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Nuclear Power in China: its role in national energy policy

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Introduction

China has the world's third largest fleet of civil nuclear power reactors after the United States and France. In June 2022, the 54 operable reactors had a total capacity of 55.8 Gigawatt electric power (GWe).[1] This was only marginally less than France's 56 operable reactors totalling 61.4 GWe.[2] A further 23.5 GWe of capacity was under construction in late 2022,[3] nearly 40 per cent of the global total.[4] In 2021, nuclear power provided roughly 4.8 per cent of China's electricity supply, 2.3 per cent of primary commercial energy supply and 25 per cent of non-hydro, low-carbon electricity.[5]

Nuclear power plays three important roles in China's energy and economic strategies. First, it enhances security of energy supply as nuclear power provides significant baseload electricity with only modest import requirements for technology and fuel. Second, the nuclear industry is relatively clean in terms of carbon dioxide emissions and air pollution, at least compared with coal which dominates China's current power generation. As its installed capacity expands, nuclear power can play an increasing role in reducing the nation's carbon emissions. Finally, the successful localization of nuclear technologies over the last 40 years has been part of a wider industrial strategy to make the country less dependent on foreign technology.

The potential role of nuclear power in supporting the low-carbon energy transition has become more apparent in light of President Xi Jinping's 2020 pledge to peak its carbon emissions before 2030 and strive to achieve carbon neutrality by 2060. In October 2021, the State Council reiterated that nuclear power would play an important role in reaching a peak in carbon emissions before 2030.[6] Projections for future levels of nuclear power generation vary greatly: from 1,000 TWh to 2,000 TWh in 2035 and from 3,000 TWh to 4,000 TWh in 2050,[7] compared with 407 TWh in 2021. In 2018, one source suggested that total capacity for nuclear power could reach 120–150 GWe by 2030.[8] However, with 23.5 GWe of capacity currently under construction with expected grid connections between 2022 and 2028, and a further 43.6 GWe planned, it is more likely that the capacity will reach 100 GWe by 2030. Set against this was a claim by the China Nuclear Energy Association that it could accelerate the completion of reactors from the target of 6–8 reactors per year to 10 per year which would boost the installed capacity to 300 GWe or more by 2030.[9]

This paper examines the development of China's civil nuclear power industry with a particular emphasis on evolving policy objectives and assesses the outlook for the industry. The next section provides the background to nuclear power in China, summarizing its history and the main actors. Section 2 examines the government's policy objectives and Section 3 presents some safety and societal concerns relating

1 GWe = Gigawatt electric power; '"China keeps enlarging nuclear power generation capacity in 2022"', CGTN, 25 June 2022, https://news.cgtn.com/news/2022-06-25/China-keeps-enlarging-nuclear-power-generation-capacity-in-2022--1b9uz0DnM3e/index.html
2 World Nuclear Association, 'Nuclear Power in France', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx

3 World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
4 International Atomic Energy Agency, 'Nuclear Power Reactors in the World', 2022 edition, IAEA-RDS-2/42, https://www.iaea.org/publications/15211/nuclear-power-reactors-in-the-world
5 BP, 'BP Statistical Review of World Energy 2022', https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
6 State Council, 'Action Plan for Carbon Dioxide Peaking Before 2030', 27 October 2021, https://english.www.gov.cn/policies/latestreleases/202110/27/content_WS6178a47ec6d0df57f98e3dfb.html
7 Energy Foundation, 'Synthesis Report 2020 on China's Carbon Neutrality', December 2020, https://www.efchina.org/Attachments/Report/report-lceg-20201210/Synthesis-Report-2020-on-Chinas-Carbon-Neutrality.pdf/view
8 'China likely to more than triple nuclear power capacity by 2030 – official', Reuters, 8 November 2018, https://www.reuters.com/article/china-nuclearpower-idUSL4N1XJ3AR
9 Bloomberg, 'China's Nuclear Industry Says It Can Accelerate Expansion Plans', 6 September 2022, https://www.bloomberg.com/news/articles/2022-09-06/china-s-nuclear-industry-says-it-can-accelerate-expansion-plans

to nuclear power. The final sections present an outlook for China's nuclear power industry and brief conclusions.

1. Nuclear Power in China

1.1 History of China's nuclear power industry

The possibility of developing nuclear power was mentioned in the First Five-Year Plan of 1953, but was then dropped as attention switched to developing an atomic bomb.[10] The 1960s saw the development of reactors for powering submarines, but only in 1970 did a power supply crisis in Shanghai bring civil nuclear power back onto the agenda. Even then, progress remained slow because neither of the two key agencies responsible for nuclear matters was interested in switching their focus from military to civil use, and the Ministry of Water Resources and Electrical Power was not supportive of nuclear power.[11] Only in 1978 did the government formally announce that China would develop civil nuclear power.[12]

Nevertheless, political struggles continued between different agencies over the choice of technology: pressurized water reactors or pressurized heavy water reactors, and imported versus indigenous technology.[13] A decision was taken in favour of the pressurized water reactor, at least in the short-term, and a compromise was made on the technology with the use of both foreign and indigenous designs. This led to the construction of the 300 megawatt (MW) Qinshan I plant in Zhejiang which was based on Chinese design but with key imported components. There were also two 944 MW units at Daya Bay in Guangdong Province, of French design, with China Light and Power (CLP) of Hong Kong as the joint-venture partner.[14] These plants came into commercial operation in 1994.

After the country's first nuclear power plants were commissioned, a decision was made to build four more plants under the slogan of 'moderate development of nuclear power' in order to sustain technical expertise but limit capital requirements.[15] The then Prime Minister Li Peng was a key supporter. The political context of the decision-making on reactor design was even more complex than before on account of the government's fragmentation, the rise in the number of corporate players and the growing interaction with foreign governments and vendors. The result was that the four new plants were built with four designs from four countries: Canada, France, Russia, and USA.[16] This fragmented strategy ran against the conventional wisdom that standardizing reactor design reduces costs and enhances construction, operation, and maintenance efficiencies leading to greater safety.[17] However, it allowed China to experiment with different partners and technologies, and avoided the risk of generic design problems that might affect the entire fleet.

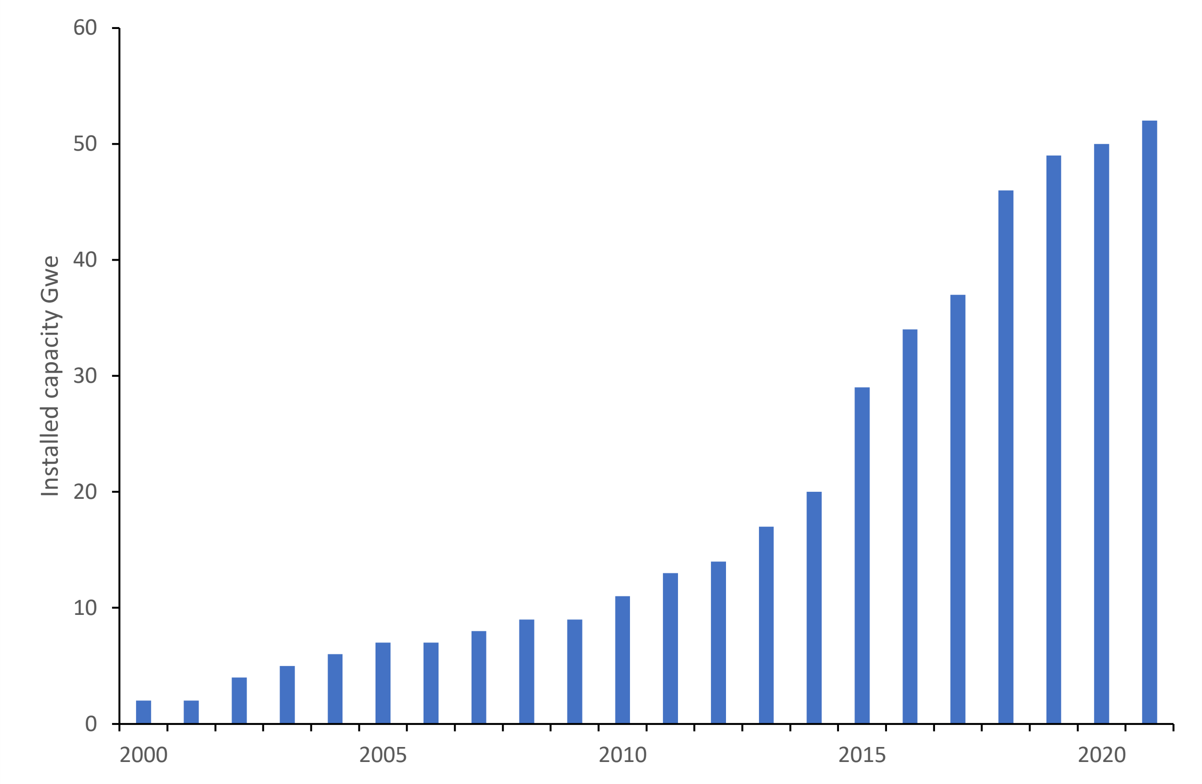
The need for large-scale, low-emission baseload triggered a revival of interest in nuclear power in the early years of the twenty-first century, as was the case with hydroelectricity. The Medium to Long-Term Plan for Nuclear Energy Development 2005–2020 set a goal of having 45 GWe in operation by 2020, with new plants along the coast and at inland locations experiencing rapid economic growth.[18] As concerns relating to greenhouse gases (GHG) and air pollution have grown, the emphasis has shifted towards the environmental benefits of nuclear power. The target for the year 2020 was raised to

[10] Sovacool, B. K. and Valentine, S. V. (2012). *The National Politics of Nuclear Power*, Routledge.
[11] Xu, Y-C. (2002). Powering China. Reforming the Electrical Power Sector in China, Ashgate.
[12] Xu, Y-C. (2010). *The Politics of Nuclear Energy in China*, Palgrave Macmillan.
[13] Ramana, M.V. and Saikawa, E. (2011). 'Choosing a Standard Reactor: International Competition and Domestic Politics in Chinese Nuclear Policy', *Energy* 36, 6779–6789.
[14] Xu, Y-C. (2010). *The Politics of Nuclear Energy in China*, Palgrave Macmillan.
[15] Xu, Y-C. (2010) *The Politics of Nuclear Energy in China*, Palgrave Macmillan; Sang, D. (2011). 'Nuclear Energy Development in China', in Xu, Y-C. (ed.) *Nuclear Energy Development in Asia. Problems and Prospects,* Palgrave Macmillan, 43–67.
[16] Xu, Y.C. (2010). *The Politics of Nuclear Energy in China*, Palgrave Macmillan.
[17] Ramana, M.V. and Saikawa, E. (2011). 'Choosing a Standard Reactor: International Competition and Domestic Politics in Chinese Nuclear Policy', *Energy* 36, 6779–6789.
[18] Xu, Y.C. (2010). *The Politics of Nuclear Energy in China*, Palgrave Macmillan.

80 GWe in the Five-Year Plan for 2011–2015. By this time, there were three Chinese companies developing and investing in nuclear power and the government was providing a feed-in-tariff for nuclear

power that was significantly above that for thermal power.[19] This reinvigoration of the nuclear power programme led to a steady acceleration of installed capacity from 2010 onwards (Figure 1).

Figure 1: Installed capacity of nuclear power plants in China, 2000–2021[20]



As part of its strategy to modernize the fleet of nuclear power plants, the government launched a bidding process for Generation III units in 2004. The winners were Westinghouse with its AP-1000 and Areva with the European Pressurized Reactor. Construction of both began in 2009. These projects were among the first of their kind to be built and have encountered technical challenges. The first units of each type were only fully commissioned in 2018. Meanwhile, the China National Nuclear Corporation (CNNC) and the China General Nuclear Power Group (CGN) built on French technology to develop the indigenous Hualong One reactor with two slightly different designs. Two Hualong One units entered commercial operation, in January 2021 and March 2022 respectively.

China's gradual indigenization of nuclear technology has yielded two benefits. First, it means that the nation's nuclear power development is relatively unaffected by deteriorating relations with the United States.[21] Second, Chinese research institutes and companies have the capacity to develop a variety of new technologies that they hope to export. These include high temperature gas-cooled, molten salt and

[19] Rutkowski, R. (2013). 'The Economics of Nuclear Power in China', Petersen Institute for International Economics, 25 October, https://www.piie.com/blogs/china-economic-watch/economics-nuclear-power-china
[20] World Nuclear Association, 'Nuclear Power in China', various years, https://world-nuclear.org/information-library.aspx
[21] Xie, E. (2020). 'China ditches US nuclear technology in favour of home-grown alternative', South China Morning Post, 14 September, https://www.scmp.com/news/china/society/article/3101304/china-ditches-us-nuclear-technology-favour-home-grown

fast neutron reactors, as well as floating plants and nuclear fusion. The first two high-temperature gas-cooled reactors operated by the Huaneng Group were connected to the grid in December 2021.[22]

Both CNNC and CGN are planning to construct ocean-going floating reactors for use in the South China Sea.[23]

The Fukushima Daiichi nuclear accident in 2011 brought a temporary halt to this programme. Construction of all new plants was suspended, all plants in operation or under construction were subject to a safety inspection and plans to construct plants at inland locations were set aside. The government permitted the construction of coastal plants to restart in late 2012, but it reduced the capacity target for 2020 from 80 GWe to 58 GWe.[24] By June 2022, 55.8 GWe of capacity was in operation, still below the revised 2020 target.[25] Although this goal for installed capacity was missed, the 14th Five-Year Plan (2021–2025) set a goal of 70 GWe of installed capacity by 2025.[26] In late 2022, a further 23.5 GWe of capacity was under construction with expected grid connections between 2022 and 2028, and 43.6 GWe was planned. The latter category included three inland plants for the first time, in Hunan, Jiangxi, and Hubei.[27]

The Chinese Government supports the development of nuclear power with a number of policy tools. First, nuclear power plants often receive favourable prices and allocations of operating hours for electricity sales. While power market reforms have the potential to undermine this favourable treatment, the recent focus of energy security has led to its continuation. Second, through state-owned banks such as the China Development Bank, the government provides cheap debt capital to the large state-owned enterprises that dominate China's nuclear power sector. Finally, central and provincial authorities help assemble land and arrange for transmission connections at new nuclear power plant sites.[28]

1.2. Actors in China's nuclear power industry

Industrial actors

Today there are four major state-owned companies involved in the nuclear power industry:

- the China National Nuclear Corporation (CNNC);
- the China General Nuclear Power Group (CGN);
- the State Power Investment Corporation (SPIC); and
- the China Nuclear Engineering and Construction Corporation (CNECC).

CNNC has been the central actor in the nation's civilian and military nuclear programmes from the time of its inception as the Ministry of Nuclear Industry. In civil nuclear power, CNNC's involvement includes the production of uranium ores, fuel fabrication, fundamental research, reactor design, reprocessing, and waste disposal. With CNECC back within the corporation, it also carries out plant construction. As of August 2022, CNNC has been operating about 20 GWe of nuclear power capacity in China.

[22] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
[23] 'China's first floating nuclear reactor may withstand once-in-10,000-years weather event, engineers say', *South China Morning Post*, 14 December 2021; 'Ocean-going nuclear plants for South China Sea', *Asia Times*, 21 March 2019, https://asiatimes.com/2019/03/ocean-going-nuclear-plants-for-south-china-sea/
[24] Xu, Y-C. (2014). 'The Struggle for Safe Nuclear Expansion in China', *Energy Policy*, 73, 21–29.
[25] 'China keeps enlarging nuclear power generation capacity in 2022', *CGTN*, 25 June 2022, https://news.cgtn.com/news/2022-06-25/China-keeps-enlarging-nuclear-power-generation-capacity-in-2022--1b9uz0DnM3e/index.html
[26] National People's Congress, 'Outline of the People's Republic of China 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035', English translation, Georgetown University, 13 May 2021, https://cset.georgetown.edu/publication/china-14th-five-year-plan/
[27] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
[28] Hibbs, M. (2018). *The Future of Nuclear Power in China,* Carnegie Endowment for International Peace.

CGN was previously the China Guangdong Nuclear Power Group, which originated in Guangdong and is 50 per cent owned by the Guangdong Provincial Government. The company is involved in the design, development, and operation of nuclear power plants. Until around 2010, CNNC was the dominant operator of nuclear power plants in China in terms of installed capacity. Since then, CGN has rapidly enhanced its position in the domestic market. In August 2022, it was operating at about 30 GWe of capacity.

SPIC was created in 2015 through the merger of the State Nuclear Power Technology Corporation and the China Power Investment Corporation. It was one of the five large generating companies created after the sector reforms of 2002. The State Power Investment Company acts primarily as an investor in nuclear power. Its installed capacity was just 2.2 GWe in August 2022, though its plans are ambitious. The four other large generating companies (Datang, Huadian, Huaneng, and Guodian) are also active in the development of nuclear power, but usually in partnership with one of the three leading players.

CNECC does not operate any plants but is the sole constructor of civil nuclear power plants in China. It was merged back into the China National Nuclear Corporation in 2018.

Each of these major corporations have large numbers of subsidiaries and joint ventures that carry out specialized engineering, mining, research, or consultancy tasks. They are part of a supply chain that comprises about 5,000 enterprises,[29] including very large entities such as the Dongfang Electric Corporation and China First Heavy Industries. The level of competition likely varies along the supply chain from being high for items such as valves and pumps to very low for reactor vessels. In addition, there are a number of industrial and research associations and research centres.

State actors

The agencies responsible for formulating nuclear power policy are the same as those leading broader energy policy, namely the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA). They develop the strategic plans and five-year plans for energy, including nuclear power. In addition, the approval of these agencies, as well as that of the State Council, is needed to construct and operate a new nuclear power plant both within China and overseas.

The most important agency regulating nuclear safety is the National Nuclear Safety Administration (NNSA). The NNSA was established in 1984 under the China Atomic Energy Authority but was transferred in 1998 to the State Environmental Protection Agency. In 2008, the State Environmental Protection Agency was upgraded to become the Ministry of Environmental Protection and again in 2018 to the Ministry of Ecology and Environment. The head of the NNSA today has Vice-Ministerial Status. The NNSA has its headquarters in Beijing and six regional offices in Shanghai, Shenzhen, Chengdu, Beijing, Lanzhou, and Dalian. The National Nuclear Safety Administration also has some responsibilities relating to nuclear security, notably the physical protection of civil nuclear installations.

The other principal agencies involved in the regulation of nuclear matters are the State Administration of Science, Technology and Industry for National Defence (SASTIND) and its subordinate, the China Atomic Energy Authority (CAEC). The main focus of SASTIND is military. However, the CAEC plays a central role in the management of issues relating to nuclear security and safeguards in the civilian arena, including nuclear material accounting and control, the physical protection of nuclear material, and the transportation of nuclear material. It also chairs the National Nuclear Accident Emergency Coordination Committee.[30] However, there are overlaps with the responsibilities of the NNSA.

The Ministry of Public Security plays a key role in counterterrorism, advising nuclear power plant operators on their security plans and systems, and coordinating with the People’s Armed Police which provides the armed guards for nuclear installations and materials.[31]

2. Policy objectives for nuclear power

[29] Hibbs, M. (2018). *The Future of Nuclear Power in China,* Carnegie Endowment for International Peace.

[30] Knox, D. (2012). ‘Nuclear Security and Nuclear Emergency Response in China’, *Science and Global Security*, 20*,* 30–63.

[31] Knox, D. (2012). ‘Nuclear Security and Nuclear Emergency Response in China’, *Science and Global Security*, 20*,* 30–63.

China's government holds four policy objectives for its civil nuclear power programme:

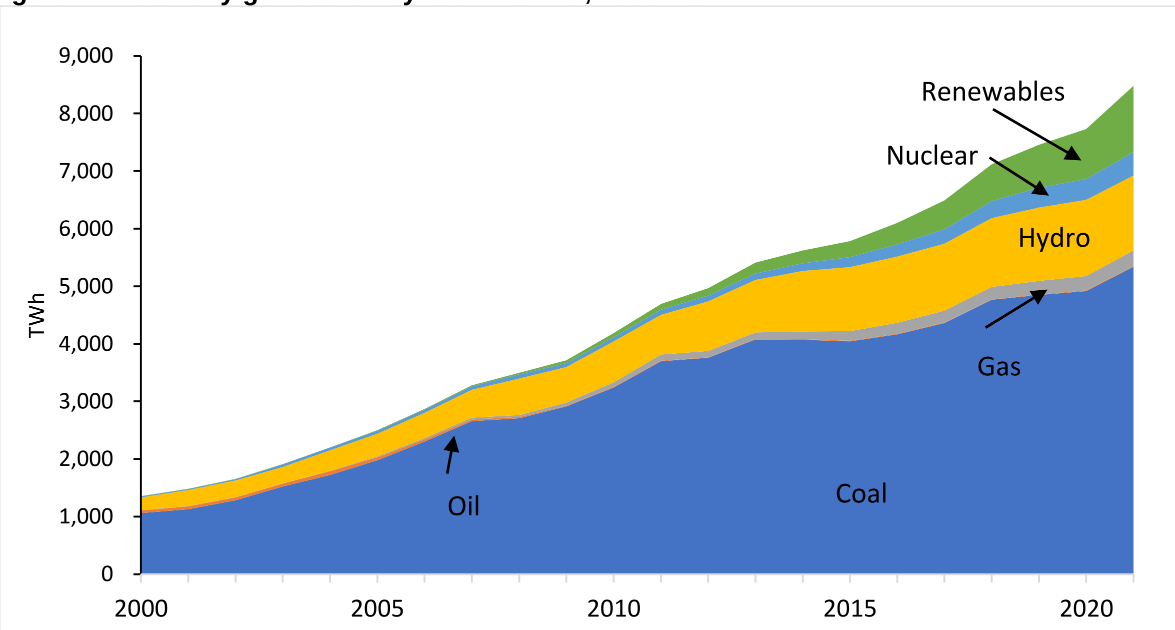
- enhancing security of energy supply;
- reducing carbon dioxide emissions;
- promoting advanced industrial and technological development;
- boosting technology exports.

2.1 Security of energy supply

The need to find long-term solutions to the nation's energy security was the prime driving force behind the launch of the civil nuclear power programme in the 1980s,[32] and this need has been reiterated by scholars ever since.[33] In simple terms, nuclear power can replace coal-fired power to a certain extent. Moreover, China was seen as having ample resources of uranium in the early decades of the programme. The issue of energy security rose to the top of the agenda after the widespread power shortages in 2003. In response, the 11th Five-Year Plan for Energy Development (2006–2010) and the Medium- to Long-Term Nuclear Energy Development Plan (2005–2020) explicitly called for the acceleration of the construction of nuclear power bases and for support for the development of high-temperature gas-cooled reactor technology as well as fast breeder reactors and nuclear fusion.[34] The latter document envisaged 45 GWe of nuclear power capacity being in operation by 2020, a target which was later raised to 80 GWe.

Despite the latter capacity target for 2020 not being met, the output of nuclear power rose from 16.7 TWh in 2000 to 73.9 TWh in 2010 and to 407 TWh in 2021 (Figure 2). However, due to the continuous increase in electricity demand, nuclear power's share of total power generation reached just 4.8 per cent in 2021, up from 2.1 per cent in 2005 (Figure 3).

Figure 2: Electricity generation by fuel in China, 2000–2021.[35]



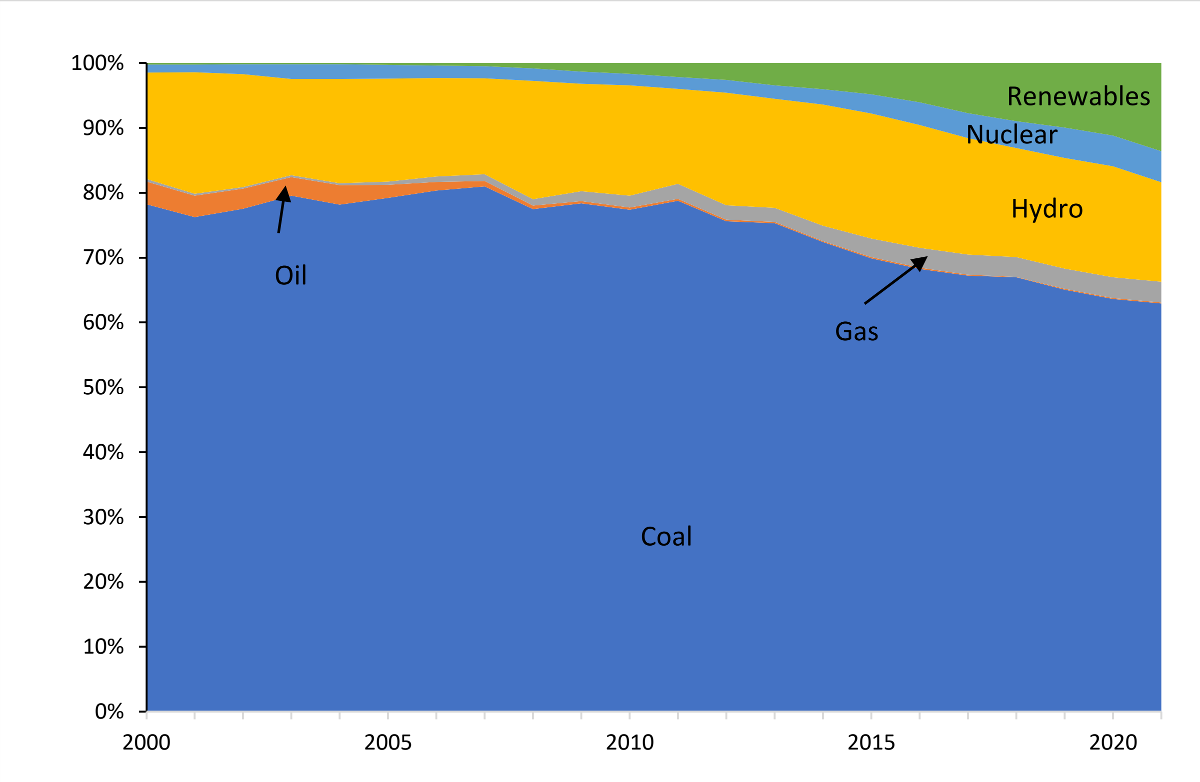
[32] Ping, Z. (1987). 'Nuclear power development in China', *IAEA Bulletin,* 2/1987, 43-46; Xu, Y-C. (2010). *The Politics of Nuclear Energy in China,* Palgrave Macmillan.

[33] Zhou, Y. (2010. 'Why is China going nuclear?', *Energy Policy,* 28, 3755–3762; Yu, S., Yarlagadda, B., Siegel, J.E., et al. (2020). 'The role of nuclear in China's energy future: insights from integrated assessment', *Energy Policy,* 139, 111344.

[34] National Development and Reform Commission, '11th Five Year Plan on Energy Development, April 2007, English version, University of South Carolina, https://china.usc.edu/national-development-and-reform-commission-%E2%80%9C11th-five-year-plan-energy-development%E2%80%9D-april-2007

[35] BP, 'BP Statistical Review of World Energy', various years.

Figure 3: Percentage share of electricity generation by fuel, 2005–2021.[36]



China's nuclear power programme has encountered two supply challenges. These relate to fuel and technology. The rapid growth of the nuclear power fleet led to the realization in the early 2000s that the country could no longer rely on its domestic resources of uranium. The emerging strategy was to source one third of requirements domestically, one third through trade imports and one third from overseas mining.[37] Chinese companies now have equity joint ventures in uranium mines in a number of countries including Canada, Kazakhstan, Namibia, Niger, and Uzbekistan.[38] Australia is another supplier of uranium. A major intensification of economic decoupling of western nations from China could threaten the supplies from Canada and Australia.

China's capacity to enrich uranium and fabricate fuel is growing rapidly.[39] Though information on current enrichment plants is not available, annual capacity was projected to reach 10.7–12.0 million separative

[36] BP, 'BP Statistical Review of World Energy', various years.
[37] Zhang, H. and Bai, Y. (2015) 'China's Access to Uranium Resources', Project on Managing the Atom, Belfer Center for Science and International Affairs.
[38] World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx
[39] Zhang, H. (2015). 'China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs', Project on Managing the Atom, Belfer Center for Science and International Affairs; 'China launches new uranium enrichment centrifuges', *World Nuclear News*, 21 March 2018, https://www.world-nuclear-news.org/Articles/China-launches-new-uranium-enrichment-centrifuges

work units (SWUs) by 2020.[40] Given that foreign companies that have built reactors in China have agreed to supply significant quantities of fresh fuel or enriched uranium, China has been able to export

enriched uranium since at least 2014.[41] In a similar manner, Chinese companies are increasing their capacity to fabricate nuclear fuels for different types of reactor and CGN has a fabrication joint-venture plant in Kazakhstan.[42]

A key question is whether the industry will develop a large programme to reprocess spent fuel in order to close the fuel cycle, or whether the spent fuel will just be placed in long-term storage. At present, most high-level waste is stored at reactor sites, though a spent fuel storage site is operational in Gansu Province. The long-term plan is to vitrify high-level waste and place it in deep geological storage in Gansu Province.[43] However, spent fuel reprocessing has been on the policy agenda since the early years of this century. More recently, the 13th Five-Year Plan for Energy Development (2016–2020) mentioned spent fuel reprocessing under energy technology innovation, as does the recent 14th Five-Year Plan for Energy-Related Innovation (2021–2025). In 2010, testing started at a 10 million tonnes per year pilot reprocessing plant in Gansu Province. A larger demonstration project with an annual capacity of 200 million tonnes is under construction at the same site and is projected to begin operating by 2025. A second plant with the same capacity is believed to be under construction and could be operating by 2030. The possibility of developing a coastal site is also being assessed.[44]

The second challenge relates to technology for the nuclear power plants. During the early years of the national programme, a debate raged between those who wanted China to rely on its own technology from the start and those who argued that such an approach would constrain the development of the programme. The latter argument prevailed and over the succeeding years the country purchased plants from France, Canada, Russia, and USA.[45] Nevertheless, Chinese companies have steadily improved their capacity to manufacture key components as well as design and construct nuclear power plants. During the 2010s, the companies were working on developing their own Generation III reactors based on US and French designs but drawing principally on domestic components. The most notable achievement is the Hualong One reactor for which there are two different designs developed by CNNC and CGN.[46] Although France's EDF and US Westinghouse won contracts to construct two EPR reactors and four AP1000 reactors respectively, all future Generation III plants will be of Chinese design.[47]

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[40] World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx; SWU = separative work unit. The Separative Work Unit (SWU) is a unit that defines the effort required in the uranium enrichment process, in which uranium-235 and -238 are separated. The separative work unit is measured in units of kg (kilograms), see https://energyeducation.ca/encyclopedia/Separative_work_unit

[41] Zhang, H. (2015). 'China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs', Project on Managing the Atom, Belfer Center for Science and International Affairs; World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.

[42] World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx; 'China-Kazakhstan venture to begin nuclear fuel production', *Eurasianet*, 18 November 2021, https://eurasianet.org/china-kazakhstan-venture-to-begin-nuclear-fuel-production

[43] World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx

[44] World Nuclear Association, 'China's Nuclear Fuel Cycle', updated August 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx; Zhang, H. (2020) 'Pinpointing China's New Plutonium Reprocessing Plant", *Bulletin of the Atomic Scientists*, 5 May, https://thebulletin.org/2020/05/pinpointing-chinas-new-plutonium-reprocessing-plant/; Zhang, H. (2021). 'China starts construction of second 200 Mt/yr reprocessing plant', *International Panel on Fissile Materials*, IPFM Blog, 21 March, https://fissilematerials.org/blog/2021/03/china_starts_construction.html

[45] Xu, Y-C. (2010). *The Politics of Nuclear Energy in China*, Palgrave Macmillan.

[46] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

[47] Xie, E. (2020). 'China ditches US nuclear technology in favour of home-grown alternative', *South China Morning Post*, 14 September, https://www.scmp.com/news/china/society/article/3101304/china-ditches-us-nuclear-technology-favour-home-grown

2.2 Carbon dioxide emission reduction

Although energy security provided the original rationale for nuclear power and remains an important motivation, the need to address carbon dioxide emissions has become an additional driver. The first official mention of nuclear power in this context was in the State Council's White Paper 'China's policies and actions for addressing climate change', published in October 2008.[48] The following year, the NDRC's Energy Research Institute included nuclear power in its report 'China's low-carbon scenario and low-carbon development path in 2050'. Nuclear power was mentioned in China's first Nationally Determined Contribution submission in 2015 and in its second submission in 2021. In October 2021, the State Council reiterated that nuclear power would play an important role in peaking carbon emissions before 2030.[49]

Coal plants and nuclear power plants were originally intended to play similar roles as baseload power plants. However, this is no longer the case in China. In the mid-2010s, new nuclear capacity was coming online at a time of slowing demand growth. As a consequence, the nuclear power fleet was operating well below full capacity, with an aggregate curtailment rate of 19 per cent in 2016.[50] Likewise, the coal-fired fleet has been operating well below optimal capacity and recent policy documents propose that the flexibility of coal-fired power plants be enhanced to balance intermittent renewable energy sources.[51] As a result, estimating the contribution of nuclear power to reducing China's CO2 emissions relies on a number of assumptions that are probably not valid. On the assumption that it is operating as baseload with minimal curtailment, a nuclear plant emits 95–97 per cent less CO2 per MWh on a lifecycle basis than a coal-fired power plant.[52] The NDRC's Energy Research Institute estimates that China's nuclear power fleet contributed a reduction of 274 million tonnes of CO2 in 2020.53 The key difference between nuclear and coal-fired power is that most of the emissions from the former are incurred during construction and from the latter during operation.

2.3 Industrial and technological policy

While security of equipment supply has been an important component of China's push to indigenize nuclear technology, a further motivation has been to become one of the leaders in this industry. But this seems to have been a relatively recent development. The Five-Year Plans for Science and Technology Development issued between 1991 and 2001 were not only very short at 7–12 pages, but made only brief and very general statements relating to the need to develop nuclear power technology and advanced fuel cycle technology.[54]

This changed in 2006 with the publication of the 53-page 11th Five-Year Plan for Science and Technology Development (2006–2010) and the 56-page Medium- and Long-term Programme for Science and Technology Development (2006–2020).[55] Both documents set out objectives for nuclear power that were much more detailed and ambitious than previous plans. The latter programme made

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48 State Council, White Paper, 'China's Policies and Actions for Addressing Climate Change', October 2008, English version, University of South Carolina, https://china.usc.edu/prc-state-council-white-paper-chinas-policies-and-actions-addressing-climate-change-october-2008

49 State Council, 'Action Plan for Carbon Dioxide Peaking Before 2030', 27 October 2021, https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html

50 Lin, C. (2017). 'Nuclear Energy Curtailment Caused About 20 billion RMB of Losses to Power Plants', 11 March, https://www.yicai.com/news/5244152.html [in Chinese].

51 National Development and Reform Commission, '14th Five-Year Plan for a Modern Energy System', 29 January 2022, P020220322583239614565.pdf (ndrc.gov.cn) [in Chinese].

52 National Renewable Energy Laboratory, 'Life Cycle Assessment Harmonization', https://www.nrel.gov/analysis/life-cycle-assessment.html; World Nuclear Association, 'How Can Nuclear Combat Climate Change?', https://www.world-nuclear.org/nuclear-essentials/how-can-nuclear-combat-climate-change.aspx

53 NDRC's Energy Research Institute, personal communication, April 2022.

54 8th Five-Year Plan for Science and Technology Development (1991–1995); 9th Five-Year Plan for Science and Technology Development (1996–2000); 10th Five-Year Plan for Science and Technology Development (2001–2005) – all in Chinese and no longer available on the internet.

55 Ministry of Science and Technology, '11th Five-Year Plan for Science and Technology Development (2006–2010)', 31 October 2016, http://www.etiea.cn/data/attachment/12345.pdf [in Chinese]; State Council, 'Medium- and Long-Term Plan for Science and Technology Development (2006–2020)', http://www.gov.cn/gongbao/content/2006/content_240244.htm [in Chinese].

specific mention of large-scale Generation III reactors, high-temperature gas-cooled reactors, as well as the need to pursue Generation IV, spent fuel reprocessing, and fusion technologies. It also emphasized the need to master and indigenize nuclear technologies and power station construction. These greater ambitions for nuclear power reflected the need to address the shortage of domestic power generation capacity being experienced at that time. In addition, these documents reveal China's greater determination to improve its science and technology R&D across the board.

Five years later, in 2010, the State Council consolidated this ambition in its policy document Cultivating and Development of Strategic Emerging Industries which was followed two years later by the National Strategic Emerging Industry Development Plan.[56] This strategy identified seven industries, of which 'new energy' was one. For the nuclear power technology industry, the latter document listed Generation III and high-temperature gas-cooled reactors, small modular reactors, and fast neutron technologies, and called for mastering these technologies. Moreover, the plan challenged the industry to become internationally competitive by 2020 in nuclear technology development, design, and equipment manufacturing. In a similar vein, the 12th Five-Year Plan for Science and Technology Development (2011–2015) set out specific aims and systems for the nuclear power industry, including establishing six R&D platforms for different parts of the industry.[57] It set deadlines between 2014 and 2020 for the construction of demonstration projects for the various technologies identified. The text on nuclear power spanned eight pages in the 110-page plan. These objectives were repeated in the 12th Five-Year Plan for Energy Science and Technology.[58]

The new leadership of Xi Jinping followed up the Strategic Emerging Industries plan in 2015 with Made in China 2025.[59] The ambitions reflected in this policy were broader than its predecessor. It had the overall aim of upgrading the nation's manufacturing industries through innovation, efficiency enhancement, and integration so that China could become a leading international manufacturer in terms of quality and sophistication.[60] The document made two mentions of nuclear energy under 'electrical equipment' and 'high-end equipment manufacturing'.

The text relating to the nuclear industry in the 13th Five-Year Plan for Energy Science and Technology (2016–2020) was almost entirely focused on frontier technologies.[61] These included high-temperature gas-cooled and thorium-based molten salt reactors, lead-based alloy-cooled reactors, and 5–10 MW small modular reactors. The document also called for a fast neutron reactor demonstration project. The latest such plan, the 14th Five-Year Plan for Scientific and Technological Innovation in the Energy Sector (2021–2025), identified successes with the Hualong One and high-temperature gas-cooled reactors, and reported that a fast neutron reactor demonstration project was under construction. The plan supported continued work on small modular reactors, marine transportable reactors, and thorium-based molten salt reactors. In addition, it reiterated the need to continue pursuing the use of nuclear power for heating, cooling, and desalination.

In summary, China's government has long placed high priority on developing indigenous capacity relating to advanced nuclear technologies. In this respect, the country has made great progress in catching up with the most advanced developments in other countries, notably with Generation III and

[56] State Council, 'Decision of the State Council on Accelerating the Cultivation and Development of Strategic Emerging Industries', 18 October 2010, http://www.gov.cn/zwgk/2010-10/18/content_1724848.htm [in Chinese]; State Council, '12th Five-Year Plan for National Strategic Emerging Industries', 9 July 2020, http://www.gov.cn/zwgk/2012-07/20/content_2187770.htm [in Chinese].
[57] Ministry of Science and Technology, '12th Five-Year Plan for Science and Technology Development (2011–2015)' 28 February 2012, http://2015.casted.org.cn/web/index.php?ChannelID=0&NewsID=4979 [in Chinese].
[58] National Energy Administration, '12th Five-Year Plan for Energy Science and Technology (2011–2015)', 20 December 2011, http://www.nea.gov.cn/131398352_11n.pdf [in Chinese].
[59] State Council, 'Notice of the State Council on the Publication of "Made in China 2025"', translation by Georgetown University, 10 March 2022, https://cset.georgetown.edu/publication/notice-of-the-state-council-on-the-publication-of-made-in-china-2025/
[60] Kennedy, S. (2015) 'Made in China 2025', Center for Strategic and International Studies, 1 June, https://www.csis.org/analysis/made-china-2025
[61] National Energy Administration, '13th FYP for Scientific and Technological Innovation in the Energy Sector (2016–2020)', http://www.nea.gov.cn/135989417_14846217874961n.pdf [in Chinese].

high-temperature gas-cooled reactors. However, it still struggles to deliver more sophisticated technologies such as fast reactors, advanced fuel development, and reprocessing.[62]

2.4. Technology export

China's energy companies have been active overseas for more than three decades. Fossil fuel companies and constructors of hydroelectric dams have been the dominant actors to date, whereas the nuclear power companies have only begun building an overseas presence in recent years. A slight exception to this trend has been the involvement of the CNNC in Pakistan. This dates back to 1993 when construction began on Pakistan's second nuclear power plant, Chasnupp 1, which was connected to the grid in 2000. This was followed by Chasnupp 2, 3, and 4, which came online in 2011, 2016, and 2017 respectively. All used the traditional Chinese CNP-300 Pressurized Water Reactor design.[63]

The Belt and Road Initiative (BRI) has taken this export drive to a new level. According to one official, China's companies have the ambition to build up to 30 civilian nuclear reactors across the world by 2030 as part of the BRI.[64] Building on its earlier involvement, and now as part of the China-Pakistan Economic Corridor, CNNC was the lead contractor to build two Hualong One reactors in Karachi. These came into operation in early 2021 and early 2022 respectively.[65] Since 2014, CNNC, CGN, and State Nuclear Power Technology Corporation have entered into agreements and memorandums of understanding in a variety of countries. In Argentina, CNNC plans to build at least one Hualong One reactor in cooperation with Nucleoeléctrica Argentina. In 2015, CGN reached an agreement to build two Canada Deuterium Uranium (CANDU) reactors in Romania. However, the Romanian Government withdrew from the agreement in 2020 and announced that the United States would finance their construction.[66] Other agreements have been reached with Armenia, Egypt, Kenya, Iran, South Africa, Sudan and Turkey, but these have yet to progress to become firm plans with contracts.[67]

In 2016, CGN joined EDF of France to help finance the construction of the Hinkley Point C reactor in the United Kingdom in the hope that it could win the opportunity to construct its own Hualong One reactors at one or more other UK locations at a future date. In January 2021, the UK Office of Nuclear Regulation announced that the Hualong One had passed the design review process and formal approval was issued in February 2022.[68] However, since early 2021, the UK Government has been looking for ways to exclude Chinese companies from domestic nuclear power projects on the grounds of national security.[69] A final decision will depend on finding ways to finance the planned reactors at Bradwell and Sizewell in the absence of Chinese involvement.

Chinese companies are also active in the Middle East Arab states. In July 2019, CNNC and the Emirates Nuclear Energy Corporation agreed to establish a platform for cooperation in nuclear technology and finance as part of a wider set of agreements signed between China and the UAE. Another country in the region to be taking active steps to develop a nuclear power programme is Saudi Arabia.[70] In 2010, the government announced its intention to embark on a nuclear power programme. A number of general

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[62] Hibbs, M. (2018). *The Future of Nuclear Power in China,* Carnegie Endowment for International Peace.
[63] World Nuclear Association, 'Nuclear Power in Pakistan', updated March 2022, http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/pakistan.aspx
[64] 'China could build 30 'Belt and Road' Nuclear Reactors by 2030: Official', *Reuters*, 20 June 2019, https://www.reuters.com/article/us-china-nuclearpower-idUSKCN1TL0HZ
[65] World Nuclear Association, 'Nuclear Power in Pakistan', updated March 2022, http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/pakistan.aspx
[66] World Nuclear Association, 'Nuclear Power in Romania', updated August 2022, https://world-nuclear.org/information-library/country-profiles/countries-o-s/romania.aspx
[67] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
[68] China Nuclear Energy Association, 'National Nuclear Power Operation (January–March 2022)', https://www.china-nea.cn/site/content/40689.html [in Chinese]; Hesketh, R., Morison, R., and Donaldson, K. (2022). 'UK Approves Chinese Nuclear Reactor for CGN's Bradwell Plant', *Bloomberg*, 7 February, https://www.bloomberg.com/news/articles/2022-02-07/u-k-approves-chinese-designed-nuclear-reactor-amid-controversy
[69] Pickard, J. and Thomas, N. (2021). 'UK looks to remove China's CGN from nuclear power projects', *Financial Times*, 25 July, https://www.ft.com/content/c4a3fe02-8535-45a4-aacf-0c4fbce8409d
[70] World Nuclear Association, 'Nuclear Power in Saudi Arabia', updated April 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/saudi-arabia.aspx

cooperation agreements were signed with countries such as Argentina, China, France, Russia, and South Korea. In 2018, the government sought proposals for the construction of large-scale commercial reactors from companies in China, Japan, Russia, South Korea, and USA. A call for bids was expected in 2020,71 but seems not to have taken place yet. The government also wants small-scale reactors for desalination. Contracts were signed with Argentinian, Chinese, and South Korean companies to deliver

different designs. In 2016 and 2017, the China Nuclear Engineering and Construction Group (a subsidiary of CNNC) entered into two memorandums of understanding relating to the feasibility and construction of high-temperature gas-cooled reactors.72 CNNC is also working with the Geological Survey of Saudi Arabia to explore for uranium resources in the Kingdom. More significant and causing international concern is that China is reported to have helped the Kingdom build a plant to make yellow cake from uranium ore.[73]

Jordan has been assessing options to develop a nuclear power programme since 2007 as it has few domestic primary energy resources except for solar energy. In 2018, the government decided to focus on small-scale reactors[74] as they would be better suited to the country's relatively small grid than large reactors. Since then, it has been exploring options for small-scale reactors with a number of companies, including China's CNNC. CNNC is also carrying out exploration for uranium in Jordan.

In summary, Chinese companies have yet to establish a strong position in the international market. Unlike Russia's Rosatom, they have not been making aggressive moves across the world. In part, this reflects the large scale of their domestic construction programmes. In addition, many of their potential customers lack the financial capacity to support a nuclear power programme and, with the exception of Pakistan, China's government appears unwilling to provide generous financial support in the way that Russia's does. There is also little sign of the government using civil nuclear power as a diplomatic or strategic tool, with the possible exception of Pakistan. Further, political opposition in the United Kingdom and Romania may reflect a wider reluctance on the part of European governments to involve Chinese companies in their domestic nuclear power programmes. Nevertheless, the construction of nuclear power plants by Chinese companies at home has not been dogged by long delays and there has been no evidence of substantial cost overruns. These features should give Chinese companies a competitive edge in overseas ventures.

3. Safety and societal concerns

3.1 Safety and human resources

Official statistics indicate that China's existing nuclear power plants have not suffered any serious incidents or accidents.[75] Events that have occurred have been assessed to be at Levels 1 and 2 on the International Nuclear and Radiological Event Scale. Nevertheless, the government has publicly acknowledged 16 safety failures in operating plants that occurred in 2016 as a result of human error. Triggers included the breaching of operational guidelines, lack of internal communication and 'pressing

[71] 'Saudi plans to invite bids for nuclear power project in 2020: sources', *Reuters*, 4 April 2019, https://www.reuters.com/article/us-saudi-nuclear/saudi-plans-to-invite-bids-for-nuclear-power-project-in-2020-sources-idUSKCN1RG1LL

[72] Ahmad, A., Salameh, R., and Ramana, M.V. (2019). 'Localizing Nuclear Capacity? Saudi Arabia and Small Modular Reactors', Issam Fares Institute for Public Policy and International Affairs, Beirut.

[73] 'Saudi Arabia, With China's help, Expands its Nuclear Program', *Wall Street Journal*, 4 August 2020, https://www.wsj.com/articles/saudi-arabia-with-chinas-help-expands-its-nuclear-program-11596575671

[74] World Nuclear Association, 'Nuclear Power in Jordan', updated May 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/jordan.aspx

[75] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

the wrong buttons'.[76] The National Nuclear Safety Administration has also identified a wide range of deficiencies in design, manufacturing, materials, and welding.[77] Together, these failings indicate weaknesses in the industry's safety culture.

A quantitative analysis of National Nuclear Safety Administration data on operational experience feedback from operating nuclear power plants in China showed that human factors were the principal cause of safety events and incidents.[78] Three different methodologies highlighted two linked factors—personnel working practices and incomplete written procedures and documents. Other causes identified

included verbal communications, work schedule, man-machine interfaces, training and qualification, and personal factors. Safety culture remains a key concern.[79]

Anecdotal evidence has highlighted two sets of factors that weaken the safety culture. The first relates to the workforce. The hiring and training of specialized technical staff has long struggled to keep pace with the industry's rapid growth.[80] As a result, many of those involved in the construction operation and inspection of plants are reported to be underqualified and overworked.[81] More intractable is the embedded political culture that appears to allow plant managers to ignore the requirements of inspectors, discourages technical staff from highlighting technical or managerial failings and a low level of transparency. The lack of transparency was illustrated by the confusion surrounding a problem with fuel rods at the Tianshan nuclear power plant in Guangdong in June 2021.[82]

3.2 Public participation

Public participation on matters relating to nuclear power has also been slow to develop. The few published assessments on the actions of operators of some of the early nuclear power plants are unfavourable. In their studies of the Rushan and Haiyang nuclear power plants, Zhou et al.[83] and He et al.[84] respectively identified that there appeared to have been almost no systematic consultation with local citizens before the start of plant construction. A more recent study involving four nuclear power plants with construction start dates between 1984 and 2009 revealed that little systematic public participation had taken place prior to construction. The one exception was the Daya Bay plant in Guangdong Province where construction began in 1984. In this case, the nuclear power plant operator instigated a two-way interaction with the citizens of Hong Kong.[85]

Until the publication of the Action Plan on Nuclear and Radiation Safety Public Communication in 2015, the need for nuclear plant operators to consult with the public was governed by documents requiring environmental impact assessments. The Nuclear Safety Law further formalizes this requirement by obligating nuclear facility operators and, to a lesser extent, the relevant provincial and municipal

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[76] Wong, S-S. (2017) 'China Nuclear Power Plant Incidents Highlight 'Systemic' Safety Concerns', *Radio Free Asia*, 9 January, https://www.rfa.org/english/news/china/concerns-01092017121057.html
[77] Hibbs, M. (2018). *The Future of Nuclear Power in China,* Carnegie Endowment for International Peace, 2018.
[78] Zou, Y., Xiao, Z., Zhang, L., Zio, E., Liu, J., and Jia, H. (2018). 'A Data Mining Framework within Chinese NPPs Operating Experience Feedback System for Identifying Intrinsic Correlations among Human Factors', *Annals of Nuclear Energy*, 16, 163–170.
[79] Lam, J.C.K., Cheung, L.Y.L., Han, Y., and Wang, S. (2022). 'China's response to nuclear safety pre- and post-Fukushima: an interdisciplinary analysis', *Renewable and Sustainable Energy Reviews*, 157, 112002.
[80] Xu, Y-C. (2014). 'The Struggle for Safe Nuclear Expansion in China', *Energy Policy*, 73, 21–29; Lam, J.C.K., Cheung, L.Y.L., Han, Y., and Wang, S. (2022). 'China's response to nuclear safety pre- and post-Fukushima: an interdisciplinary analysis', *Renewable and Sustainable Energy Reviews*, 157, 112002.
[81] Wong, S-S. (2017). 'China Nuclear Power Plant Incidents Highlight 'Systemic' Safety Concerns', *Radio Free Asia*, 9 January, https://www.rfa.org/english/news/china/concerns-01092017121057.html; Anonymous, 'Is China Overconfident in Nuclear Power Safety?', https://www.zhihu.com/question/36213956/answer/180452015 [in Chinese].
[82] Cohen, Z. (2021). 'US assessing reported leak at Chinese nuclear power facility', *CNN Politics*, 14 June, https://edition.cnn.com/2021/06/14/politics/china-nuclear-reactor-leak-us-monitoring/index.html
[83] Zhou, Y., Rengifo, C., Chen, P., and Hinze, J. (2011). 'Is China ready for its nuclear expansion?', *Energy Policy,* 39, 771–781.
[84] He, G., Mol, A.P.J., Zhang, L., and Lu, Y. (2013). 'Public Participation and Trust in Nuclear Power Developments in China', *Renewable and Sustainable Energy Reviews*, 23, 1–13.
[85] Dai, Y. (2019). 'Policy instrument designed to gain transition legitimacy: a case of Chinese nuclear development', *Environmental Innovation and Societal Transitions*, 30, 43–58.

governments, to consult relevant stakeholders on nuclear safety matters that are deemed to be of public interest. Formats can include questionnaires, hearings, discussions, and symposiums. In addition, the operators are required to provide feedback as part of the consultation process.

This new emphasis on public engagement has forced the plant operators of operating or planned nuclear power plants to work with the governments of nearby cities to hold public meetings in every community within 30 km of the plant site. These meetings not only provide information on the project but also emphasize economic benefits such as jobs, infrastructure, and public services.[86]

3.3 Public opinion

Public opinion in China on civil nuclear power has been relatively positive. However, perceptions of risk among residents near the Tianwan nuclear power plant in Jiangsu Province were significantly higher immediately after the Fukushima Daiichi nuclear accident in 2011 than beforehand.[87] In a more wide-ranging survey of more than 2,600 citizens across 28 provinces carried out in 2015, 78 per cent of respondents indicated general support for the development of nuclear power in China, much higher than in most Organisation for Economic Co-operation and Development (OECD) countries.[88] This high level of support may have been due, in part, to the consistently pro-nuclear stance of the state-owned media.[89] However, of those that supported nuclear power development, 28 per cent were against the sites being located inland, away from the coast.

This general support for nuclear power was also revealed in a survey in Shandong Province where citizens saw a range of benefits from nuclear power, including a stable and cheaper electricity supply and a decreased use of fossil fuels.[90] Nevertheless, in both these and other studies, the level of support decreased in response to the questions relating to a new nuclear power plant in the local area.[91] In a similar way, local newspapers tended to emphasize the risks arising from nuclear power more than the national press.[92] As expected, most respondents were concerned about safety risks, though the general level of knowledge on nuclear power appeared to be low.[93] Other studies revealed that opposition to nuclear power was particularly pronounced when the context was about a nearby nuclear power plant. This finding was supported by studies of willingness to pay higher electricity prices for sources of clean

[86] Interview in China, November 2018.

[87] Huang, L., Zhou, Y., Han, Y., Hammitt, J.K., Bi, J., and Liu, Y. (2013). 'Effect of the Fukushima Accident on the Risk Perception of Residents near a Nuclear Power Plant in China', *Proceedings of the National Academy of Sciences*, 110 (49), 19742–19747.

[88] Wu, Y. (2017). 'Public Acceptance of Constructing Coastal/Inland Nuclear Power Plants in Post-Fukushima China', *Energy Policy*, 101, 484–491.

[89] Wang, Y., Li, N., and Li, J. (2014). 'Media Coverage and Government Policy of Nuclear Power in the People's Republic of China', *Progress in Nuclear Energy*, 77, 214–223; Du, Q. and Han, Z. (2020). 'The framing of nuclear energy in Chinese media discourse: a comparison between national and local newspapers', *Journal of Cleaner Production*, 245, 118695.

[90] Yuan, X., Zuo, J., Ma, R., and Wang, Y. (2017). 'How Would Social Acceptance Affect Nuclear Power Development? A Study from China', *Journal of Cleaner Production*, 163, 179–186.

[91] Guo, Y. and Ren, T. (2017). 'When it is Unfamiliar to Me: Local Acceptance of Planned Nuclear Power Plants in China in the Post-Fukushima Era', *Energy Policy*, 100, 113–125.

[92] Du, Q. and Han, Z. (2020). 'The framing of nuclear energy in Chinese media discourse: a comparison between national and local newspapers', *Journal of Cleaner Production*, 245, 118695.

[93] Wu, Y. (2017). 'Public acceptance of constructing coastal/inland nuclear power plants in post-Fukushima China', *Energy Policy,* 101, 484–491; Yuan, X., Zuo, J., Ma, R., and Wang, Y. (2017). 'How would social acceptance affect nuclear power development: a study from China', *Journal of Cleaner Production*, 163, 179–186.

energy other than nuclear power.[94] Studies carried out since 2015 have confirmed a generally positive attitude to nuclear power.[95]

A number of studies have shown that trust is a key factor in determining public acceptance, especially in the absence of any deep knowledge of nuclear power.[96] The level of trust in government appeared to be significantly higher than in nuclear power plant operators, with non-government organizations and scientists being granted either an intermediate or higher level of trust.[97] The key contrast with OECD

countries was the high level of trust in government exhibited by respondents in China. The government's assertion that nuclear power benefited the nation appears to be an important factor determining support, especially among those with less knowledge.[98] Environmental awareness also increases individuals' support for nuclear power.[99] As in earlier years, proximity to a nuclear power plant reduces acceptance.[100]

4. Outlook for China's nuclear power industry

With at least 55 GWe of operable capacity and 23 GWe under construction, it is likely that total installed capacity will reach the 14th Five-Year Plan target of 70 GWe by 2025. Beyond that, time projections diverge, though by around 2030 China is likely to overtake the United States (currently 95 GWe) as having the largest fleet of reactors in the world (Table 1). Although a further 43 GWe is planned and another 97 GWe proposed, the rate at which projects are approved and constructed remains uncertain.[101] However, China's ambitions for the nuclear fleet remain strong and domestic projections of future capacity are significantly higher than those of the International Energy Agency and the US Energy Information Administration. In a similar way, projections of the share of nuclear power in the country's electricity supply vary greatly, depending on assumptions concerning economic growth, the scale of renewable energy, and the climate mitigation scenario (Table 2).

Table 1: Projections of China's installed civil nuclear power (GWe)

	June 2022	2025	2030	2035	2040	2050
Chinese sources						

[94] Sun, C. and Zhu, X. (2014). 'Evaluating the public perceptions of nuclear power in China: Evidence from a contingent valuation survey', *Energy Policy*, 69, 397–405; Sun, C., Lyu, N., and Ouyang, X. (2014). 'Chinese Public Willingness to Pay to Avoid Having Nuclear Power Plants in the Neighbourhood', *Sustainability*, 6, 7197–7223.
[95] Hao, Y., Guo, Y., Tian, B., and Shao, Y. (2019). 'What affects college students' acceptance of nuclear energy? Evidence from China', *Journal of Cleaner Production*, 222 (2019), 746–759; Fang, X., Qu, Z., Sun, C., Wu, C., and Wei, J. (2022). 'Public attitude and policy selection of future energy sustainability in China: evidence of the survey of college students', *Energy Policy*, 165, 112961; Gong, P., Wang, L., Wei, Y., and Yu, Y. (2022). 'Public attention, perception, and attitude towards nuclear power in China: A large-scale empirical analysis based on social media', *Journal of Cleaner Production*, 373, 133919.
[96] He, G., Mol, A.P.J., Zhang, L., and Lu, Y. (2013). 'Public Participation and Trust in Nuclear Power Developments in China', *Renewable and Sustainable Energy Reviews*, 23, 1–13.; Wang, Y. and Li, J. (2016). 'A Causal Model Explaining Chinese University Students' Acceptance of Nuclear Power', *Progress in Nuclear Energy*, 88, 165–174; Guo, Y. and Ren, T. (2017). 'When it is unfamiliar to me: Local acceptance of planned nuclear power plants in China in the post-Fukushima era', *Energy Policy*, 100, 113–125; Xiao, Q., Liu, H., and Feldman, M. (2017). 'How Does Trust Affect Acceptance of a Nuclear Power Plant (NPP): A Survey Among People Living with Qinshan NPP in China', *PLoS ONE*, 12(11), e0187941; Wu, Y. (2017). 'Public acceptance of constructing coastal/inland nuclear power plants in post-Fukushima China', *Energy Policy*, 101, 484–491.
[97] Xiao, Q., Liu, H., and Feldman, M. (2017). 'How Does Trust Affect Acceptance of a Nuclear Power Plant (NPP): A Survey Among People Living with Qinshan NPP in China', *PLoS ONE*, 12(11), e0187941; Wu, Y. (2017). 'Public acceptance of constructing coastal/inland nuclear power plants in post-Fukushima China', *Energy Policy*, 101, 484–491.
[98] Zhou, L. and Dai, Y. (2020). 'Which is more effective in China? How communication tools influence public acceptance of nuclear power energy', *Energy Policy*, 147, 111887.
[99] Hao, Y., Guo, Y., Tian, B., and Shao, Y. (2019). 'What affects college students' acceptance of nuclear energy? Evidence from China', *Journal of Cleaner Production*, 222, 746–759; Wang, J., Li, Y., Wu, J., Gu, J., and Xu, S. (2020). 'Environmental beliefs and public acceptance of nuclear energy in China: A moderated mediation analysis', *Energy Policy*, 137, 11141.
[100] Hao, Y., Guo, Y., Tian, B., and Shao, Y. (2019). 'What affects college students' acceptance of nuclear energy? Evidence from China', *Journal of Cleaner Production*, 222, 746–759; Wang, J., Li, Y., Wu, J., Gu, J., and Xu, S. (2020). 'Environmental beliefs and public acceptance of nuclear energy in China: A moderated mediation analysis', *Energy Policy*, 137, 11141.
[101] World Nuclear Association, 'Nuclear Power in China', updated October 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

State Council[102]	55.8					
14th Five-Year Plan[103]		70				
Nuclear Energy Association[104]			110			
CNNC[105]				180		
CGN[106]				200		
Tsinghua ICCSD[107]						327
Jiang et al. 2018[108]						554
International sources						
IEA World Energy Outlook 2020[109]					135–164	
EIA International Energy Outlook 2021[110]						143

Table 2: Projections of the share of nuclear power in China's electricity

	June 2022	**2035**	**2040**	**2050**	**2060**
Chinese sources					
BP, 2022[111]	4.8%				
China Electricity Council[112]		20%			
Jiang et al., 2018[113]				20%	
CET 2023[114]					5%
International sources					
IEA, 2020[115]			12–19%		
Energy Foundation, 2020[116]				10–25%	
US EIA 2021[117]				7.7–10.7%	
IEA, 2021[118]					9%*, 15%*

Note: * refers to shares of primary energy supply

[102] 'China keeps enlarging nuclear power generation capacity in 2022', *State Council*, 26 June 2022, https://english.www.gov.cn/news/videos/202206/26/content_WS62b7b0b7c6d02e533532cc28.html

[103] National People's Congress, 'Outline of the People's Republic of China 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035', English translation, Georgetown University, 13 May 2021, https://cset.georgetown.edu/publication/china-14th-five-year-plan/

[104] Wang, B. (2021). 'China nuclear energy plan is 70 GW by 2025 and 180 GW by 2035', *NextBigFuture*, 7 April, https://www.nextbigfuture.com/2021/04/china-nuclear-energy-plan-is-70-gw-by-2025-and-180-gw-by-2035.html

[105] Wang, B. (2021). 'China nuclear energy plan is 70 GW by 2025 and 180 GW by 2035', *NextBigFuture*, 7 April, https://www.nextbigfuture.com/2021/04/china-nuclear-energy-plan-is-70-gw-by-2025-and-180-gw-by-2035.html

[106] Murtaugh, D. and Chia, K. (2021). 'China Climate Goals Hinge on $440 Billion Nuclear Power Plan to Rival U.S.', *Bloomberg*, 2 November, https://www.bloomberg.com/news/features/2021-11-02/china-climate-goals-hinge-on-440-billion-nuclear-power-plan-to-rival-u-s?leadSource=uverify%20wall

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

[108] Jiang, K., He, C., Dai, H., Liu, J., and Xu, X. (2018). 'Emission scenario analysis for China under the global 1.5 ºC target', *Carbon Management*, 9 (5), 481–491, https://www.tandfonline.com/doi/full/10.1080/17583004.2018.1477835

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If these projections are met, even the more modest ones, nuclear power will make a growing and significant contribution to China's electricity supply security and carbon emissions. A number of factors could undermine these ambitions:

- A serious nuclear accident either in China or elsewhere in Asia would likely reduce public support for nuclear power and could trigger policy or safety reviews that could slow China's nuclear expansion.
- The progressive development of a national power market accompanied by a sustained growth in renewable energy could make nuclear power uncompetitive at times of surplus supply in the absence of either targeted support for nuclear power or a carbon price which is much higher than what we see today.
- As mentioned above, a severe economic decoupling from the West could constrain the supply of uranium to levels below what is required to fuel the more ambitious projected installed reactor capacities. A key factor will be how rapidly China can operationalize and scale up its reprocessing capacity.
- Finally, the more ambitious projections will place great pressure on both the companies and the government to recruit and train a sufficiently skilled workforce to construct and operate these plants safely and securely.

China's government will continue to promote nuclear industrial and technological development within the nuclear sector. Notable technologies will include small modular reactors, advanced reactors of different types and marine transportable reactors. Future success with nuclear fusion and fuel reprocessing is less predictable.

These developments will assist in boosting technology exports. However, these exports are likely to grow slowly, with carefully selected partners, due to heavy commitments to build out the domestic fleet of reactors. In addition, many potential customers lack the finance to pay and, with the exception of Pakistan, China has been less generous than Russia in providing financial support. Finally, the push back against China within Europe is likely to intensify, at least in the near future, resulting in governments choosing vendors from countries other than China.

5. Key Conclusions

China has the most ambitious civil nuclear power programme in the world. By 2030, the country will probably have the largest installed capacity of nuclear power reactors, ahead of the United States. This source of electricity will enhance the nation's energy security and contribute to the reduction of CO_2 emissions from power generation. By 2050, aggregate installed capacity could exceed 300 GWe. However, a serious nuclear accident either within China or elsewhere could undermine public confidence in nuclear power and constrain the further expansion of capacity.

Since the launch of its civil nuclear power programme in 1978, China has been determined to be self-sufficient in all the relevant technologies. After years of relying on foreign vendors, it is close to achieving this aim. The recently commissioned Hualong One reactors are of Chinese design and comprise mainly Chinese components. China's nuclear industry is also developing many different reactor technologies, including small modular reactors; maritime nuclear reactors; advanced nuclear technologies, such as high-temperature gas-cooled reactors and molten salt reactors; and nuclear fusion. In pursuit of supply security, it has built substantial capacity for uranium enrichment and fuel fabrication. As the country lacks sufficient uranium resources, it is building capacity for spent fuel reprocessing.

Their scale, combined with the depth and breadth of their technological expertise, make Chinese companies potentially powerful actors in the international civil nuclear power industry. To date, however, these companies have been too preoccupied with domestic projects to expend much effort pursuing international opportunities. In addition, with the exception of Pakistan, China's government has yet to give substantial financial or diplomatic support for such overseas ventures. When these two factors change, Chinese companies could become the world's dominant vendors of nuclear power technology.