able to compete with its international counterparts at the same starting line.

SMRs have the advantages over large PWRs: their small size (>300 MWe) would be suitable for many developing and emerging economies that have smaller electricity grids; their modular design would make it easier to control the product quality, shorten the site construction period and allow large size NPPs to be built gradually over some years to reduce the pressure on initial investment. Their multiple usage design would help manage deep decarbonisation by meeting the demand for district heating, seawater desalination, industrial process heating, and potentially hydrogen production – all necessary for deep decarbonisation in energy production and consumption. Because of these advantages, an increasing number of countries with or without NPPs in operation have already expressed interest in adopting SMRs technology, such as Estonia, Ghana, Jordan, Kenya, Poland, Saudi Arabia, and Sudan, and South Africa.

According to IAEA, over 50 models of SMRs are being developed, some using the mature LWR technology (Gen-III/III+), while others using Gen-IV technology with coolant system using other materials. About half of them were planned for deployment by 2030.[16] Russia is in lead in SMR development. The world's first floating SMR was deployed in the Russian Arctic port town, Pevek and has been in commercial operation since May 2020. This nuclear facility in Pevek was on a badge about the size of a city block, providing electricity and heating to the community of 4,300 people. Russia also has several SMRs with RITM-200 design operating on its fleet of nuclear-powered icebreakers. Rosatom was upgrading RITM-200 technology for land deployment of SMRs to supply electricity to isolated power systems or remote areas and consumers

Since the late 1990s, U.S. DOE increased its support for national laboratories' research on advanced reactor technologies and various SMR technologies in areas of improvement that include safety, waste generation, performance, resistance to weapon proliferation, 'modular sizes,' and integration of electric and non-electric applications (such as heat and hydrogen production.[17] More than $1.3 billion private investment was behind SMR development too under the DOE's cost-sharing arrangement. In recent years, Britain, Canada, France, and South Korea all adopted new policies in supporting the development of their own models of SMRs. Canada sees itself holding the Tier 1 position in nuclear industry globally and the new roadmap of nuclear development to 2050 is designed to 'maintain Tier I status through investment in R&D'; SMR development was a core part of the roadmap.[18] In revealing *France 2030*, French President Emanuel Macron stated at a meeting of French entrepreneurs, company leaders and university students: 'We must wage the battle of innovation and industrialisation at the same time. We must rebuild the framework for productive independence for France and Europe.' *France 2030* includes €8 billion to help develop

[16] IAEA, 'Advances in Small Modular Reactor Technology Developments,' Vienna: IAEA, September 2020.
[17] National Academies of Sciences, Engineering, Medicine, *Review od DOE's Nuclear Energy Research and Development Program*, NAP, 2008.
[18] Natural Resources Canada, ''Canadian Nuclear Roadmap to 2050 Policy Objectives,' 2021.

innovative, small-scale nuclear reactors as part of 'the battle of innovation and industrialisation at the same time.' According to Macron, innovation would be key amid global competition for leadership and in this race 'the winner takes all.'[19] What Macron said confirmed the observation of many: 'the 2020s could become the era of a big race for technology leadership' in global energy transition.[20] This is a race not only about new ideas or inventions, but about who can scale up their products and commercialise them first.

While many still wonder whether SMRs would be the fad or the future, major countries in the world are engaging in a global race over SMR technology development in 'the second nuclear era.'[21] Whoever gets its product out first controls the market and standards. This was where the Chinese nuclear industry saw its opportunity. History of technology has shown time and again that fast followers and practitioners of reverse innovation can gain considerable market share – and the nations that host them can gain a significant number of jobs and growth in income from this kind of innovation.[22]

CNNC started its concentrated R&D work on SMRs around the same time as that in the US and South Korea and ahead of some European counterparts. In 2010, CNNC formally started its work on concept development, basic and detailed designs, and third-party verification of its ACP 100 at the same time to speed up the process. Even though ACP 100 uses the mature PWR technology, it is not a matter of just shrinking the size or creating a miniature of large GEN-III reactor. There was a huge amount of research, development and demonstration (R&DD) work needed. Like other SMRs, ACP 100 is not a new technology per se, but it a new design and new way of 'packaging' that has two key advanced features: a passive safety system and the integrated reactor design.

Passive safety was especially emphasised by the entire nuclear community after the Fukushima Daiichi disaster in 2011 when human intervention was needed and one person – the only casualty – died in the intervention to cool the core reactor. A passive safety system takes advantages of natural forces or phenomena such as gravity, pressure differences or natural heat convection to accomplish safety functions without requiring an active power source for core cooling during transients. ACP100 adopts a fully passive safety system, which consists of passive core cooling system, passive residual heat removal system, passive containment heat removal system, passive inhabitation system, automatic depressurization system, and passive hydrogen control system.

An integrated design would allow all components to be included in a single vessel – the core reactor, once- through steam generators, canned motor pumps, reactor internals and all necessary parts. The integrated reactor head package of ACP 100 for instance consists of 4 main pumps and 16 once- through steam generators. The rationale behind the two key features of SMRs is to achieve safety and security in design – 'defence in design' or 'safety in design.'

The small and integrated design of ACP 100 also has the advantage in non-residential area and planned restricted zone in time of emergency. For large reactors, the non-residential area would be <500 metres, in comparison with 300 m for

[19] 'Macron unveils massive 'France 2030' green investment plan,' DW News, 12 October 2021.
[20] IRENA, 'Geopolitics of the Energy Transformation: The Hydrogen Factor,' Abu Dhabi, 2022, p.22.
[21] DT Ingersoll, 'Deliberately small reactors and the second nuclear era,' *Progress in Nuclear Energy*, 2009, 51:589-603.
[22] The best example would be solar PV panel manufacturing. By 2019, solar PV module shipments from China had reached 63% of the global total, even though the technology had initially been developed in the US and other advanced economies. Scaling up and commercialisation of a technology is part and parcel of the entire process of innovation. See the discussion in Richard K Lester and David M Hart, *Unlocking Energy Innovation*, MIT Press, 2012; Marine Hadengue, Nathalie de Marcellis-Warin and Thierry Warin, 'Reverse Innovation: A Systematic Literature Review,' *International Journal of Emerging Markets*, 2017, 12(2): 142-182.

ACP 100, planned restricted areas for large reactors is <5 km while that for ACP 100 is >800 meres; and internal zone for emergency plan zone for large reactors is 3-5 km, while that for ACP 100 is less than 400 m; and external zone of emergency plan zone for large reactors is about 7-10 km while that for ACP 100s is 3~5 km. In other words, the limited non-residential area and emergency zone make it possible for SMRs to be built in inland provinces in China where population density is high – a heated debate topic in China.

CNNC started working on ACP 100 in part for inland provinces, but more for the market in the Middle East and North African region where not only the demand for electricity was rising quickly, but also water shortages threatened livelihoods and the economy. One main usage of SMRs was for water desalination. SMR research speeded up after the Fukushima nuclear melt down as the future of large size NPPs became so uncertain. CNNC suddenly saw the potential opportunity in leading SMR development. Research on NuScale, an American designed model of SMR, had started in the lab at Oregon State University in early 2000 and a decade later, the research moved to the Idaho National Laboratory with the cost-sharing arrangement and other support from DOE. However, uncertainty of funding and long and costly certification processes were long considered a major hurdle for new reactor design development.[23]

CNNC decided to compete in speed. It undertook R&DD activities simultaneously. For instance, 18 special demonstration works were under way at the same time in 2010 to allow the designers to get the firsthand data to start the first round of design. In the following four years, it went through various stages of design, preliminary safety analysis, and the third-party (National Nuclear & Radiation Safety Centre) verifications at the same time. This allowed CNNC to start preparing the generic reactor safety review to be submitted to IAEA in 2015. In April 2016, IAEA completed ACP 100 generic reactor safety review, the very first SMR in the world that went through the review process at IAEA.

This IAEA safety review process was not as important for other advanced economies as for China. As it is discussed above, the stringent regulations in EU and the US are often taken as the global standards. Whenever the Chinese engineers design reactors, (ACP 100 was only one of them) they aim to meet the regulations and standards set at EU and US. The absence of a comprehensive atomic energy law in China means that the Chinese nuclear energy industry needs the legitimacy and a ticket from elsewhere to be able to compete on a global market. IAEA offers the open opportunity for the Chinese companies to do so. Of course, before any reactor to be built in a country, it needs to get licensed by the hosting country's regulatory agency too. This is reason CGN applied for licensing of HPR 1000 in both Britain and in EU, or Korea's APR 1400 tried to do in the US.

In the following three years after the IAEA review in 2016, CNNC did more demonstration work until ACP 100 was approved as a project to be built in Hainan Island, next to two units of HPR 1000. The construction of ACP began in 2021. CNNC now argues that ACP 100 can be part of the 'going out' project because it controls not only the design, but also is able to manufacture all components, including reactor pressure vessel, once-through steam generator, shielded primary pump, pressuriser, etc. Except for Russia, only Argentina had one micro reactor (CAREM-25) under construction since 2014. CNNC hopes ACP 100 is ahead of the game vis-a-via other SMRs.

Immediate deployable (2006-2020) in operation or under	Near-Term deployable (2020-2040) Certified or at advanced design	Mid- to long-term deployable (2028-2050+) Conceptual design for future

[23] GAO, 'Nuclear Reactor,' July 2015; Hearing on U.S. Leadership in Nuclear Energy and the Nuclear Energy Leadership Act, US Senate Committee on Energy and Natural Resources, 30 April 2019.

construction	stage	deployment
In Operation: Russia: KLT-40S China: HTR-PM (20/12/2021) Under construction: Argentina: CAREM-25 (08/02/2014) China: ACP 100 (07/07/2021)	South Korea: Smart Russia: RITM 200; ABV-6M; SVBR100; BREST300-OD South Africa: PBMR 400 Japan: 4S; GTHTR300 USA: NuScale; mPower	India: AHWR300 France: Flexible; SG-HTGR Italy: IRIS Japan: DMS; IMR Russia: VVER-300; VK-300 South Africa: TH-100 US: Westinghouse SMR; G4M; SMR160

Development of ACP 100 represents one way of innovation – adapting and upgrading mature technology to compete when market is looking for alternative products. It follows the similar path of wind and solar technology development in China. Neither technology was developed initially in China. Technologies 'regularly and frequently cross borders through a diversity of channels, including foreign direct investment, formation of joint ventures, licensing, consulting contracts, and joint research and development (R&D).'[24] When they do, they then need a willingness to invest in the continuing process of innovation – R&DD, commercialisation, scaling up and marketisation. This is the stage where risks are high, and rewards are uncertain.[25] This is where China has shown the concerted government policies in supporting the technology upgrading and scaling up. It is still too early to tell whether ACP 100 will be able to follow wind, solar and electrical vehicle to succeed in the global commercialisation of cleaner energy technologies. The pattern nonetheless is similar.[26]

Small Modular Reactors (SMRs) with Advanced Technologies

The development of the world's first land-based high temperature gas cooled reactor (or high temperature reactor, HTR, in short) tells a different story about nuclear innovation and how China is seeking the next general reactor technologies. In 200s, US DOE and its counterparts from 9 countries provided a technology roadmap for the so-called Generation-IV nuclear reactor technologies, that included six systems. HTGR and molten-salt reactor (MSRs) were among them. The concept of HTR was based on commercial reactors that had been built and operated initially in UK and France[27] and then were upgraded to advanced high-temperature reactor technologies in the US and Germany. The technology was abandoned in Germany because of the shift of government policy on nuclear energy in the aftermath of the Chernobyl and in the US because it was considered too expensive to be commercially viable. HTGR had been one of the frontier technologies supported by the government throughout the 1990s and 2000s. The Chinese scientists and engineers continued the research and commissioned the first experimental HTR (HTR-10) in 2003. The construction of the second module, HTR-PM with 200 MWe capacity, started in 2011 and achieved first criticality in 2021.

Many countries nowadays are interested in and developing advanced High Temperature Gas Cooled Reactors (HTGRs)

[24] Kelley Sims Gallagher, *The Globalisation of Clean Energy Technology*, MIT Press, 2014, p.5.
[25] Richard K Lester and David M Hart, *Unlocking Energy Innovation*, MIP Press, 2012.
[26] Gregory F Nemet, *How Solar Energy Became Cheap*, Earthscan from Routledge, 2019; Julia Kirch Kirkegaad, *Wind Power in China,* Routledge2019.
[27] Britain and France developed in the 1950 initially to extract plutonium. While France gave up the technology and switched to PWR in 1970, Britain continued. It is the only country where commercial gas-cooled reactors are still in operation. In the US, the gas reactors were in operation at Fort Saint Vrain (1979-1989) and Peach Bottom (1967-1974)..

that use helium as a coolant. Such reactors can achieve very high fuel utilization rates and operate at high very temperatures. They also produce process heat, which can be used for hydrogen production and low-temperature applications such as seawater desalination and district heating. Several countries currently invest in research on small modular HTGR designs that solely rely on inherent safety characteristics and design features instead of active engineered safety systems. HTGR has becomes a very attractive technology in recent years because the reactor is designed to provide, besides electricity, high temperature process steam and process heat for various industrial applications – to decarbonise hard-to-abate sectors such as industry and transport and achieve a successful energy transition to net zero by 2050. It is considered by some senior officials at IAEA as the 'most suitable reactor type for nuclear hydrogen production,' over which It is also because the design is supposed to be 'inherently safe'.

Currently, some 20 designs of modular HTRs are at different stages of development, in several countries, including China, Indonesia, Japan, Kazakhstan, Republic of Korea, Russia, South Africa, United States and the European Union. In UK, the government confirmed that it would build an HTGR as the centrepiece of its $225-million Advanced Modular Reactor Research, Development & Demonstration Program in 2021. The Japan Atomic Energy Agency (JAEA) resumed operation of its high temperature engineering test reactor in mid-2021 and planned to conduct a range of tests using the HTTR. It is also looking to have a demonstration operation of hydrogen production using the HTTR up and running by 2030.

China's HTR is ahead of them all. China expects to move to commercialisation of the HTR-PM600, which will consist of six reactor modules and one steam turbine generating 650 Mwe, sometime around 2030. Back in 2002, the editor of the journal, *Nuclear Engineering and Design*, claimed, 'the HTR-10 is the first reactor in the world which justifiably bam be termed "inherently safe" [and]is the first of the Generation-IV reactors; it exists not only on paper but it exists in reality.'[28] In 2004, IAEA also organised representatives from 40 some countries to visit HTR-10 project; nearly all brushed aside the research on HTR technology, as the technology was too far away from being commercialised and might never be commercialised given the previous experience in Germany and the US.

In China, research on high-temperature reactor was initiated at the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University; aat the turn of the century, INET brought investments from CNNC and Huaneng, a utility company, to get ready for the demonstration stage of the technology development. This tends to be the difficult stage as private investment often refuses to come in at a high-risk stage of technology development while it is beyond the public support of basic R&D.[29] For the similar reasons, when HTR was included as one of the key technology developments in the National Mid- and Long-Term Science and Technology Development in 2006, Made in China 2025 in 2015, in every Five-Year Plan and its associated energy program since 2004, the voice of opposition was loud and clear, not because of the anti-nuclear sentiment, but because the country was experiencing severe shortages of electricity at the time. Government support met relentless opposition and criticism from incumbent energy industries and others for wasting money and time in supporting such blue-sky research while the country was facing severe shortages of electricity supply. Indeed, the internal debates between the powerful National Development and Reform Commission and the Ministry of Science and Technology reveal a great deal how policies were made in China – a topic beyond the scope of the paper. After 2011, it was widely acknowledged that HTGR was not only one of the more mature advanced reactor concepts, but also China had already had its experimental one in operation for a decade.[30]

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28 G Lohnert, 'Editor's Forward,' *Nuclear Engineering and Design*, 2002, 218(1-3): 1-2.
29 Kelly Sims Gallagher, et al, 'Energy-Technology Innovation,' *Annual Review of Environment and Resources*, 2006, 31:193-237.
30 GAO, *Nuclear Reactors*, July 2015, p.16.

Research on molten-salt cooled reactor technology tells a different story. In the US, the Oak Ridge National Laboratory pioneered MSR research in the 1950s and built and operated a small MSR in 1965-69. MSR technology has three advantages: no meltdown, no proliferation, and burning up nuclear waste.[31] In the early 1970s, the federal government increased its research and funding focus on other competing technologies and formally terminated the Oak Ridge molten salt program in January 1973. In the early 2000s, under the initiative of Generation-IV International Forum (GIF), research on MSR seemed to provide some hope with an increasing concerns of climate change. Research on MSRs was resumed and quickly stopped as huge amounts of government funding went to gas fracture drilling while the nuclear sector was hit by another disaster at Fukushima, Japan. 'Unsure of its domestic agenda,' in 2010, DOE 'encouraged the federal Oak Ridge National Laboratory … to share the residual knowledge and technology from that [MSR] program with China.'[32] The Chinese welcomed it, identified MSRs as a high development priority, and immediately committed $500 million in MSR research.

Some at DOE argued that most of the U.S. intellectual property related to MSR was already in the public domain; when the U.S. government was spending very little on advanced reactor research, China's experiments might yield a breakthrough that would provide an alternative to the massive consumption of fossil fuels.[33] The collaboration between Oak Ridge National Laboratory and the Chinese Academy of Science (CAS) began in 2011. The long-term goal of the Shanghai Institute of Applied Physics, one of the institutes of CAS and the chief collaborator of the project, was to commercialise the technology by 2040. Some scientists in the US welcomed the cooperation and collaboration with the Chinese scientists; some saw the collaboration was the only means to develop the technology into a commercial stage as many working at MSR in the US national laboratories were retiring. Many were disappointed too with the lack of federal support in their research at home. 'Cheaper and cleaner nuclear plants could finally become reality – but not in the United States, where the technology was invented more than 50 years ago,' wrote Richard Martin, senior editor of the *MIT Technology Review*. 'The Shanghai Institute of Applied Physics in China plans in the next few years to build an experimental reactor whose design makes a meltdown far less likely.'[34] When China was about to switch on its molten-salt cooled reactor in 2021, some in the US called it as a game changer for the transition to low-carbon energy, while the Europeans commented 'China shows us the path to nuclear future.'[35]

Conclusion

Challenge scientific cooperation and collaboration could not have been more apparent: Collaboration on basic research – the open-ended study of theoretical knowledge – is clearly beneficial to all while the practical uses for which are not always immediately apparent. What if scientific cooperation gives the industry in another country an edge? The question has been repeatedly asked in Europe and the US in recent year after China made some headway in technology innovation and was thereby identified as a strategic competitor. 'For those of us engaged in international scientific collaboration,' wrote three academics, 'serious cooperation between US and Chinese scientists is getting more difficult as geopolitical tensions increase.' Meanwhile there are enormous potential gains from cooperation.[36] How to manage

[31] Thomas J Dolan, ed., *Molten Salt Reactor and Thorium Energy*, Elsevier, 2017.
[32] Richard K Lester, 'A Roadmap for U.S. Nuclear Energy Innovation,' *Issues in Science and Technology*, 2016, 32(2):48.
[33] David Lague and Charlie Zhu, 'Special Report: The U.S, Government Lab Behind China's Nuclear Power Push,' *Router*, 21 December 2013.
[34] Richard Martin, 'Fail-Safe Nuclear Power,' *MIT Technology Review*, 2 August 2016.
[35] Smriti Mallapaty, 'China Prepares to Test Thorium-Fuelled Nuclear Reactor,' *Nature*, 19 September 2021.
[36] Valerie J Karplus, Granger Morgan and David Victor, 'Finding Safe Zones for Science,' *Issues in Science and Technology*, 2021, 38(1):76-81. For the discussion, see William Hannas and Didi Kirsten Tatlow, eds., *China's Quest for Foreign Technology: Beyond Espionage,* Routledge, 2020.

science and technology cooperation without triggering political mines is the challenge.

The key point is that the global transition to low-carbon sources of energy presents enormous challenge to the entire world; it also offers tremendous opportunity for human progress and innovation. Advanced nuclear technologies may at least give us some breathing space or at best provide a carbon-zero energy future. Nuclear energy development in every country depends, among other factors, on how government frames the issue: as a way to help manage energy security and avoid volatility of other energy supplies, a way to help build country's comprehensive research and manufacturing capacities, a way to protect national security and ensure nuclear non-proliferation, or a way to build diplomatic ties with its key allies. How the issue is framed can sway the public in supporting or opposing nuclear development. In general, nuclear energy issue does not come to public attention especially in embarking countries.

Furthermore, nuclear energy technology development needs government support: consistent policies are much more important than public funding that is often used as a leverage to get private support if policy incentives are available. Finally, nuclear development and nuclear technology innovation are always global exercises; both cooperation and competition are needed. The balance, however, shifts at different stages of innovation. Therefore, to assess China as a competitor in nuclear energy industry, we need to develop a more comprehensive analysis on various stages of technology innovation and the strategies required.

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