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CHINA-RUSSIA NUCLEAR INDUSTRY COOPERATION

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Abbreviations

ASE	AtomStroyExport
CEFR	China Experimental Fast Reactor
CEP	Centrifuge Enrichment Plant
CFR	China Fast Reactor
CGN	China General Nuclear Power Group
CIAE	China Institute of Atomic Energy
CNECC	China Nuclear Engineering and Construction Group
CNEIC	China Nuclear Energy Industry Corporation
CNNC	China National Nuclear Corporation
CNNP	China National Nuclear Power Company
CNPE	China Nuclear Power Engineering
FNPP	Floating Nuclear Power Plant
FNR	Fast Neutron Reactor
GW	Gigawatt
HEU	Highly Enriched Uranium
HTGR	High-Temperature Gas-Cooled Reactor
HWRR	Heavy Water Research Reactor
IAEA	International Atomic Energy Agency
IPPE	Institute of Physics and Power Engineering
ITER	International Thermonuclear Experimental Reactor
JNPC	Jiangsu Nuclear Power Corporation
MCP	Main Circulation Pump
MOX	Mixed Oxide
MSZ	MashinoStroelny Zavod
MW	Megawatt
MWe	Megawatts of electrical capacity
NIKIET	NA Dollezhal Scientific Research and Design Institute of Power Engineering
NPP	Nuclear Power Plant
PIMCU	Priargunsky Industrial Mining and Chemical Union
PRC	People's Republic of China
PWR	Pressurized Water Reactor
RCIF	Russia-China Investment Fund for Regional Development
RMB	Renminbi
SASAC	State-owned Assets Supervision and Administration Commission
SDN	Specially Designated Nationals
SOE	State-Owned Enterprise
SPIC	State Power Investment Corporation

SNPTC	State Nuclear Power Technology Corporation
SWU	Separative Work Unit
TENEX	Techsnabexport
USD	United States Dollars
VNIIEF	All-Russian Scientific Research Institute of Experimental Physics
VVER	Water-water energy reactors

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INTRODUCTION

In May 2021, Russian president Vladimir Putin and Chinese president Xi Jinping presided over a groundbreaking ceremony for their countries' biggest[i] joint nuclear energy project to date: the construction of four new nuclear reactors in China's Jiangsu and Liaoning Provinces.[ii] The 20 billion renminbi (RMB) ($2.81 billion USD)[iii] construction project is part of a package of strategic cooperation agreements signed by Russia and China in 2018.[1] More generally, it is a manifestation of growing China-Russia cooperation in the nuclear field since the 1990s, which has accelerated in recent years due to both countries' ambitious nuclear energy goals and increasingly close relationship.

The two countries are natural partners in this sector. Russia, a historic pioneer in the field of nuclear energy, is today the world's top exporter of nuclear reactors and holds the record for the greatest number of nuclear reactors under construction simultaneously. Its history of providing China with nuclear technology and expertise dates back to the 1950s, when the Soviet Union sold China its first nuclear reactor.

China is rapidly expanding its domestic nuclear capacity as part of an effort to reduce its dependence on coal power, which has caused severe pollution and made China the world's largest carbon dioxide emitter. Furthermore, as Russia becomes increasingly isolated in the world due to its 2014 annexation of Crimea and 2022 invasion of Ukraine, it has grown more reliant on China to prop up its economy – and its energy sector, in particular.

Nuclear energy, while making up a smaller share of Russia and China's economies and electricity generation than fossil fuels, is a key strategic technology that has grown steadily in both countries. Despite this, it has received relatively little attention from Western observers. English-language literature on the subject tends to focus on Russian and Chinese nuclear energy developments independently of one another,[2] or on Russia and China as competitors in the global nuclear energy market.[3] Work that specifically centers on cooperation between China and Russia in the nuclear energy sector remains scarce.

This report will attempt to fill this gap in the literature by examining the nature of nuclear cooperation between China and Russia over the past three decades. It finds that while collaborative efforts remain a relatively small proportion of the two countries' respective nuclear industries, they have grown steadily and promise to grow further as the two enjoy increasingly close relations. In March 2023, China and Russia signed an agreement to deepen their nuclear energy cooperation, especially in development of fast reactors, production of uranium-plutonium fuel, and handling of spent nuclear fuel.[4]

However, this relationship is disproportionately focused on projects in China, and rapidly transforms into a competitive relationship in the international nuclear energy market, where both states are vying for market share. In this way, nuclear energy can be seen as a microcosm of the greater China-Russia relationship: increasingly closely aligned out of mutual self-interest, but still wary and prone to competition when the two states' interests diverge.

Further, while the larger China-Russia partnership has become increasingly lopsided with Russia finding itself in the position of junior partner, nuclear energy is a rare area where Russia

[i] China and Russia had never previously constructed this many reactors as part of a single project.

[ii] The ceremonies for both locations were held simultaneously, with Xi and Putin presiding over video call.

[iii] All RMB to United States Dollar (USD) currency conversions use an exchange rate of 7.11 RMB to 1 U.S. dollar, the rate as of 1 January 2024.

continues to play the more senior role. However, this dominance is also likely to wane in the coming years as China's nuclear industry continues to mature.

Section 1 will provide an overview of each country's most important nuclear industry players, as well as their policy priorities and current agendas for the sector. Section 2 will provide a brief history of Soviet-era cooperation, followed by an examination of the various joint projects in the nuclear sector that Russia and China have undertaken since the early 1990s. Section 3 will discuss China-Russia competition in the global nuclear energy market. Finally, the report will conclude with an analysis of the relationship and implications for the United States and the West.

Section 1. China and Russia's Nuclear Industries

Both China and Russia's nuclear industries are dominated by a small number of large state-owned enterprises (SOEs) and largely driven by government priorities rather than purely commercial considerations. This section will provide an overview of each country's nuclear industry as well as the plans and priorities guiding their nuclear energy development into the future.

China's Nuclear Industry

China's nuclear industry is dominated by the China National Nuclear Corporation (CNNC) and China General Nuclear Power Group (CGN). These two state-owned enterprises and their subsidiaries together operate nearly all of the country's nuclear power plants (NPPs) and are also responsible for reactor design, nuclear fuel production, and other parts of the nuclear fuel cycle, as well as exports of nuclear technology. The State Power Investment Corporation (SPIC) is the third largest NPP operator and designer in China. Other, less prominent, companies in the industry are too numerous to detail in this report.[5]

China National Nuclear Corporation (CNNC) [中国核工业集团有限公司]

The China National Nuclear Corporation (CNNC) is the dominant company in China's nuclear industry, responsible for research and development of both civilian and military nuclear technologies, uranium mining and enrichment, and other important nuclear industry functions such as waste disposal. A national state-owned enterprise under the State Council's State-owned Assets Supervision and Administration Commission (SASAC),[iv] CNNC was founded in 1988 by the State Council and owns shares in most of China's nuclear energy projects.[6] The company is a successor to the Ministry of Nuclear Industry, which built China's first nuclear weapons.[7] It is also responsible for international cooperation, and nuclear industry imports and exports.[8]

CNNC has over 200 subsidiary businesses and research institutes,[9] including China National Nuclear Power Company (CNNP), China National Uranium Corporation, and CNNC International.[10] The China National Uranium Corporation has a monopoly on domestic uranium mining in China.[11] In 2018, CNNC took over China Nuclear Engineering and Construction Group (CNECC), China's main nuclear construction company.[12] According to its website, CNNC owns 24 nuclear reactor units, including the multi-unit Qinshan Nuclear Power Plant, China's first domestically-designed nuclear plant, and has 6 more under construction.[13]

In March 2019, CNNC announced plans for a "China nuclear civil-military fusion industrial development fund."[14] In June 2021, the U.S. Department of Treasury Office of Foreign Asset Control (OFAC) added CNNC to its list of non-SDN Chinese Military-Industrial Complex Companies, likely due to its involvement in China's nuclear weapons production.[15]

China General Nuclear Power Group (CGN/CGNPC) [中国广核集团]

The China General Nuclear Power Group, formerly known as China Guangdong Nuclear Power Group, is a national SOE directly supervised by SASAC. When the company was established in 1994, its ownership was primarily split between the Guangdong provincial

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[iv] Established in 2003, SASAC is a government body tasked with managing China's state-owned enterprises.

government and CNNC, and most of its operations were located in Guangdong Province in southeastern China. Since then, it has expanded its operations, transferred the majority of its shares to SASAC, and moved its headquarters from Shenzhen to Beijing.[16]

CGN subsidiaries include CGN Electric Power, CGN Power Co. (which operates CGN's nuclear power plants), CGNPC Uranium Resources Co. (a uranium fuel supplier), and the non-nuclear CGN New Energy Holdings, among others.[17] As of December 2023, CGN had a total installed nuclear power capacity of 30.57 gigawatts (GW)[v] at 27 reactor units, and was building or planned to build 11 more units with 13.25 GW of capacity.[18]

CGN and affiliates were added to the U.S. Entity List in 2019 for "efforts to acquire advanced U.S. nuclear technology and material for diversion to military uses in China."[19] It also appeared (along with CNNC) on a list of Chinese military-linked companies released by the U.S. Department of Defense in 2020.[20]

State Power Investment Corporation (SPIC) [国家电力投资集团]

The State Power Investment Corporation is a national SOE formed in 2015 from the merger of the former China Power Investment Corporation (CPI) and the State Nuclear Power Technology Corporation (SNPTC).[21] SPIC is one of the three main developers and operators of nuclear power in China, though unlike CNNC and CGN its business scope is not specifically focused on nuclear power. SPIC claims to have six nuclear reactor units in operation, for a total installed capacity of 8.09 GW of electricity, with four more reactors are under construction.[22]

SPIC was the lead entity in the design of Guohe One [国和一号], a nuclear reactor which it describes as the most advanced third-generation nuclear power technology in the world.[23] Guohe One, also known as CAP1400, is a pressurized water reactor (PWR) developed based on the AP1000 from the American company Westinghouse.[24]

China's Policy Goals and Plans for the Nuclear Industry

China's highest-level development agenda is set by the Five-Year Plans, policy documents which lay out the country's economic and social development priorities every five years. The current (14th) Five-Year Plan was approved in 2021 and covers the period from 2021-2025. The sections on modern energy infrastructure and environmental protection are the most relevant to the development of nuclear power in China, and include the following goals:[25]

- Reduce carbon emissions per unit of GDP by 18% by 2025.
- Reach peak carbon emissions by 2030 and achieve net-zero carbon emissions by 2060.
- Increase the proportion of non-fossil fuel energy in total energy consumption to 20% by 2025.
- Increase total operating capacity of nuclear power to 70 GW by 2025.
- Construct the Hualong One [华龙一号], Guohe One, and high-temperature gas-cooled reactor (HTGR) demonstration projects and promote the construction of third-generation nuclear power along the coast.
- Promote advanced reactors such as modular small-scale reactors, 600megawatt (MW) commercial HTGRs, and offshore floating nuclear power platforms.

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[v] For reference, one gigawatt is enough to power about 750,000 homes in the United States. See: AJ Dellinger, "Gigawatt: The solar energy term you should know about", CNET, 16 November 2021, https://www.cnet.com/home/energy-and-utilities/gigawatt-the-solar-energy-term-you-should-know-about/

- Construct low- and medium-level radioactive waste disposal sites for nuclear power plants as well as spent fuel reprocessing plants.

Researchers from Tsinghua University found that in order to achieve carbon neutrality by 2060, China would need to increase nuclear power consumption by 382% compared to 2025, solar by 587%, and wind by 346%, while reducing consumption of coal, natural gas, and oil by 96%, 75%, and 65%, respectively. If it proceeds according to plan, China is predicted to overtake the United States as the world's largest producer of nuclear power by 2030.[26]

It is worth noting that China had only 51 GW of installed nuclear energy capacity in approximately 50 reactor units at the end of 2020, failing to meet the target of 58 GW set by the 13th Five Year Plan. This was likely due to a two-year halt on new reactor construction following a safety review in the wake of the Fukushima nuclear disaster. (As of September 2023, the installed capacity reached 55 reactors and nearly 57 GW.)[27] Despite the delay, the 14th Five Year Plan sets a new goal of 70 GW by 2025. This is less ambitious than numbers given by some Chinese nuclear organizations, government agencies, and officials (albeit over differing time periods). For example, the chairman of CGN put forth the goal of 200 GW by 2035, nearly four times China's currently installed capacity and enough to power a dozen Beijing-sized cities.[28]

Regardless of which capacity targets it decides upon, China is currently on a reactor building spree. 80% of its nuclear reactors were built in the last decade, and half the new reactors it needs to reach the 70 GW target by 2025 were already under construction in 2021.[29] There are reportedly plans for the construction of 150 new reactors in the next 15 years, at a cost of approximately $440 billion USD.

Although China's main priority is in increasing the efficiency, self-sufficiency, and cleanliness of its domestic energy supply, its new nuclear construction plans are not limited to Chinese territory. In 2019, former CNNC chair Wang Shoujun [王寿君] said that China could build as many as 30 overseas nuclear reactors by 2030 as part of the Belt and Road Initiative, which could earn China as much as 1 trillion RMB ($140.65 billion USD).[30] CNNC and CGN are also jointly developing a low-power floating nuclear reactor that will be deployed in the South China Sea, the first of 20 planned reactors that China hopes to deploy in the disputed waters.[31]

The majority of China's domestic reactors are either indigenous or significantly modified foreign designs. Of China's 55 operational reactors by the end of 2022, 28 – just over half – were second generation reactors designated CPR-1000, ACPR-1000, or M310+, which are Chinese designs based on the French M310 reactor. 11 were other Chinese indigenous designs, including three third-generation Hualong One reactors. 16 were relatively unmodified imports: six from France, two from Canada, four from the United States, and four from Russia (at the Tianwan NPP). The small China Experimental Fast Reactor is also Russian-designed.[32]

While China's current nuclear capacity includes a variety of reactor types and models, several new reactor technologies have received particular emphasis in China's future plans. The Hualong One (HPR-1000), a joint project of CGN and CNNC, is China's first indigenously designed third-generation pressurized water reactor (PWR). It and the CAP1000 (a Chinese version of Westinghouse's AP1000) are the most common models for new reactors: of the 22 reactors currently under construction in China as of mid-2023, ten are Hualong One models and three are CAP1000s. According to the World Nuclear Association, China has plans to build at least 21 more Hualong One models and 21 more CAP1000s, and has proposed nearly 150 further reactors of these two models (though these proposals are largely tentative, for now, and do not have concrete start dates). The Hualong One in particular is being promoted as China's leading nuclear technology for export. China is also seeking to build more small modular PWRs (less than

300 MW capacity), fast neutron reactors (FNRs), and HTGRs.[33] These technologies could be particularly useful to China's energy efficiency and environmental priorities: small modular reactors can be placed on floating platforms or replace generators in existing fossil fuel plants without the need to construct a new nuclear power plant; fast neutron reactors can recycle spent nuclear fuel (and also potentially produce weapons-grade plutonium);[34] and HTGRs are generally safer than traditional PWRs.[35]

It remains to be seen whether China can meet its carbon emission reduction goals and reach 70GW of nuclear energy capacity by 2025 as planned, as it has failed to reach its targets before. However, the explosion of new NPP construction certainly bodes well for meeting these goals. China's development of indigenous reactor technologies like the Hualong One, Guohe One, and CFR-600 fast neutron reactor will help meet its growing energy needs while lowering emissions, and even enable it to challenge Russian dominance of the global nuclear energy market. However, China has not fully phased out cooperation with foreign partners. China's nuclear industry initially developed with a great deal of help from the former Soviet Union, and cooperation with Russia still plays a significant role today. China is moving forward with plans to construct new Russian water-water energy reactors (VVER), a type of PWR, and imports nuclear fuel assemblies from Russia to power some of its reactors (particularly those constructed with Russian help). It also continues to make use of Russian technology and expertise to help it develop fast neutron reactors, which form an important part of China's nuclear energy strategy in the future.

RUSSIA'S NUCLEAR INDUSTRY: ROSATOM [POCATOM]

Rosatom (sometimes spelled Rusatom) is a Russian state-owned megacorporation that holds a monopoly over Russia's nuclear energy industry, encompassing the entire nuclear cycle. Created in 2004 as the Federal Atomic Energy Agency, it replaced the abolished Ministry of Atomic Energy (Minatom) and was reorganized from an executive body into a state corporation in 2007.[36]

Rosatom is Russia's largest electricity producer, producing roughly 20% of Russia's electricity,[37] and one of the largest nuclear energy companies in the world, comprising over 300 organizations and enterprises and employing over 275,000 people. Rosatom subsidiary Atomenergoprom is a holding company for the entirety of Russia's civil nuclear energy industry, including the nuclear plant operator Rosenergoatom, the nuclear plant construction firm AtomStroyExport (ASE), the nuclear fuel producer TVEL, and the uranium exporter Techsnabexport (TENEX). Rosatom owns and operates all of Russia's 38 reactor units at 11 nuclear power plants,[38] and has 34 reactor units in various stages of development overseas, including in China. As of 2023, Rosatom is the leading company in the world for number of simultaneous nuclear reactor construction projects.[39]

Besides civilian nuclear energy, Rosatom is responsible for Russia's nuclear weapons complex, developing and producing all nuclear munitions in Russia. It oversees the activities of 17 research and development (R&D) organizations and enterprises,[40] including the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), which was one of the key entities responsible for the USSR's development of nuclear weapons and is now tasked with maintenance and improvements to Russia's nuclear arsenal.[41]

RUSSIA'S POLICY GOALS AND PLANS FOR THE NUCLEAR INDUSTRY

Russia's overall energy policies are set by the *Energy Strategy of Russia*, which was first approved by the Russian government in 2000 and confirmed in 2003 for the period up to 2020.

The most recent version, approved in 2020, covers the period up to 2035. Despite various amendments over the past two decades, the strategy's main priorities have remained largely consistent: increasing energy efficiency, reducing environmental damage from energy production, increasing sustainable development, energy development and technological development, and improving international competitiveness.[42]

On the subject of nuclear power, the 2020 *Energy Strategy of Russia* noted that electricity generated by NPPs in Russia had increased by 25% between 2008 and 2018, coinciding with eight new nuclear reactor units being put into operation, while NPP exports to other countries had also increased. The strategy identified two main obstacles in the development of Russia's nuclear industry: the high cost of ensuring nuclear safety and disposing of radioactive waste, and the low percentage of profitable uranium reserves in Russia's total mineral base.[43] The *Strategy* laid out the following goals for Russia's nuclear energy industry:

- Improve the efficiency of nuclear power and ensure the economic competitiveness of new NPPs. To quantify this goal, the document set targets for the percentage of Russia's total installed nuclear generation capacity that should be made up of generation 3+ NPPs and modernized nuclear reactor units. In 2018, this percentage was 13%. Russia aims to increase it to 26% by 2024 and to 40% by 2035.
- Develop and implement new technology involving the parallel use of thermal (conventional) and fast neutron nuclear reactors in a closed nuclear cycle, i.e., a system that reprocesses and reuses spent nuclear fuel. The *Strategy* noted that Russia was already a global leader in this technology, and that this parallel use of thermal and fast neutron reactors can help solve problems of nuclear fuel production, minimize radioactive waste, and ensure compliance with nonproliferation rules. As a quantifiable indicator, the document set targets for the total installed capacity of fast neutron reactors in Russia: 1.48 GW by 2024 (unchanged from 2018), and ultimately 1.78 GW by 2035.
- Develop uranium deposits in Russia and other countries to ensure a sufficient raw material base for nuclear energy.
- Develop nuclear fuel cycle technologies based on new generation gas centrifuges, modernization of separation and sublimation plants, and increased economic efficiency of nuclear fuel and its components, as well as creating facilities for production of new types of fuel.
- Create enterprises in a closed nuclear fuel cycle for the management of spent fuel and radioactive waste and production of fuel from regenerated materials.
- Improve decommissioning technologies for NPPs.
- Create low-capacity NPPs for power supply in remote and isolated territories.

In 2021, the Russian government drafted a decarbonization strategy target of net zero carbon emissions by 2060 – the same goal as China – and this target was reiterated by President Putin at an energy forum in Moscow that year.[44] However, because of the international sanctions imposed on Russia as a result of its 2022 invasion of Ukraine, Russia's Ministry of Energy has stated the Russian fuel and energy sector may no longer be able to meet its carbon emissions reduction targets.[45]

In addition to government policy documents, specific plans for the implementation of Russia's nuclear power development goals are set by Rosatom, which has largely been able to avoid sanctions at the time of writing.[vi] In 2012, Rosatom released its development plan up to the year 2030. Overall, the company sought to achieve greater product innovation, global competitiveness, and market expansion to ultimately become a top three company in every part of the global nuclear energy market by 2030. The share of revenue from foreign operations was anticipated to rise from 33% in 2011 to 50% by 2030, while the share of revenue from new products would rise from 4% in 2011 to 40% by 2030.[46] A 2020 update to the strategy reaffirmed these goals, specifying that Rosatom aimed to increase revenue to 4 trillion rubles (about $44.94 billion USD)[vii] by 2030, now with "more than half" coming from foreign operations and over 40% from new products.[47]

In 2021, Rosatom drafted a plan for the development of new nuclear technologies until 2030. The estimated cost of the plan is 506 billion rubles ($5.68 billion USD), of which 150.3 billion ($1.69 billion USD) would come from Russian government funding and the rest from extra-budgetary sources. The majority of the funding is for "Small Atom," a 260 billion ruble ($2.92 billion USD) plan to construct low-power nuclear reactors: NPPs with a generation capacity up to 300 MW. Rosatom hopes to have its first small reactor export contract by 2026, and contracts for six such units by 2030. It aims to become the world leader in the small NPP market, with a market share of around 20% by 2030.[48]

Russia has also commissioned the first "small nuclear reactor" in the world, the 70 MW floating nuclear reactor *Akademik Lomonosov*. "Small Atom" includes plans for the construction of four more such floating reactors domestically by 2028. The main purpose of small and floating reactors is to supply power to remote areas, such as the Baimsky mining project in Chukotka.

The second-largest part of Rosatom's plan is the 222.65 billion ruble ($2.5 billion USD) "Zero Waste Atom," which involves the construction of fast neutron reactors and developing technology for a closed nuclear fuel cycle. Rosatom plans to launch the lead-cooled fast reactor BREST-300 by the end of 2027 and complete the design of the sodium-cooled BN-1200 by the end of 2030. The development of these two reactors as well as Russia's plans more generally for a closed nuclear fuel cycle based on fast reactors fall under the purview of Rosatom's Proryv [Прорыв] (Breakthrough) project.[49]

The third major section of the plan is "Clean Atom for the World," which aims to increase Russia's sale of nuclear fuel to foreign NPPs. By 2030, Rosatom hopes to increase is nuclear fuel market share to 24%, up from 17% in 2021.

Finally, there is a 23.39 billion ruble ($263 million USD) plan to confirm the feasibility of nuclear power as a tool for fighting climate change. It is largely a campaign to promote the inclusion of nuclear power in climate policy.[50]

In March 2021, Rosatom's publication *Strana Rosatom* said that nuclear energy should make up 25% of Russia's energy balance by 2045.[51] The production and consumption of nuclear energy in Russia has steadily increased since at least 1990, from 10.9% in that year to 20.7% in 2020.[52]

In September 2021, Rosatom CEO Alexey Likhachev announced that the company plans to expand most of Russia's existing nuclear power plants with around 15 new (generation 3+) 1.2

[vi] While the EU has avoided sanctioning Rosatom, the U.S. has targeted several of its subsidiaries. For example, see: "Imposing Additional Sanctions on Those Supporting Russia's War Against Ukraine," U.S. State Department, 20 July 2023, https://www.state.gov/imposing-additional-sanctions-on-those-supporting-russias-war-against-ukraine/

[vii] All ruble to USD conversions use an exchange rate of 89 rubles to 1 USD, the rate as of 1 January 2024. The value of the ruble has been highly volatile since the 2022 invasion of Ukraine.

GW reactor units. The new units will replace older nuclear reactors built in the 1970s, which Rosatom will gradually decommission.[53]

Taken together, these initiatives address most of the policy goals Russia has set for nuclear energy (though their success is not guaranteed, as it requires overcoming formidable technological hurdles). The Proryv project directly serves the goals of increasing nuclear energy efficiency, developing fast neutron reactors, and closing Russia's nuclear fuel cycle. "Small Atom" and the floating nuclear reactor address the need to supply low-power reactors to remote areas of Russia. The recently announced plans to construct new third-generation reactors serve Russia's desire to upgrade to its nuclear infrastructure. China's contribution to these goals is mostly as a source of revenue for Rosatom: Russia's nuclear industry is self-sufficient enough that it does not directly need Chinese cooperation to accomplish its domestic nuclear energy goals (with a few exceptions, as shown in the following section).

SECTION 2. CHINA-RUSSIA NUCLEAR COOPERATION

HISTORICAL NUCLEAR COOPERATION

The Soviet Union was one of the first countries in the world to develop nuclear power. It initially developed the technology in its pursuit of nuclear weapons, detonating its first atomic bomb in 1949. In 1954 the Soviet Union's Institute of Physics and Power Engineering (IPPE, now a Rosatom subsidiary) completed the world's first nuclear powered electrical generator, the AM-1, in the closed city of Obninsk. The AM-1 operated until 1959.[54]

In the same period, the People's Republic of China (PRC) was in its infancy and relied heavily on the USSR for its own nuclear development. In 1950, the two countries signed an agreement for the joint exploration of non-ferrous and rare metals (e.g. uranium) in China's Xinjiang region.[55] China then secretly agreed to provide uranium to the USSR in exchange for Soviet technical expertise in the nuclear field.[56] The groundwork for further cooperation was laid in a 1955 bilateral agreement in the field of nuclear physics and the peaceful use of nuclear energy. China's first nuclear reactor, the Heavy Water Research Reactor (HWRR), was a 7 MW unit imported from the Soviet Union and constructed with Soviet assistance between 1956 and 1958.[57] The USSR also trained China in the construction of nuclear weapons and promised to supply a prototype atomic bomb.[58]

The deterioration of Sino-Soviet relations known as the Sino-Soviet Split abruptly ended all nuclear cooperation between the two countries in 1959. Moscow withdrew its scientific advisors and did not deliver the promised prototype bomb. Sino-Soviet cooperation in the nuclear field ceased for several decades,[59] and China proceeded to develop its nuclear infrastructure independently. However, China did not connect its first nuclear reactor to the electrical grid until 1991, when Phase I of the Qinshan NPP became operational.[60]

China-Russia nuclear cooperation was rekindled in the 1990s, after the fall of the Soviet Union. In 1992, the two countries signed a new nuclear cooperation agreement that laid the groundwork for the Tianwan Nuclear Power Plant in Lianyungang, their first joint nuclear project since the 1950s.[61] The Tianwan NPP and all subsequent nuclear cooperation between the two countries will be discussed in the remainder of Section 2.

TIANWAN NUCLEAR POWER PLANT

The Tianwan nuclear power plant, located near Lianyungang in China's Jiangsu province, is the largest nuclear plant in China. A joint project between Russia and China, it currently consists of six operational reactors, constructed in three phases of two reactors each. Two more units – Phase IV – are currently under construction. When all eight units are completed and commissioned, Tianwan will have a total capacity of around 8.1 GW of electricity, making it the largest nuclear power plant in the world. The plant is owned and operated by Jiangsu Nuclear Power Corporation (JNPC), a joint venture between CNNC (which owns half the shares), China Power Investment Corporation, and Jiangsu Guoxin Group.[62]

Phase I, the first two reactor units, began construction in 1999 and was commissioned in 2007. It was based on a 1992 cooperation agreement between China and Russia and reportedly cost $3.2 billion USD, of which China contributed $1.8 billion. Construction was carried out by the Rosatom subsidiary ASE, which was responsible for designing the plant, supplying and installing equipment, commissioning the plant, and training Chinese personnel. The reactors are

Russian AES-91 type VVER-1000 pressurized water reactors, each with an electrical generation capacity of 1.06 GW, which were designed by the Rosatom subsidiary OKB Gidropress.[63]

In 2010, ASE and JNPC signed a contract to cooperate on the construction of Phase II (Units 3 and 4) of the Tianwan plant. Units 3 and 4 are Russian-designed VVER-1000 reactors, similar to Units 1 and 2. While Rosatom designed the nuclear components of the project, JNPC was responsible for the design and supply of non-nuclear components.[64] Put into operation in 2018, the two units have a power generation capacity of 1.126 GW, an improvement on the Phase I reactors.[65] ASE has handed ownership of the four Russia-constructed Tianwan reactors to Chinese operators.[66]

Phase III of Tianwan consists of the plant's only two domestically designed units. Their construction was carried out by CNNC subsidiary China Nuclear Power Engineering (CNPE) and did not include significant Russian involvement.[67] Units 5 and 6 are ACPR-1000 pressurized water reactors with a capacity of 1.08 GW each. They began construction in 2015 and 2016, respectively,[viii] and entered commercial operation in 2020 and 2021.[68]

In June 2018, Russia and China signed an agreement to cooperate on the construction of Phase IV (Units 7 and 8) of the Tianwan plant. The general contract for the project was signed in 2019 between ASE and CNNC. Units 7 and 8 are Russian-designed VVER-1200 reactors that will be 20% more powerful than the earlier VVER-1000s (with an electrical capacity of 1.128 GW), require fewer personnel, and last 60 years (twice as long as the operating period for the earlier generation). The two reactors are planned to begin operation in 2026 and 2027.[69] First concrete for Unit 7 was poured in May 2021, while Unit 8 began construction in February 2022.[70]

It is not readily apparent why China constructed Tianwan Phase III indigenously but chose to import Russian reactors for Phase IV, as it did for the first two phases. The decision was not related to any performance issues with Phase III: according to the World Nuclear Association, CNNC announced that Tianwan Phase IV would consist of Russian VVERs at least as early as 2013, before Phase III was approved to begin construction. Nor is the VVER-1200 obviously superior to Chinese technologies: the 1.2 GWe third-generation reactor is comparable to the Hualong One reactors China is building elsewhere.[71] It is possible that although China generally prioritizes indigenous designs, it is still interested in continuing to acquire advanced foreign technologies such as the VVER-1200. After all, imports and technology transfer agreements from other countries have been critical to China's development of its indigenous nuclear technology to date. Furthermore, the Tianwan NPP has always been a joint Chinese-Russian endeavor and is emblematic of the two countries' cooperation in nuclear energy; in light of this background, it is perhaps not surprising that an expansion of the Tianwan plant in particular would involve Russian technology.

[viii] Phase III was originally intended to begin construction in 2011, but the Fukushima nuclear disaster caused the project to be delayed by about five years.

The six operational reactor units of the Tianwan nuclear power plant, 2021.
Source: Global Times *https://www.globaltimes.cn/page/202104/1221395.shtml*

XUDABAO/XUDAPU NUCLEAR POWER PLANT

The same June 2018 package of agreements that laid the groundwork for Tianwan Units 7 and 8 also included an agreement to cooperate on the construction of Units 3 and 4 of Xudabao (also known as Xudapu) nuclear power plant, located in northeastern Liaoning province. Xudabao 3 and 4 will be Russian-designed VVER-1200 reactors, the same type used in Tianwan Phase IV.[72] Construction on Unit 3 began in July 2021, while Unit 4 commenced construction in May 2022. Rosatom will design the nuclear island and is responsible for supplying key equipment, supervising installation, and providing commissioning services, while China is supplying turbine generators and supporting systems. The reactors are expected to begin operation in 2027-2028.[73]

Despite their names, Xudabao 3 and 4 are actually the first reactors in that plant to begin construction. The $17 billion USD nuclear plant was originally planned to feature six American AP1000 reactors (or their localized Chinese variant, CAP1000). The site was selected in 2010, but plans were significantly delayed after the Fukushima nuclear accident in 2011. In 2016, CGN subsidiary China Nuclear Power Engineering Company (CNPEC) signed a contract with China Nuclear Industry 22 Construction Company (a subsidiary of China Nuclear Engineering and Construction Corporation, which is now part of CNNC) for the construction of Xudabao Units 1 and 2.[74] However, Xudabao 1 only began construction in November 2023, and Xudabao 2 is not expected to begin construction until 2024.[75] Possibly for this reason, Rosatom was eventually contracted to build Units 3 and 4 (now VVER reactors). The plant is owned by Liaoning Nuclear Power Company Ltd., a joint venture owned primarily (70%) by CNNC, with minority stakes owned by Datang International Power Generation Company and the State Development and Investment Corporation.[76] Rosatom subsidiary TVEL signed a contract in 2019 to supply Xudabao Units 3 and 4 with nuclear fuel, including fuel assemblies.[77]

Both China's failure thus far to construct the long-planned Xudabao Units 1 and 2 and its decision to use Russian VVER reactors for Units 3 and 4 were the result of years of delays impacting the installation of American AP1000/CAP1000 reactors in general. The AP1000 was once intended to be the basis of China's third generation nuclear power. However, planned installations of AP1000 reactors at various Chinese nuclear powerplants were impeded by serious financial, technological, regulatory, and logistical hurdles: in fact, outside the Xudabao plant, China quietly canceled plans for eight new AP1000s in 2016-2017, replacing them with indigenous designs. The problems were such that the Nicobar Group, a consulting firm specializing in China's nuclear industry, reported that Beijing seemed to be "abandoning the AP1000 technology tree."[78] (Such implementation problems were not limited to China: serious financial and logistical problems with planned AP1000 reactors in the United States caused Westinghouse to declare bankruptcy in 2017.[79])

The installation of new AP1000/CAP1000 reactors in China was further hindered by policy changes in the United States restricting technology transfer to China. In 2018, the US Department of Energy issued a new policy curtailing cooperation with China on new reactor and small reactor technology, as well as restricting exports of U.S. nuclear technology to China that would compete with U.S. nuclear power. CGN's placement on the U.S. Department of Commerce's Entity List in 2019 presented another obstacle.[80]

On one hand, the Xudabao case shows that the decline of the AP1000 is an opportunity for Rosatom, which remains a tried-and-tested reactor supplier for China. On the other hand, Xudabao appears to be more an exception than the rule: China's preferred alternative to the CAP1000 has been its own indigenous Hualong One, not imports from Russia.[81] Furthermore, the CAP1000 itself still cannot be counted out: China approved two new reactors of this model in October 2022, and Westinghouse recently appears to be making a resurgence in the global market.[82]

A digital rendering of what Xudabao 3 and 4 could look like when completed.
Source: AtomStroyExport
https://www.world-nuclear-news.org/Articles/First-concrete-poured-for-Xudabao-3

China Experimental Fast Reactor (CEFR)

The China Experimental Fast Reactor (CEFR) is China's first fast nuclear reactor,[83] located outside Beijing at the China Institute of Atomic Energy (CIAE), an institute of the Chinese Academy of Sciences affiliated with CNNC.[84] It is a sodium-cooled pool-type reactor designed to operate with 65 MW of thermal power and 20 MW of electrical power.[85] The reactor was officially approved by the State Council in 1995 as a major project of the 863 Program, a national initiative for high-tech research and development, and began construction in 2000.[86]

CEFR was designed and constructed by a consortium of Russian firms led by OKBM Afrikantov, also including OKB Gidropress, NA Dollezhal Scientific Research and Design Institute of Power Engineering (NIKIET), the Kurchatov Institute, and other Russian institutions. OKBM Afrikantov, OKB Gidropress, and NIKIET are Rosatom subsidiaries, while the Kurchatov Institute is a National Research Center .[87] Russian work on the reactor began in 1992, when OKBM Afrikantov, the St. Petersburg Institute "Atomenergoproekt" (SPbAEP), and the Institute of Physics and Power Engineering (IPPE) – all Rosatom subsidiaries – collaborated to develop the original concept of the CEFR, including its technical requirements and main components. The concept was approved in 1993 by the China Nuclear Energy Industry Corporation (CNEIC), CNNC's export/import subsidiary. From 1995-1998, Russian specialists developed the technical design of the CEFR, and after 1999 they performed testing for many components of the reactor (primarily at OKBM Afrikantov). In July 2000, the governments of Russia and China signed a cooperation agreement for CEFR in Beijing.[88]

CEFR began construction in 2000. Between 2003 and 2005, Russian firms delivered equipment for the construction of the reactor plant, including reactor vessel components, steam generators, instruments, level gauges, electromagnetic pumps, and fuel. From 2006-2011, Russian specialists were involved in the installation, commissioning, and start-up of the reactor. OKBM Afrikantov, IPPE, and the RIAR Training Center (another Rosatom subsidiary) also trained Chinese personnel who would work at the CEFR plant.[89] The Rosatom fuel company TVEL has worked with CIAE since 1999 to supply fuel for the reactor.[90]

CEFR first achieved criticality in 2010, connected to the grid in July 2011, and achieved stable operation at full power for 72 hours in December 2014 and for 144 hours in December 2015.[91] It was designed to have a service life of 30 years.[92] The reactor was shut down sometime after completing a low-power test phase in 2015, then restarted in June 2020 "for high-power operations," and apparently shut down again in July 2020. The reactor was restarted again in January 2021 and re-connected to the grid on 15 February 2021.[93] Although it has intermittently supplied power for the electrical grid, CEFR's 20 MW capacity is very low for a nuclear reactor and its purpose is fundamentally experimental.

China Experimental Fast Reactor (CEFR), China's first fast neutron nuclear reactor
Source: China Institute of Atomic Energy (CIAE)
https://www.iaea.org/newscenter/news/new-crp-neutronics-benchmark-of-cefr-start-up-tests-i31032

CHINA FAST REACTORS (CFR-600)

The CFR-600 (China Fast Reactor 600) is a sodium-cooled pool type reactor developed by CIAE based on China's experience with the CEFR. The reactor, considered the second step in CIAE's fast reactor development program, will have an electrical capacity of 600 MW and a thermal capacity of 1.5 GW, and is designed to operate for 60 years. Besides simply supplying electricity, the reactor is intended to demonstrate the capability of fast reactors to serve as breeder reactors, i.e. reactors that produce plutonium that can then be repurposed as nuclear fuel. It will be able to flexibly use either Uranium Oxide (UO_2) or Mixed Oxide (MOX) as fuel. More specifically, the reactor will initially use uranium fuel, which will then be converted into MOX.[94] MOX fuel is made by mixing depleted uranium with plutonium that is produced as a byproduct of used nuclear reactor fuel.[95]

China is building two CFR-600 reactors on Changbiao, a small islet off the coast of Xiapu, Fujian Province. The first unit began construction in December 2017 and is planned to be connected to the grid in 2023. The second unit began construction in December 2020 and is planned to connect to the grid in 2026.[96] When complete, the Xiapu NPP will be the first NPP outside Russia with a large-capacity fast neutron reactor.[97]

Unlike CEFR, the CFR-600 reactor was designed and constructed by CNNC and other Chinese firms, rather than primarily by Russian firms. However, Russian specialists were involved in the development of the reactors. OKBM Afrikantov signed agreements with relevant Chinese firms to provide key equipment for reactor operations and for handling nuclear fuel, Russian calculation codes for safety systems, services and technical support for reactor installation and commissioning, training of Chinese personnel in the use of the supplied equipment, and expert inspection of the CFR-600 units.[98]

The Russian company Mashinostroitelny Zavod (MSZ), a subsidiary of Rosatom nuclear fuel company TVEL, signed an agreement with CNNC subsidiary CNLY in December 2018 to provide nuclear fuel for the CFR-600 reactors. The company also provided test equipment for the reactors, including assemblies of the control and protection system.[99]

An Al Jazeera report in May 2021 raised concerns that the CFR-600 breeder reactors could be used to produce weapons-grade plutonium for China's rapidly expanding nuclear arsenal. In 2017, the same year the first CFR-600 reactor began construction, China stopped annual voluntary declarations of its civil plutonium stock to the International Atomic Energy Agency (IAEA) and did not add the new reactors to the IAEA's database.[100] A 2021 report from the Nonproliferation Policy Education Center assessed that reprocessing nuclear fuel for civilian energy purposes is not economically sensible, which raises suspicion that the CFR-600 reactors may have a dual purpose. The report estimated that China could obtain as many as 1,270 nuclear warheads by 2030 if one considers the plutonium production capabilities of its ostensibly civilian fast neutron reactor programs.[101] In its 2023 China Military Power Report, the U.S. Department of Defense estimated that China's total number of nuclear warheads surpassed 500 as of May 2023 and observed that Beijing was rapidly expanding its nuclear arsenal and building hundreds of new missile silos in recent years. The report projected that at current rates of expansion, China's arsenal could reach 1,000 warheads by 2030.[102] This is the third-largest nuclear arsenal in the world but still far smaller than the American and Russian stockpiles of 3,708 and 4,477 warheads,[ix] respectively.[103]

After CFR-600, the next step in the CIAE's fast reactor program will be the CFR-1000 reactor, a commercial-scale fast breeder reactor with an electrical capacity between 1 and 1.2 GW. Construction could start in 2028, possibly on the same site as the CFR-600 reactors. It is not yet clear whether Russia will be involved in this future project.[104]

In March 2023, Russia and China signed an agreement to deepen cooperation in development of fast reactors.[105]

CFR-600 reactor under construction
Source: Nuclear Engineering International magazine https://www.neimagazine.com/news/newschina-begins-construction-of-cfr-600-fast-reactor-6018483

[ix] These numbers do not include around 1,500 "retired" warheads awaiting dismantlement in each country.

Sanming BN-800 Reactors

The Sanming fast neutron nuclear plant was an unrealized project that was originally intended to be the successor to the CEFR. In 2009, AtomStroyExport signed an agreement with CIAE and CNEIC to design two commercial 800 MW fast neutron reactors for China. The original plan would have featured Russian BN-800 breeder reactors, which would be installed in Sanming, Fujian Province. In 2010, a CNNC-led joint venture called Sanming Nuclear Power Corporation, Ltd. was established to oversee construction and operation of the plant.[106] The project was originally scheduled to begin construction in 2013, but never materialized.[107] Instead, it appears to have been abandoned in favor of CFR-600 demonstration reactors constructed elsewhere in the same province.

Floating Nuclear Reactors

Floating nuclear power plants are primarily intended to provide electricity to remote coastal regions, making them a strategically useful commodity for places such as China's outposts in the South China Sea, or the more remote parts of the Russian Far East.

In July 2014, Rosatom Overseas signed a Memorandum of Intent with CNNC New Energy (a joint venture of CNNC and China Guodian Group) to cooperate in the creation of floating nuclear power plants.[108] In 2017, China's CNNC announced plans to build as many as 20 floating nuclear plants in the South China Sea, which could supply electricity and water to Chinese-controlled features in that region, many of which are disputed territories or artificially constructed.[109] So far, however, China's planned floating NPPs have not been completed and do not appear to involve significant Russian collaboration.

In 2019, Rosatom completed the world's first floating nuclear power plant (FNPP), the *Akademik Lomonosov*. In 2020, the plant entered commercial operation in Pevek, Chukotka,[x] in Russia's Far Eastern region.[110] In September 2021, Rosatom awarded a $226 million USD contract to the Chinese shipbuilding firm Wison (Nantong) Heavy Industries Co. to build two hulls for two more planned FNPPs, which will be used to supply power to the Baimsky mining and processing plant in Chukotka.[111] Besides the existing *Akademik Lomonosov*, Russia has plans to construct four more such plants for Chukotka, including the two with China-supplied hulls.[112]

The Akademik Lomonosov, the world's first floating nuclear power plant.
Source: BBC https://www.bbc.com/news/world-europe-49446235

[x] Russia's easternmost and most sparsely populated federal subject.

HANZHONG AND LANZHOU URANIUM ENRICHMENT PLANTS

China currently has three uranium enrichment plants: Plant 405 in Hanzhong, Shaanxi Province, Plant 504 in Lanzhou, Gansu Province, and Plant 814 at Emeishan and Jinkouhe in Sichuan Province. The facilities in Hanzhong (also known as Hanzhun) and Lanzhou were constructed entirely or partially by Russia, more specifically by the Rosatom subsidiary Tenex.[113]

In 1992 and 1996, the governments of Russia and China signed agreements for the provision of Russian gas centrifuge plants to China to produce low-enriched uranium. Under the first phase of the agreement, Tenex constructed a centrifuge enrichment plant (CEP) at Hanzhong in 1996, providing 200,000 Separative Work Units (SWU) of uranium enrichment capacity annually. A second module (Phase II) was constructed at the site in 1998, adding a further 300,000 SWU.[114]

Phase III of the agreement was a 500,000 SWU centrifuge facility constructed in Lanzhou in 2001. Unlike the Hanzhong plant, the Lanzhou enrichment site was originally constructed domestically and had existed prior to Russian involvement. A gaseous diffusion plant was established there in 1964 and was used to produce highly-enriched uranium (HEU) for China's nuclear weapons program until 1979, before switching to commercial operations from 1980-1997. This original plant was replaced by the Tenex-constructed CEP in 2001, and China undertook three more expansions with indigenously-constructed centrifuges starting in 2007. Lanzhou CEP 2, 3, and 4 became operational in 2010, 2012, and 2016, and a CEP 5 finished construction in 2023.[115]

In 2007, Tenex agreed to build another 500,000 SWU expansion for the Hanzhong enrichment plant, as the fourth and final stage of the initial agreement. The new centrifuges entered operation in 2013. In 2008 Tenex also agreed to supply the Hanzhong plant with low-enriched uranium from 2010 to 2021. This uranium was used to produce fuel for China's first four AP1000 reactors (at Haiyang and Sanmen).[116] Since then, China has further expanded the facility with indigenously-designed centrifuges. The Hanzhong enrichment plant is currently China's largest commercial uranium enrichment facility.[117]

Hanzhong uranium enrichment plant (Plant 405)
Source: Sina http://slide.mil.news.sina.com.cn/slide_8_400_25908.html#p=2

NUCLEAR FUEL FABRICATION AND PURCHASE AGREEMENTS

China's nuclear fuel fabrication – that is, turning enriched uranium and plutonium into fuel rods that can be loaded into reactors – is carried out by CNNC at facilities in Yibin, Sichuan Province, and in Baotou, Inner Mongolia. These facilities produce fuel for all of China's indigenous reactor designs, including the Hualong One. Fuel for foreign-designed reactors is sometimes produced domestically through a combination of indigenous and transferred technologies, and sometimes directly imported from foreign suppliers.[118] China continues to rely on Russia to provide nuclear fuel for Rosatom reactors, but the fuel plant in Yibin has the technology and license to produce its own fuel for Russian-designed VVERs, which can eventually eliminate the need to import fuel from Russia.

To create fuel in a form usable for nuclear reactors, fissile materials (Uranium-235 or Plutonium-239) must be fabricated into "assemblies," which are designed to differing specifications depending on the type of reactor they will be used in. A nuclear fuel assembly is a bundle of hollow metal rods that contain uranium or plutonium fuel formed into solid ceramic pellets. Fuel assemblies for Russian pressurized water reactors (VVERs), such as those in the Tianwan and Xudabao NPPs, are designed and produced by the Rosatom subsidiary TVEL.[119] In fact, TVEL has contracts to supply nuclear fuel to all the Chinese NPPs that Rosatom was involved in constructing: the VVER reactors at Tianwan and Xudabao as well as China's experimental fast neutron reactors.

The fuel currently used in Tianwan Units 1-4 is produced either by TVEL directly (at the Novosibirsk Chemical Concentrates Plant) or under a TVEL license at the Yibin fuel plant. The Yibin plant is China's primary PWR fuel fabrication plant, operated by China Jianzhong Nuclear Fuel, a CNNC subsidiary. TVEL directly supplied all the fuel for the Tianwan NPP after its first reactor was commissioned, but also transferred technology for the Yibin plant to produce its own VVER fuel. The Yibin plant began manufacturing its own VVER fuel in 2009.[120] According to a top TVEL executive, this is the first instance of Russian-designed nuclear fuel assemblies being fabricated outside Russia. TVEL supplies China with components for the fuel assemblies as well as equipment that can "enhance automation and quality of fuel manufacturing," which include a welding complex, a rod geometry control system and VVER fuel rod lacquering equipment.[121] In 2010, the first Chinese-produced VVER fuel assemblies passed inspection and were loaded into Tianwan Units 1 and 2.[122] Despite the technology transfer, China has continued to sign fuel purchase agreements with TVEL for both existing and future nuclear reactors, indicating that it is not yet ready to fully phase out nuclear fuel imports from Russia.

In 2013, TVEL signed a $1 billion USD contract with JNPC and CNEIC to supply TVS-2M fuel and accessories for Tianwan reactors 3 and 4 until 2025. TVEL also updated Tianwan Units 1 and 2 to use TVS-2M fuel in 2014, increasing their fuel cycle length from 12 to 18 months.[123] In 2019, TVEL signed another contract with CNNC to supply fuel for Tianwan Units 7 and 8, which recently began construction.[124]

Later in 2019, TVEL and CNNC signed yet another fuel contract, this time for the supply of nuclear fuel assemblies to Xudabao Units 3 and 4, the pair of VVER-1200 units that began construction in 2021 and 2022. This contract, like others before it, covered both initial fuel assembly supply and future refueling.[125]

TVEL has also provided fuel for China's fast neutron reactors. It has delivered 64.4% HEU fuel for the CEFR since 1999. The most recent CEFR fuel supply contract was signed at the end of 2016 for the delivery of two batches of fuel in 2017-2018. Although CEFR was originally expected to switch to plutonium-based MOX fuel in 2015, it continued to use imported HEU fuel as of late 2019.[126] The reason for this is unclear, but it is possible that China has not been able to produce enough MOX fuel to supply CEFR, or that China is reconsidering its fuel strategy for the fast reactor.[127]

At the end of 2018, TVEL's Mashinostroitelny Zavod subsidiary signed an agreement with CNNC subsidiary CNLY to supply nuclear fuel for China's two CFR- 600 reactors at Xiapu, which are currently under construction. TVEL has established a new production facility in Elektrostal (near Moscow) to produce fuel for the CFR-600s,[128] and completed three batches of fuel shipments to China in 2022.[129] Fuel exports for the Xiapu NPP in particular appear to have been a significant driver of Rosatom's revenue growth that year.[130] They are also notable as an instance of Russia providing fuel for reactors that were not primarily designed by Rosatom.

In March 2023, as part of their agreement to deepen nuclear energy cooperation, Rosatom and China's Atomic Energy Agency agreed to cooperate in development of fast reactors, production of uranium-plutonium fuel, and handling of spent nuclear fuel.[131]

There has been one noteworthy attempt at cooperation in nuclear fuel production which did not involve Chinese NPPs. In 2018, TVEL and CNEIC discussed jointly constructing a nuclear fuel fabrication plant in Ukraine to produce VVER fuel for Ukrainian NPPs.[132] The deal never came to fruition, and Ukraine instead extended fuel contracts with the U.S. company Westinghouse, the only company besides TVEL authorized to produce VVER fuel for export, as part of an effort to promote energy independence from Russia.[133]

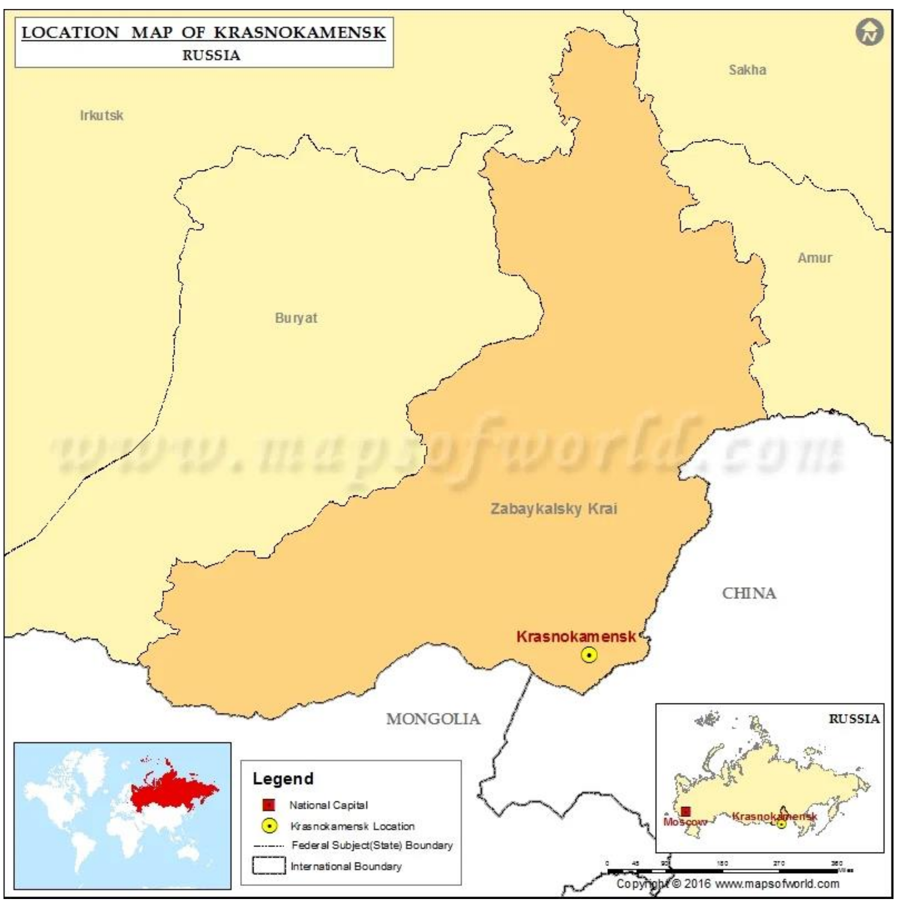
A selection of TVEL-designed nuclear fuel assemblies.
Source: TKB https://мкб.рф/2021/03/17/germaniya-odobrila-sozdanie-sp-framatome-i-tvel-po-vypusku-topliva-dlya-aes/

MINE NO. 6

China's current uranium procurement strategy aims to procure 1/3 from domestic production, 1/3 from direct purchases from foreign exporters, and 1/3 from investment in overseas uranium production.[134] In 2017, Russia and China established the Russia-China Investment Fund for Regional Development (RCIF). As its first project, the RCIF signed an agreement in March 2018 with ARMZ Uranium Holding and Priargunsky Industrial Mining and Chemical Union (PIMCU), subsidiaries of Rosatom, to work on a uranium mine project in the Zabaikalsky Krai region of Siberia, near the city of Krasnokamensk. The project, Mine No. 6, was scheduled to begin operations in 2023, but still appeared to be under construction as of this writing.[135]

According to the agreement, CNNC (through the RCIF) will contribute the majority of the funding for the project (16 billion rubles, or $180 million USD) in exchange for a 49% stake in the mine. The mine will also export half of its annual production (around 600 tons of uranium ore) to China each year. Although China itself is a relatively uranium-poor country, this is reportedly a relatively small amount by Chinese standards: China imports 18,000 tons of uranium annually, mainly from Kazakhstan. On the other hand, Russia's need for the project is reportedly much more significant. Its uranium demand is about 3,000 tons per year, and the already-developed reserves in this area were projected in 2018 to run out by 2022. Further, without the renewed development of Mine No. 6, the depletion of local uranium reserves would necessitate the resettlement of Krasnokamensk's 55,000 residents. Mine No. 6 itself has had a long history of failure stretching back to the 1980s, repeatedly failing to attract enough investment funds from domestic investors.[136]

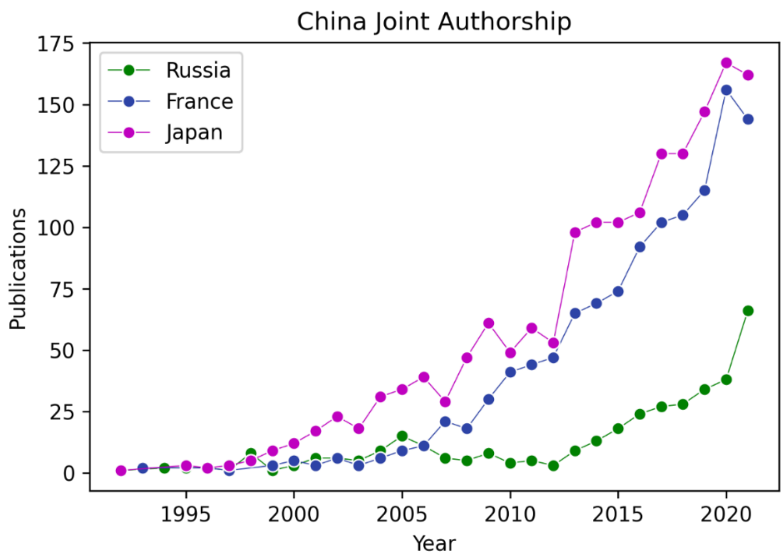
RCIF Chairman Wang Feng said the project was symbolic of the importance of China-Russia cooperation in the nuclear industry. "It is very important that the fund's first project is connected with nuclear energy. You could say both countries made the political decision that the first project would be Mine No. 6."[137]



The location of Krasnokamensk in Zabaikalsky Krai, the site of Mine No. 6.
Source: Maps of World https://www.mapsofworld.com/where-is/krasnokamensk.html

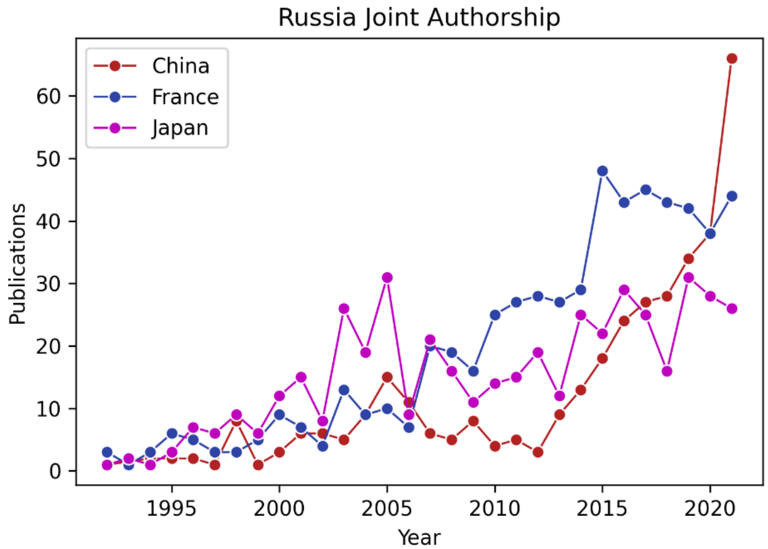
NUCLEAR RESEARCH COLLABORATION

Russia and China have also cooperated on scientific research in related fields. A metadata analysis of research papers published in scientific journals in the last three decades found that the number of nuclear-related research papers with both Russian and Chinese authors has risen sharply since 2012. In part, this reflects an overall upward trend in the amount of nuclear research conducted in both countries. Joint authorship with Japan, France, and the United States has also markedly increased since the 1990s for both China and Russia. The United States (excluded from the following graphs to preserve legibility) remains by far the most common national origin of international nuclear research partners for both.[xi]



Still, the rise in China-Russia collaboration is significant in itself, and is likely indicative of an increasingly close relationship between the two countries. As recently as 2016, China was Russia's fourth-largest international collaborator by volume of joint publications on nuclear research, but by 2020, it surpassed both France and Japan and is now in second place behind only the U.S. On the other hand, Russia (which produces a much lower volume of research papers overall than China) still lags behind the U.S., France, and Japan as a collaborator on Chinese nuclear research, and the gap continues to grow. This suggests an imbalance in the relationship: as in other areas, Russia has grown more dependent on China in nuclear research while China maintains a diverse range of international collaborators.

[xi] See Appendix 1 for methodology and graphs including the U.S. data.



One interesting ongoing example of China-Russia cooperation on nuclear research is the creation of the China Fusion Experimental Test Reactor (CFETR), a tokamak reactor planned for completion in 2030 which will explore technologies related to thermonuclear fusion.[138] The project is funded by the National Natural Science Foundation of China and the Russian Foundation for Basic Research, and managed by the St. Petersburg Peter the Great Polytechnic University and the University of Science and Technology of China and the Hefei Institute of Plasma Physics (both under the Chinese Academy of Sciences)

In February 2020, Russia's Research Institute of Atomic Reactors (NIIAR), part of Rosatom, signed a contract with China's Fangda Carbon New Material Company to carry out scientific research related to China's HTR-PM600, a proposed scaled-up version of China's existing HTR-PM high-temperature gas-cooled demonstration reactor. The research contract, which will last until 2024, is meant to test the suitability of graphite as the construction material for the proposed reactor's core.[139]

Section 3. China-Russia Competition in the Nuclear Export Market

Although China and Russia have closely collaborated on a variety of nuclear engineering projects, they have not collaborated on projects outside their own two countries (the discussion about jointly developing a fuel plant in Ukraine aside).[140] Rather, Rosatom CEO Alexey Likhachev has called China one of Russia's main competitors on the international nuclear energy market, along with the United States.[141]

Currently, Russia is by far the most dominant player in exports of both nuclear reactors and nuclear fuel (fuel usually used for its own exported reactors). It has 34 overseas reactor units completed or under construction,[xii] and produces about 35% of the world's enriched uranium reactor fuel.[142] As the only nuclear reactor supplier in the world that covers the entire nuclear fuel cycle, Rosatom is an especially good option for countries seeking their first nuclear power plants, which may lack infrastructure or expertise for uranium enrichment, fuel production and recycling, radioactive waste disposal, plant maintenance, and other necessary tasks. Rosatom's claimed foreign orders in 2021 exceeded $130.9 billion USD,[143] and its technology and fuel sales surged over 20% in 2022 despite the war in Ukraine. This increase was driven significantly by Chinese patronage, but also reflects purchases from countries like India, Egypt, and Turkey, and even some EU members states like Hungary.[144]

By contrast, China is a relative newcomer to the nuclear export market. It has only exported reactors to Pakistan, where it has constructed four CNP-300 reactors at the Chashma NPP and is either building or planning to build five HPR-1000 Hualong One reactors at Chashma and the Karachi Coastal NPP.[145]

However, China has ambitious plans to become a major nuclear power exporter which will bring it into direct competition with Rosatom. As noted earlier, former CNNC chair Wang Shoujun has said that China could build up to 30 overseas nuclear reactors by 2030 under the Belt and Road Initiative.[146] China has signed agreements or held discussions on the construction of nuclear power plants in countries on multiple continents, including Pakistan, Argentina, Turkey, the UK, and various African countries. Russia is a competitor for nuclear power contracts in some of the same countries.[147] For example, in 2022 Argentina signed an $8 billion USD deal with CNNC for the construction of a Hualong One reactor for its planned Atucha III nuclear power plant (though the project was held up in September 2022 over Argentina's demand that it be allowed to manufacture the fuel domestically).[148] Rosatom had previously pitched its own 1 GW VVER for Argentina, but the deal has not progressed,[149] in part due to economic problems in Argentina.[150] Turkey's president has also announced that the country's third NPP will likely be built by China,[151] while Chinese companies lobbied to build Bangladesh's second NPP (although China was unsuccessful here).[152] Both countries have previously purchased Russian nuclear plants.

Unlike the United States, Russia and China both have the advantage of generous government support for their nuclear corporations.[153] With this state backing, they are able to take contracts that would be too risky or unprofitable for private companies and offer extremely favorable deals to clients that might not be able to afford the full cost of nuclear powerplant construction. For example, China is financing 85% of its planned reactor in Argentina, while Rosatom offered a similar deal for a potential project in Egypt.[154] In this way, even if the projects do not turn a profit for the Russian or Chinese suppliers, Russia and China can force out local

[xii] In Bangladesh, Belarus, China, Egypt, Hungary, India, Iran, and Turkey.

private competitors as well as private nuclear suppliers from other countries, and use these construction projects to advance longer-term economic and strategic interests.

Nuclear power plant contracts are very long-term commitments, not only because the plants take years to construct but also because they must be continuously maintained and refueled (and ultimately de-commissioned) over their multi-decade life spans. In the case of foreign-supplied NPPs, especially when the customers do not have much indigenous nuclear capacity, the client countries become dependent on the foreign contractor to handle most of these functions. This may give powerful nuclear exporting states like Russia and China significant political influence in client countries.[155] In a sense, this means that China-Russia competition in the global nuclear energy market is also a geopolitical battle for influence between China and Russia, especially in developing countries.

Russia has been known to use its supply of energy to other countries as a tool in service of political or strategic goals, with the punitive suspension of gas supplies to Poland and Bulgaria in April 2022 a recent example.[156] While Russia has not leveraged nuclear energy contracts in such a blatantly coercive way, there are concerns that dependence on Russian-built NPPs in places like Turkey, Hungary, and even the already Russia-aligned Belarus may make those countries more amenable to Russian interests.[157] Although sanctions related to the 2022 invasion of Ukraine have largely avoided targeting Rosatom, Russian aggression has pushed Ukraine to seek to end its reliance on Russian nuclear fuel.[158] In the wake of the invasion, Finland has also canceled a Rosatom contract to build an NPP,[159] and other European countries such as Czechia[160] and Sweden[161] have likewise sought to move away from Russian nuclear fuel imports.

China does not currently have a reputation for using energy as leverage, which could make it a more attractive option to countries concerned about preserving their sovereignty.[162] However, China has been accused of using its construction and funding of other Belt and Road overseas infrastructure projects to engage in undue influence over recipient countries, exploitative resource extraction, and similar tactics. Chinese nuclear exports may also be used as a tool of influence in other countries. As China's international reputation worsens, this may ultimately cause it to lose clients. For instance, in 2020, Romania canceled its contract for two CGN-supplied nuclear reactors in favor of a deal with the United States,[163] while the UK government recently bought out CGN's share in its Sizewell C nuclear plant, citing security concerns.[164]

China-Russia competition in the international nuclear market is likely to intensify over the next decade. Each country brings its own strengths and weaknesses to this competition. Russia has a considerable head start, with 34 overseas NPPs completed or under construction (to China's four), and foreign orders hovering around $140 billion USD in the past several years.[165] Russia's nuclear fuel and technology exports have continued to grow despite the war in Ukraine, and Rosatom's pre-established relationships with its international clients may prove resilient. China has a long way to catch up, with only a small number of exported reactors to date. On the other hand, Russia has a much weaker overall economy compared to China and finds itself under severe economic and diplomatic sanctions. Even though Rosatom thus far has largely escaped these sanctions,[166] Russia's invasion of Ukraine has seriously damaged its relations with the West and is likely to be an obstacle to new nuclear contracts.[167] In addition, an economically struggling Russia may be less willing to generously fund future overseas nuclear plants if they are not certain to be profitable. At the same time, China is rapidly expanding its own nuclear capacity. It has used technology transfers from Russia, the United States, France, and other countries to develop its own designs, both for domestic energy production and export. In construction of NPPs, there has been a strong trend toward increased localization of equipment, for indigenous as well as imported designs.

China's first imported commercial reactor in Daya Bay (a French M310) used just 1% Chinese equipment, while today some of the new Hualong Ones claim over 85% localization.[168] China's self-sufficiency in the field is also bolstered by an explosion of research in the nuclear energy field, surpassing Russia in volume of papers published. These developments give China significant advantages going forward.

SECTION 4. IMPLICATIONS AND CONCLUSIONS

Several trends emerge from this study of China-Russia nuclear cooperation. The first is the fact that cooperation has grown since the 1990s, with even more rapid growth in recent years as China has sought cleaner energy sources to meet its massive domestic demand for electricity. Most of the joint projects identified in this report were either initiated or saw renewed cooperation in the last six years: Tianwan Units 7 and 8, Xudabao Units 3 and 4, and the CFR-600 reactors all began construction in 2017 or later. The Chinese contract to provide hulls for Russian floating NPPs and the agreement to fund the uranium mine in Krasnokamensk were also signed in this time period. A March 2023 agreement to deepen nuclear energy cooperation promises further joint projects in the years ahead.

Secondly, nearly all nuclear energy projects that have involved cooperation between China and Russia are physically located in China. China is attempting to rapidly expand its domestic nuclear capacity and has a history of importing critical technologies (such as reactors and enrichment plants) as needed to meet its goals. In fact, China's first nuclear reactor, its first fast neutron reactor, its largest nuclear power plant, and its largest uranium enrichment plant were all built with imported Russian (or Soviet) technology. By contrast, it is evident that Russia, with its decades of accumulated technical experience, tried-and-tested indigenous technologies, and relatively less ambitious nuclear expansion goals, does not need Chinese assistance to meet its domestic demand for nuclear power. China helps Rosatom mainly in the sense that it is an important source of revenue, a reliable client with deep pockets that is highly unlikely to collaborate with Western-led sanctions on Russia. Thus, although China has eclipsed Russia in economic might, geopolitical clout, and technological output since the early days of Sino-Soviet cooperation, the nuclear energy field is one of a shrinking number of areas in which Russia remains the dominant partner in the bilateral relationship.

The main weak link in Russia's domestic nuclear industry, despite its overall dominance in this sector, is its lack of profitable uranium deposits with which to produce reactor fuel. Indeed, one of the very few instances of China-Russia nuclear energy cooperation within Russia itself is China's funding of the Krasnokamensk uranium mine, which can be seen as Beijing exploiting a known weakness in its potential competitor. The terms of this mine deal, under which China will receive 50% of the mined uranium, are reminiscent of China's oft-criticized resource extraction projects in Africa and other parts of the developing world.[169] China is investing in such joint uranium production projects while also developing domestic uranium resources in an effort to reduce its dependence on foreign exporters.

Third, despite the increasing volume of cooperation in the form of Chinese imports of Russian nuclear technology and expertise, China strongly prioritizes developing indigenous technology for domestic use and export. The Hualong One is a case in point: having emerged as a clear winner in China's drive to develop indigenous third-generation reactors, it now dominates China's new reactor construction plans. Even looking specifically at the areas of cooperation examined in this report, there are indications that China prefers to transition to indigenous nuclear development over imports in the long run, as with other industries. Beijing contracted Rosatom to build CEFR, then abandoned plans to import Russian BN-800 fast neutron reactors, instead choosing to build CNNC-designed CFR-600 reactors as the next step of its FNR development. China likewise appears to have abandoned early plans for Russian cooperation in constructing its floating NPPs. The Hanzhong and Lanzhou enrichment plants were originally set up with Russian technology, but expansions after 2007 have all been indigenous. The Yibin fuel production plant uses transferred Russian technology to allow China to produce its own nuclear fuel, including for Russian-designed reactors, which may eventually eliminate the need to import fuel from Russia. The Xudabao NPP may seem to be a counterexample, but China decided to install Russian VVERs only after its original construction plans were delayed for nearly a decade.

How should Western countries see Russia and China's nuclear cooperation? On one level, if the two countries' collaboration helps them expand their use of civil nuclear energy, this is a net positive for the world. China is currently the world's worst carbon dioxide emitter due to its heavy dependence on coal, while Russia is the fourth worst emitter.[170] Nuclear energy is one of the cleanest and safest energy generation technologies per unit of electricity,[171] and each new nuclear reactor reduces its country's overall carbon dioxide output. In this regard, Russia and China's interests are aligned with American and Western interests, even if their climate plans are still insufficient overall.[172]

The geopolitical dimensions of this cooperation are more complex. As noted, Russia's export of reactors and other nuclear energy products is a means of increasing its influence over other countries. However, it is not clear how much this applies to modern China. While China certainly has relied on Russian (including Soviet) imports and technical assistance to build up its nuclear industry and acquire key technologies, it now has a much larger economy than Russia and generally wields greater geopolitical clout. Unlike Rosatom's other clients, China also has a large number of operating and planned reactors from a diverse range of suppliers besides Russia. These are primarily domestic companies but also include French, American, and Canadian firms, which insulate it from the pitfalls of overdependence on a single foreign power. In addition to growing its indigenous scientific expertise, China has also adapted transferred technologies to become self-sufficient in many aspects of its nuclear fuel cycle, including NPP design and construction, uranium enrichment, and fuel processing.[173]

On the other hand, Russia's economy is flailing amidst heavy sanctions imposed by the West, first in the wake of Russia's annexation of Crimea in 2014 and more recently in response to its full-scale invasion of Ukraine in 2022. Amidst these economic struggles, China has become Russia's largest trading partner and in many ways a life raft for the Russian economy.[174] In this regard, Russia needs China to buy as many Russian exports as possible, including nuclear products. However, Rosatom has remained largely exempt from sanctions due to fears of negative effects on countries that rely on Russian fuel and nuclear services and has maintained its global market dominance with sales to a variety of countries besides China. Therefore, while the benefits Russia and China extract from cooperation may not be the same, in most respects it is a win-win relationship without a significant power imbalance.

In the future, this relatively balanced dynamic may change if either Russia's diverse portfolio of clients dries up or China's indigenous technology begins to lag far behind Russia's. China in particular is likely to take advantage of any future decline in Rosatom's position to extract more favorable deals with Russia. Another possibility is that China-Russia cooperation will eventually diminish as a result of China becoming self-sufficient, or if their bilateral relationship degrades.

Russia and China's nuclear exports abroad are of more obvious concern to the West, because both countries (especially Russia) are strong competitors to Western nuclear exports, and because of the political influence that comes with these exports. Notably, this political influence includes not only leverage over the policies of the client countries, including U.S allies, but also potentially a greater voice for Russia and China in the formulation of international nonproliferation safeguards and other nuclear safety standards.[175] The United States' own nuclear exports have largely collapsed over the last two decades in the face of serious financial, technical, logistical, and administrative challenges.[176] Both Russia and China are seeking to develop fast neutron reactors which can recycle spent nuclear fuel. Thus far, China's FNR program was constructed and fueled with Russian help, and the March 2023 agreement promises future cooperation in this area. Breeder reactors have legitimate civilian uses, including increasing fuel sustainability, closing the nuclear fuel cycle, and reducing dependence on nuclear fuel imports in the long run. However, outside observers have raised concerns that the new CFR-600 demonstration reactors in Fujian, and similar future technology based on them, can be used for dual-use purposes including producing weapons-grade plutonium for China's nuclear weapons. It is improbable that Russia's involvement in Chinese FNR projects includes the intent to advance China's nuclear weapons program. In fact, some Russian scholars have argued that Chinese nuclear weapons development poses a potential security risk to Russia as well as the United States.[177]

Nevertheless, this appears to be a possible consequence of the two countries' collaboration in this field and highlights what may be the most significant long-term implication of China-Russia nuclear cooperation: despite the immediate mutual benefits of cooperation for both countries, Russia is empowering China in ways that may undermine Russian interests in the long run. China has demonstrated a consistent pattern of using nuclear imports and expertise from Russia and other countries to acquire key technologies, which then become a foundation for its own indigenous nuclear industry, including uranium enrichment plants, nuclear fuel fabrication facilities, fast neutron reactors, and other technological assets. In building, operating, and adapting imported technologies, China gains the necessary expertise to develop homegrown technology (such as the Hualong One reactor, whose predecessors were based on French designs) which it is now attempting to export on the global market. Most key areas where China still lags behind Russia in nuclear technology – such as FNRs and nuclear waste management – are notably also areas of planned future cooperation mentioned in the recent March 2023 agreement.

Because China's nuclear industry, like Russia's, is state-owned and backed by considerable government funding, China is one of the only countries capable of seriously challenging Rosatom's global dominance in the nuclear energy market. This growing potential is such that at least one American scholar has argued for Washington to support China's nuclear exports as a means of curtailing Russia's geopolitical influence.[178] While the ideal scenario would be reviving the U.S.'s own nuclear exports, this is much easier said than done, and an environment of fierce competition between Russia and China may indeed be preferable to one monopolized by a single U.S. adversary.

China's Russia-aided nuclear industry development will continue to increase its energy independence and reduce its reliance on Russia for energy in the long run, thus enabling China to compete with Rosatom on the global market. Although nuclear collaboration between China and Russia is rising in absolute terms, this collaboration will likely see diminishing marginal returns for China as its indigenous capabilities continue to improve. An increase in China's generation of nuclear power will also reduce its demand for fossil fuel imports, a prospect that should worry Russia, given that fossil fuels are its most important export and China its biggest customer. In the end, nuclear cooperation between China and Russia can be seen as a microcosm of the complex relationship between the two countries: cooperation based on mutual interests masking more deep-seated rivalries, and a once-dominant Russia gradually being reduced to the status of junior partner (though this has yet to happen in the nuclear field). As Western countries consider further sanctions on Russia, export controls targeting Chinese enterprises, or other policies that would impact the nuclear energy industry, they should be aware of how each policy will affect the China-Russia dynamic. Will it weaken one to the benefit of the other? Will it push them into closer cooperation with one another? Or will it perhaps create openings for Western or Western-aligned countries to compete with the two nuclear titans? As the United States works to revive its nuclear energy exports, it should closely monitor the multifaceted relationship between its Russian and Chinese competitors. There may yet be opportunities to drive a wedge into the burgeoning duopoly.

APPENDIX 1. CHINA-RUSSIA JOINT AUTHORSHIP IN NUCLEAR RESEARCH

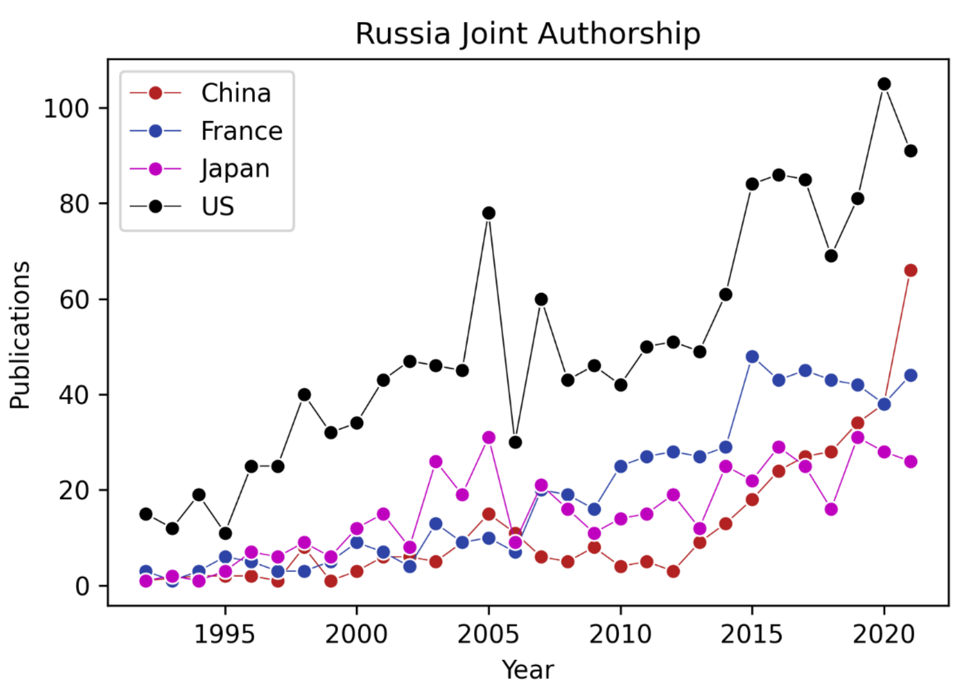
To analyze trends in China-Russia cooperation on nuclear research, documents related to nuclear energy were collected from the OpenAlex Elasticsearch index. OpenAlex is an open-source repository of scientific publication metadata that houses over 200 million different publications from around the world and in multiple languages, though the corpus focuses mostly on English language sources and more well-known publishers. Elasticsearch is a scalable database system that enables quick, query-based document retrieval.

The following terms were used as a basis to retrieve nuclear energy related documents: 'nuclear fusion, nuclear fission, nuclear power, nuclear waste, ITER, [xiii] tokamak, nuclear engineering, fusion power, fission power, thermonuclear, radioactive waste, nuclear transmutation, nuclear reactor, liquid thorium, uranium enrichment, neutron reactor'.

These terms were searched in the title, abstract, and "concept" fields of the documents within our Elasticsearch index. The concept field of documents contains general topical areas related to that document and has been provided by OpenAlex - terms such as "nuclear fusion" can appear here, which are useful markers for documents related to our query.

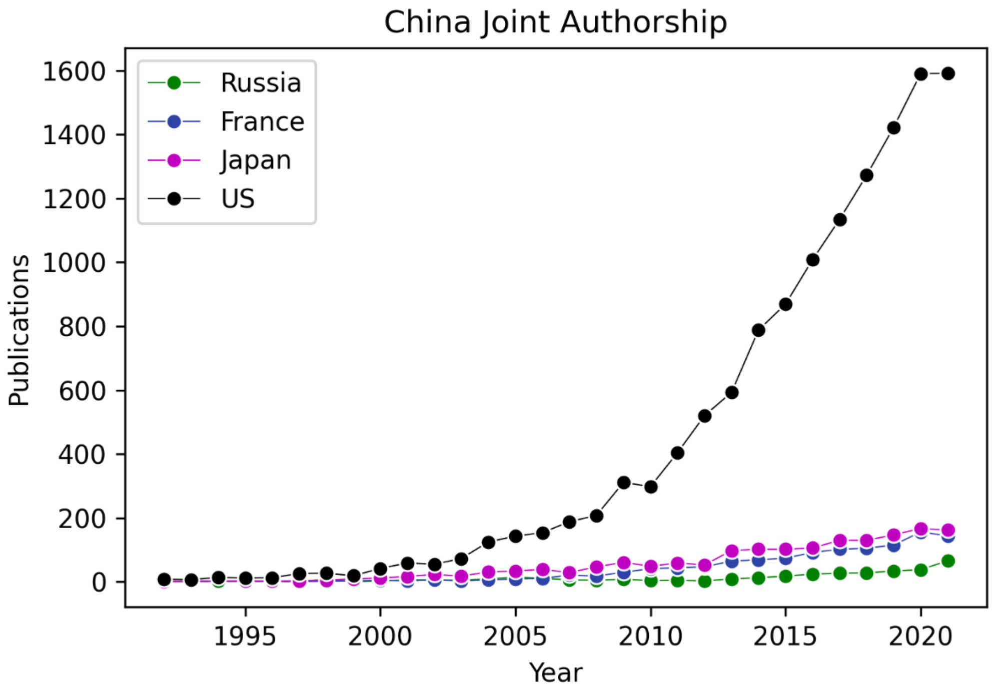
Documents were collected using the query terms above and author affiliation country as filters. For example, to determine the "cooperation between Russia and China", documents were retrieved where at least one author had a Chinese affiliation AND at least one author had a Russian affiliation. The various filter requirements were applied for each relationship requested to generate the plots. About 30% of the documents retrieved had more than 9 authors and another 30% had fewer than 5 authors (the other 40% have between 5 and 9 inclusive).

Document Count vs Time for Russia with authors from the U.S., Japan, France, and China



[xiii] International Thermonuclear Experimental Reactor

Document Count vs Time for China with authors from the U.S., Japan, France, and Russia



Note that the graphs presented in the body of the report represent the same dataset as the graphs in this appendix, but exclude the data for U.S.-China and U.S.-Russia collaboration.

ENDNOTES

[1] "Xi, Putin witness launch of biggest China-Russia nuclear energy project," Business Standard, 19 May 2021, https://www.business-standard.com/article/international/xi-putin-witness-launch-of-biggest-china-russia-nuclear-energy-project-121051901177_1.html.
[2] Jane Nanako, "The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China," CSIS, March 2020, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/200416_Nakano_NuclearEnergy_UPDATED%20FINAL.pdf?heOTjmYgA_5HxCUbVIZ2PGedzzQNg24v.
[3] David W. Yellen, "The trade war we want China to win: China's nuclear exports can challenge Russian dominance," Atlantic Council, 26 February 2020, https://www.atlanticcouncil.org/blogs/energysource/the-trade-war-we-want-china-to-win-chinas-nuclear-exports-can-challenge-russian-dominance/.
[4] "Rosatom and the PRC Atomic Energy Agency signed a program of cooperation in the field of fast neutron reactors" [Росатом и Агентство по атомной энергии КНР подписали программу сотрудничества в области реакторов на быстрых нейтронах], Rosatom, 22 March 2023, https://rosatom.ru/journalist/arkhiv-novostey/rosatom-i-agentstvo-po-atomnoy-energii-knr-podpisali-programmu-dolgosrochnogo-sotrudnichestva-v-obla/.
[5] "China,"," IAEA Country Nuclear Power Profiles, accessed 2022, https://cnpp.iaea.org/countryprofiles/China/China.htm; "Nuclear Power in China," World Nuclear Association, January 2023, https://web.archive.org/web/20230315204951/https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.
[6] "Appendix 1: Nuclear Organisations in China," World Nuclear Association, accessed 27 April 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx.
[7] "China National Nuclear Corporation," FAS, accessed 27 April 2022, https://nuke.fas.org/guide/china/contractor/cnnc.htm.
[8] "Profile," CNNC, accessed 27 April 2022, https://en.cnnc.com.cn/2020-01/07/c_446500.htm.
[9] "China National Nuclear Corporation," China Defense Universities Tracker (ASPI), accessed 27 April 2022, https://unitracker.aspi.org.au/universities/china-national-nuclear-corporation/.
[10] "Profile," CNNC, accessed 27 April 2022, https://en.cnnc.com.cn/2020-01/07/c_446500.htm.
[11] "China's Nuclear Fuel Cycle," World Nuclear Association, accessed 27 April 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.
[12] "Reorganization of China National Nuclear Corporation and China National Nuclear Corporation," State-owned Assets Supervision and Administration Commission, 31 January 2018, https://web.archive.org/web/20190512031710/http:/www.sasac.gov.cn/n2588035/n2641579/n2641660/c8551590/content.html.
[13] "Nuclear Power" [核电], CNNC, accessed 13 March 2023, https://web.archive.org/web/20230313191512/https://www.cnnc.com.cn/cnnc/cyyfw63/hd38/index.html.
[14] "Announcement of the establishment plan of the China Nuclear Military-Civil Integration Industry Development (Zhejiang) Investment Fund" [中核军民融合产业发展（浙江）投资基金组建方案公示], Lishui City Government, 23 March 2019, https://web.archive.org/web/20190801203920/http:/czj.lishui.gov.cn/csdt/wzgg/201903/t20190323_3670205.htm.
[15] "Issuance of Executive Order Addressing the Threat from Securities Investments that Finance Certain Companies of the People's Republic of China & related FAQs; Introduction of Non-SDN Chinese Military-Industrial Complex Companies List," U.S. Department of the Treasury, 3 June 2021, https://home.treasury.gov/policy-issues/financial-sanctions/recent-actions/20210603.
[16] "Appendix 1: Nuclear Organisations in China," World Nuclear Association, accessed 27 April 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx.
[17] "Appendix 1: Nuclear Organisations in China," World Nuclear Association, accessed 27 April 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx; "Introduction," CGN, 24 August 2016, https://web.archive.org/web/20200223185015/http://en.cgnpc.com.cn/encgn/c100052/2016-08/24/content_d188b0101d0444ffbe9561544a767b64.shtml.
[18] "CGN Guangdong Taipingling Nuclear Power Project Units 3 and 4 Approved" [中广核广东太平岭核电项目 3、4 号机组获核准], Xinhua Finance [新华财经], 29 December 2023, https://www.cnfin.com/dz-lb/detail/20231229/3993727_1.html.
[19] Elina Teplinsky, Anne Leidich, and Aaron R. Hurtman, "Four China Nuclear Industry Companies Added to 'Entity List'," Pillsbury Law, 15 August 2019, https://www.pillsburylaw.com/en/news-and-insights/china-industry-entity-list.html.
[20] Bethany Allen-Ebrahimian and Zach Dorfman, "Defense Department produces list of Chinese military-linked companies," Axios, 24 June 2020, https://www.axios.com/defense-department-chinese-military-linked-companies-856b9315-48d2-4aec-b932-97b8f29a4d40.html.
[21] "About SPIC," SPIC, accessed 27 April 2022, http://eng.spic.com.cn/2021/whoweare/aboutspic/.
[22] "Nuclear Power," SPIC, accessed 27 April 2022, http://eng.spic.com.cn/2021/whatwedo/mainbusinesses/nuclearpower/.
[23] "Guohe One," SPIC, accessed 27 April 2022, http://eng.spic.com.cn/2021/whatwedo/subbrands/guoheone/.
[24] "China launches CAP1400 reactor design," World Nuclear News, 29 September 2020, https://world-nuclear-news.org/Articles/Large-scale-Chinese-reactor-design-officially-laun.
[25] "The Fourteenth Five-Year Plan for the National Economic and Social Development of the People's Republic of China and Outline of Long-term Goals for 2035" [中华人民共和国国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要], Government of People's Republic of China, 13 March 2021, https://web.archive.org/web/20230208155713/http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm; "Make an effort to achieve carbon neutrality goals" [努力推动实现碳达峰碳中和目标], National Development and Reform Commission, 11 November 2021, https://www.ndrc.gov.cn/wsdwhfz/202111/t20211111_1303691.html?code=&state=123.
[26] Tim McDonnell, "China is rapidly becoming the leading nuclear energy superpower," Quartz, 30 September 2020, https://qz.com/1910492/chinas-carbon-pledge-hinges-on-a-buildout-of-nuclear-power/.
[27] "National Nuclear Power Operations" [全国核电运行情况（2023 年 1-9 月）], China Nuclear Energy Association [中国核能行业协会], 3 November 2023, https://www.china-nea.cn/site/content/44010.html.

[28] "China wants to build 150 nuclear reactors? The development of nuclear power is unstoppable, and the cost is only one-third of that of the United States and France" [中国要造 150 座核反应堆？核电发展势不可挡，成本仅有美法的三分之一], CNNPN, 5 November 2021, https://www.cnnpn.cn/article/26374.html.
[29] Jocelyn Timperley, "Will China gamble on a nuclear future?," Energy Monitor, 15 March 2021, https://www.energymonitor.ai/finance/regulation-policy/will-china-gamble-on-a-nuclear-future.
[30] "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.
[31] Viet Phuong Nguyen, "China's Risky Plan for Floating Nuclear Power Plants In The South China Sea," The Diplomat, 10 May 2018, https://thediplomat.com/2018/05/chinas-risky-plan-for-floating-nuclear-power-plants-in-the-south-china-sea/.
[32] "Nuclear Power in China," World Nuclear Association, January 2023, https://web.archive.org/web/20230315204951/https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.
[33] "Nuclear Power in China," World Nuclear Association, accessed 27 April 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.
[34] "China's new nuclear reactors could yield weapons-grade plutonium, warns US commander," South China Morning Post, 22 April 2021, https://www.scmp.com/news/world/united-states-canada/article/3130518/chinas-new-nuclear-reactors-could-yield-weapons.
[35] "China's HTR-PM reactor achieves first criticality," World Nuclear News, 13 September 2021, https://www.world-nuclear-news.org/Articles/Chinas-HTR-PM-reactor-achieves-first-criticality.
[36] Alexander Nikitin, "Rosatom state corporation," Bellona, 26 November 2007, https://bellona.org/news/nuclear-issues/nuclear-russia/2007-11-rosatom-state-corporation.
[37] "About Us," Rosatom, accessed 27 April 2022, https://www.rosatom.ru/en/about-us/.
[38] "Russian Federation," IAEA, accessed 27 April 2022, https://cnpp.iaea.org/countryprofiles/Russia/Russia.htm.
[39] "Projects," Rosatom, accessed 27 April 2022, https://rosatom.ru/en/investors/projects/.
[40] Julian Cooper, "How much does Russia spend on nuclear weapons?," SIPRI, 1 October 2018, https://www.sipri.org/commentary/topical-backgrounder/2018/how-much-does-russia-spend-nuclear-weapons.
[41] "Nuclear Center" [Ядерный центр], VNIIEF, accessed 27 April 2022, http://www.vniief.ru/about/.
[42] "Russian Federation," IAEA, accessed 27 April 2022, https://cnpp.iaea.org/countryprofiles/Russia/Russia.htm.
[43] "Energy Strategy of the Russian Federation for the Period up to the year 2035" [ЭНЕРГЕТИЧЕСКАЯ СТРАТЕГИЯ: Российской Федерации на период до 2035 года], Government of Russia, 9 June 2020, http://static.government.ru/media/files/w4sigFOiDjGVDYT4IgsApssm6mZRb7wx.pdf.
[44] "Russia drafts new, more ambitious decarbonisation strategy - Kommersant newspaper," Reuters, 7 October 2021, https://www.reuters.com/business/environment/russia-considering-more-ambitious-climate-targets-2021-10-06/; "Russia Aiming for Carbon Neutrality by 2060, Putin Says,"," Moscow Times, 13 October 2021, https://www.themoscowtimes.com/2021/10/13/russia-aiming-for-carbon-neutrality-by-2060-putin-says-a75284.
[45] "Plus carbonization of the whole country" [Плюс карбонизация всей страны], Kommersant, 17 March 2022, https://www.kommersant.ru/doc/5259768.
[46] I.A. Karavaev, "Development strategy of SC Rosatom until 2030" [Стратегия развития ГК «Росатом» до 2030 года], Rosatom, June 2012, http://2012.atomexpo.ru/mediafiles/u/files/Present2012/Karavaev.pdf.
[47] "Our Mission and Corporate Values," Rosatom, accessed 27 April 2022, https://rosatom.ru/en/about-us/our-mission-and-corporate-values/.
[48] "Rosatom drafts 506-bln-ruble development plan for new nuclear technologies to 2030," Interfax, 8 June 2021, https://interfax.com/newsroom/top-stories/71983/.
[49] "About the Project," Proryv2020, accessed 21 January 2023, https://web.archive.org/web/20230121174949/https://proryv2020.ru/en/o-proekte/
[50] "Rosatom has prepared a plan for the development of new nuclear technologies until 2030 for 500 billion rubles," Metallurgprom, 8 June 2021, https://metallurgprom.org/en/news/russia/8616-rosatom-podgotovil-plan-razvitija-novyh-atomnyh-tehnologij-do-2030-goda-na-500-mlrd-rublej.html.
[51] "Rosatom's development plan," Nuclear Engineering International, 11 March 2021, https://www.neimagazine.com/news/newsrosatoms-development-plans-8592063.
[52] "Russian Federation," IAEA, accessed 27 April 2022, https://cnpp.iaea.org/countryprofiles/Russia/Russia.htm.
[53] "Russia to commission 15 new nuclear power units by 2035 — Rosatom," TASS, 20 September 2021, https://tass.com/economy/1340313.
[54] "Outline History of Nuclear Energy," World Nuclear Association, accessed 27 April 2022, https://world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx.
[55] "Agreement on the Sino-Soviet Petroleum Co., Ltd," Common Program, 27 March 1950, http://www.commonprogram.science/documents/27-03-1950.pdf.
[56] "Chinese Becomes A Nuclear Nation," Atomic Archive, accessed 27 April 2022, https://www.atomicarchive.com/history/cold-war/page-12.html.
[57] "The decommissioning of China's first heavy water research reactor has been approved by the state" [我国第一座重水研究堆退役获国家立项批复], Nuclear Radiation and Safety Center, 19 November 2019, http://www.chinansc.cn/dtzx/yjzx/201911/t20191119_743136.shtml.
[58] "Chinese Nuclear Program," Atomic Heritage Foundation, 19 July 2018, https://www.atomicheritage.org/history/chinese-nuclear-program.
[59] Ibid.
[60] "China Nuclear Power" [中国核电], Shanghai Nuclear Power Office, accessed 28 April 2022, https://web.archive.org/web/20220216034823/http://www.smnpo.cn/zghd.htm.
[61] "Sino-Russian Nuclear Energy Cooperation Model Project - Tianwan Nuclear Power Plant" [中俄核能合作典范项目——田湾核电站], CNNPN, 2 December 2021, https://www.cnnpn.cn/article/26766.html.
[62] "Fuel loading completed at fifth Tianwan unit," World Nuclear News, 13 July 2020, https://www.world-nuclear-news.org/Articles/Fuel-loading-completed-at-fifth-Tianwan-unit.

[63] "Final acceptance of initial Tianwan units," World Nuclear News, 6 May 2010,https://world-nuclear-news.org/Articles/Final-acceptance-of-initial-Tianwan-units; "Tianwan NPP (China)," AtomStroyExport, accessed 27 April 2022, https://web.archive.org/web/20100914115226/http://www.atomex.ru/project/eng.
[64] "ASE contracted to build Tianwan phase 2," World Nuclear News, 23 November 2010, https://www.world-nuclear-news.org/NN-ASE_contracted_to_build_Tianwan_phase_2-2311104.html; "NPP CONSTRUCTION ABROAD" [СООРУЖЕНИЕ АЭС ЗА РУБЕЖОМ], RosEnergoAtom, accessed 27 April 2022, https://www.rosenergoatom.ru/stations_projects/perspektivy-sooruzheniya-rossiyskikh-aes-za-rubezhom/.
[65] "The second phase of Tianwan nuclear power project was fully put into operation on schedule, which is the largest nuclear energy cooperation project between China and Russia" [田湾核电二期工程按期全面投产，系中俄两国最大核能合作项目], The Paper, 24 December 2018, https://m.thepaper.cn/wifiKey_detail.jsp?contid=2767324&from=wifiKey#.
[66] "Tianwan 4 handed over to China as upgrading of simulators begins," Nuclear Engineering International, 8 January 2021, https://www.neimagazine.com/news/newstianwan-4-handed-over-to-china-as-upgrading-of-simulators-begins-8443140.
[67] "Tianwan Nuclear Power Plant," NS Energy, accessed 27 April 2022, https://www.nsenergybusiness.com/projects/tianwan-nuclear-power-plant/.
[68] "Tianwan 6 enters commercial operation," World Nuclear News, 3 June 2021, https://world-nuclear-news.org/Articles/Tianwan-6-enters-commercial-operation.
[69] "AtomStroyExport unveils schedule for China projects," World Nuclear News, 3 April 2019, https://www.world-nuclear-news.org/Articles/AtomStroyExport-unveils-schedule-for-China-project; "Tianwan Nuclear Power Plant," NS Energy, accessed 27 April 2022, https://www.nsenergybusiness.com/projects/tianwan-nuclear-power-plant/.
[70] "The First Concrete has been Laid at Tianwan NPP Power Unit 8 (China)," Rosatom, 28 February 2022, https://www.rosatom.ru/en/press-centre/news/the-first-concrete-has-been-laid-at-tianwan-npp-power-unit-8-china/.
[71] "Nuclear Power in China,"," World Nuclear Association, accessed March 2023, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.
[72] "Start of new unit construction at China's Tianwan and Xudapu nuclear power plants," Rosatom, 19 May 2021, https://www.rosatom.ru/en/press-centre/news/start-of-new-unit-construction-at-china-s-tianwan-and-xudapu-nuclear-power-plants/.
[73] "First concrete poured for Xudabao 3," World Nuclear News, 3 August 2021, https://www.world-nuclear-news.org/Articles/First-concrete-poured-for-Xudabao-3; "First concrete for unit 4 at China's Xudabao NPP," Nuclear Engineering International, 25 May 2022, https://www.neimagazine.com/news/newsfirst-concrete-for-unit-4-at-chinas-xudabao-npp-9722984.
[74] "Contract for nuclear islands of Xudabao Phase I," World Nuclear News, 14 October 2016, https://www.world-nuclear-news.org/NN-Contract-for-nuclear-islands-of-Xudabao-Phase-I-1410164.html.
[75] "Nuclear Power in China," World Nuclear Association, accessed January 2024, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
[76] "First concrete poured for Xudabao 3," World Nuclear News, 3 August 2021, https://www.world-nuclear-news.org/Articles/First-concrete-poured-for-Xudabao-3.
[77] "TVEL will supply fuel for new power units of the Xudapu NPP" [«ТВЭЛ» поставит топливо для новых энергоблоков АЭС «Сюдайпу»], Atomic Energy.ru, 7 November 2019, https://www.atomic-energy.ru/news/2019/11/07/98859.
[78] "China prepares for start of world's first AP1000," Nuclear Engineering International, 15 June 2018, https://www.neimagazine.com/news/newschina-prepares-for-start-of-worlds-first-ap1000-6207502.
[79] Tom Hals and Emily Flitter, "How two cutting edge U.S. nuclear projects bankrupted Westinghouse," Reuters, 2 May 2017, https://www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle-idUSKBN17Y0CQ.
[80] "Another six nuclear power units have been approved, why China has launched new nuclear power for four consecutive years" [又有六台核电机组获批， 中国为何连续四年上马新核电], Sina Finance, 21 April 2022, https://finance.sina.cn/2022-04-21/detail-imcwiwst3210939.d.html.
[81] Echo Xie, "China Ditches US Nuclear Technology in Favour of Home-Grown Alternative," World Nuclear Industry Status Report, 16 September 2020, https://www.worldnuclearreport.org/China-Ditches-US-Nuclear-Technology-in-Favour-of-Home-Grown-Alternative.html.
[82] Sonal Patel, "China Will Add Two More AP1000 Nuclear Reactors," Power Magazine, 13 October 2022, https://www.powermag.com/china-will-add-two-more-ap1000-nuclear-reactors/.
[83] "China Experimental Fast Reactor Completes First Cycle Trial Operation" [中国实验快堆完成首循环试运行], National Nuclear Safety Administration, 5 August 2020, https://web.archive.org/web/20200928064236/http://nnsa.mee.gov.cn/ywdt/yjzx/202008/t20200805_792846.html.
[84] "China Institute of Atomic Energy" [中国原子能科学研究院], CIAE, accessed 27 April 2022, http://www.ciae.ac.cn/subpage/gaikuang_1.htm.
[85] "China Experimental Fast Reactor" [中国实验快堆], CIAE, accessed 27 April 2022, http://www.ciae.ac.cn/subpage/pingtai_2.htm.
[86] "China Experimental Fast Reactor (CEFR)," CIAE, accessed 27 April 2022, http://www.ciae.ac.cn/eng/cefr/index.htm.
[87] "Chinese fast reactor begins high-power operation," World Nuclear News, 19 February 2021, https://world-nuclear-news.org/Articles/Chinese-fast-reactor-begins-high-power-operation.
[88] "The launch of the CEFR reactor is the result of many years of cooperation with China" [Пуск реактора CEFR – результат многолетнего сотрудничества с КНР], Atomic Energy.ru, 26 November 2014, www.atomic-energy.ru/technology/53288.
[89] Ibid.
[90] "China begins construction of CFR-600 fast reactor," Nuclear Engineering International, 4 January 2018, https://www.neimagazine.com/news/newschina-begins-construction-of-cfr-600-fast-reactor-6018483
[91] "China Experimental Fast Reactor" [中国实验快堆], CIAE, accessed 27 April 2022, http://www.ciae.ac.cn/subpage/pingtai_2.htm.
[92] "The launch of the CEFR reactor is the result of many years of cooperation with China" [Пуск реактора CEFR – результат многолетнего сотрудничества с КНР], Atomic Energy, 26 November 2014, www.atomic-energy.ru/technology/53288.
[93] "China's CEFR fast reactor begins 'high-power operations'," International Panel on Fissile Materials, 15 February 2021, https://fissilematerials.org/blog/2021/02/chinas_cefr_fast_reactor_.html.
[94] "CFR-600 (China Institute of Atomic Energy, China)," IAEA, October 2013, https://aris.iaea.org/PDF/CFR-600.pdf.

95 "Mixed Oxide Fuel," World Nuclear Association, accessed 27 April 2022, https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx.
96 "Concerns grow over China nuclear reactors shrouded in mystery," Al Jazeera, 19 May 2021, https://www.aljazeera.com/economy/2021/5/19/concerns-grow-over-china-nuclear-reactors-shrouded-in-mystery; "China starts building second CFR-600 fast reactor," World Nuclear News, 19 December 2020, https://world-nuclear-news.org/Articles/China-starts-building-second-CFR-600-fast-reactor.
97 "Russia completes fuel deliveries for China's CFR-600 fast reactor", Nuclear Engineering International, 3 January 2023, https://www.neimagazine.com/news/newsrussia-completes-fuel-deliveries-for-chinas-cfr-600-fast-reactor-10486493.
98 "Rosatom to provide technical support to China in the CFR-600 nuclear reactor project" [Росатом окажет Китаю техподдержку в проекте ядерного реактора CFR-600], RIA, 7 August 2018, ttps://ria.ru/20180807/1526059134.html.
99 "TVEL ships testing equipment for China's fast reactor," Nuclear Engineering International, 30 December 2021, https://www.neimagazine.com/news/newstvel-ships-testing-equipment-for-chinas-fast-reactor-9354390.
100 "Concerns grow over China nuclear reactors shrouded in mystery," Al Jazeera, 19 May 2021, https://www.aljazeera.com/economy/2021/5/19/concerns-grow-over-china-nuclear-reactors-shrouded-in-mystery.
101 Henry D. Sokolski, "China's Civil Nuclear Sector: Plowshares to Swords?," Nonproliferation Policy Education Center, March 2021, https://npolicy.org/article_file/2102_Chinas_Civil_Nuclear_Sector.pdf.
102 "Military and Security Developments Involving the People's Republic of China," U.S. Department of Defense, 2023, https://media.defense.gov/2023/Oct/19/2003323409/-1/-1/1/2023-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF.
103 "Status of World Nuclear Forces," Federation of American Scientists, accessed 27 March 2023, https://web.archive.org/web/20230327130934/https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.
104 "Chinese fast reactor begins high-power operation," World Nuclear News, 19 February 2021, https://world-nuclear-news.org/Articles/Chinese-fast-reactor-begins-high-power-operation.
105 "Rosatom and the PRC Atomic Energy Agency signed a program of cooperation in the field of fast neutron reactors" [Росатом и Агентство по атомной энергии КНР подписали программу сотрудничества в области реакторов на быстрых нейтронах], Rosatom, 22 March 2023, https://rosatom.ru/journalist/arkhiv-novostey/rosatom-i-agentstvo-po-atomnoy-energii-knr-podpisali-programmu-dolgosrochnogo-sotrudnichestva-v-obla/.
106 "Joint venture launched for Chinese fast reactor," World Nuclear News, 30 April 2010, https://www.world-nuclear-news.org/C-Joint_venture_launched_for_Chinese_fast_reactor-3004104.html.
107 Brian Wang, "Russia's fast neutron 789MWe reactor commercially operating and several countries are building 14 new fast reactor designs by 2028," Next Big Future, 1 November 2016, https://www.nextbigfuture.com/2016/11/russias-fast-neutron-789mwe-reactor.html.
108 "Rusatom Overseas and CNNC New Energy (China) signed a Memorandum on the project to create floating nuclear power plants" [«Русатом Оверсиз» и CNNC New Energy (КНР) подписали Меморандум по проекту создания плавучих атомных электростанций], Atomic Energy, 30 July 2014, https://www.atomic-energy.ru/news/2014/07/30/50598.
109 Viet Phuong Nguyen, "China's Planned Floating Nuclear Power Facilities in South China Sea: Technical and Political Challenges," Belfer Center, 21 November 2018, https://www.belfercenter.org/publication/chinas-planned-floating-nuclear-power-facilities-south-china-sea-technical-and.
110 "ROSATOM: world's only floating nuclear power plant enters full commercial exploitation," Rosatom, 22 May 2020, https://rosatom.ru/en/press-centre/news/rosatom-world-s-only-floating-nuclear-power-plant-enters-full-commercial-exploitation/.
111 Amber Wang, "First Chinese firm wins contract for Russian floating nuclear power project," South China Morning Post, 16 September 2021, https://www.scmp.com/news/china/diplomacy/article/3148884/first-chinese-firm-wins-contract-russian-floating-nuclear.
112 "Russia advances on plans for new floating nuclear plants," Bellona, 16 September 2021, https://bellona.org/news/nuclear-issues/2021-09-russia-advances-on-plans-for-new-floating-nuclear-plants.
113 "Development history of enriched uranium and nuclear fuel in China" [中国浓缩铀与核燃料发展历程], CNNPN, 11 October 2021, https://web.archive.org/web/20220428164832/https://www.cnnpn.cn/article/26084.html.
114 "Russia and China sign enrichment plant agreement," World Nuclear News, 27 May 2008, https://www.world-nuclear-news.org/Articles/Russia-and-China-sign-enrichment-plant-agreement.
115 Ibid.; "Development history of enriched uranium and nuclear fuel in China" [中国浓缩铀与核燃料发展历程], CNNPN, 11 October 2021, https://web.archive.org/web/20220428164832/https://www.cnnpn.cn/article/26084.html; Hui Zhang, "The Development Status of China's Uranium Enrichment," Belfer Center, July 2020, https://www.belfercenter.org/sites/default/files/files/publication/The%20Development%20Status%20of%20China%27s%20Uranium%20Enrichment.pdf; Hui Zhang, "China started operation of two new enrichment plants in 2023," International Panel on Fissile Materials, 15 December 2023, https://fissilematerials.org/blog/2023/12/china_started_operation_o_1.html.
116 "Development history of enriched uranium and nuclear fuel in China" [中国浓缩铀与核燃料发展历程], CNNPN, 11 October 2021, https://web.archive.org/web/20220428164832/https://www.cnnpn.cn/article/26084.html.
117 Hui Zhang, "The Development Status of China's Uranium Enrichment," Belfer Center, July 2020, https://www.belfercenter.org/sites/default/files/files/publication/The%20Development%20Status%20of%20China%27s%20Uranium%20Enrichment.pdf; "Russia and China sign enrichment plant agreement," World Nuclear News, 27 May 2008, https://www.world-nuclear-news.org/Articles/Russia-and-China-sign-enrichment-plant-agreement.
118 "China's Nuclear Fuel Cycle," World Nuclear Association, accessed 22 February 2023, https://web.archive.org/web/20230222215845/https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.
119 "Nuclear Fuel and its Fabrication," World Nuclear Association, accessed 3 May 2022, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx.
120 "China's Nuclear Fuel Cycle," World Nuclear Association, accessed 3 May 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.

[121] "TVEL Fuel Company of Rosatom supplied equipment for VVER fuel fabrication at Yibin plant in China," Rosatom, 25 July, 2019, https://rosatom.ru/en/press-centre/news/tvel-fuel-company-of-rosatom-supplied-equipment-for-vver-fuel-fabrication-at-yibin-plant-in-china/.
[122] "Chinese VVERs start using domestically made fuel," World Nuclear News, 31 August 2010, https://www.world-nuclear-news.org/ENF-Chinese_VVERs_start_using_domestically_made_fuel-3108104.html.
[123] "TVEL wins $1bn nuclear fuel contract for China's Tianwan 3&4." NS Energy, 22 October 2013, https://www.nsenergybusiness.com/news/newstvel-wins-1bn-nuclear-fuel-contract-for-chinas-tianwan-34/.
[124] "Russia's Tvel to supply fuel for Tianwan 7&8," Nuclear Engineering International, 26 July 2019, https://www.neimagazine.com/news/newsrussias-tvel-to-supply-fuel-for-tianwan-7-8-7331132/.
[125] "TVEL will supply fuel for new power units of the Xudapu NPP" [«ТВЭЛ» поставит топливо для новых энергоблоков АЭС «Сюдайпу»], Atomic Energy.ru, 7 November 2019, https://www.atomic-energy.ru/news/2019/11/07/98859.
[126] "Russia to supply more HEU fuel for Chinese Experimental Fast Reactor," International Panel on Fissile Materials, 29 December 2016, https://fissilematerials.org/blog/2016/12/russia_to_supply_more_heu.html;"Russia delivers a batch of HEU fuel for China's CEFR fast neutron reactor," International Panel on Fissile Materials, 10 July 2019, https://fissilematerials.org/blog/2019/07/russia_delivers_a_batch_o.html.
[127] Mark Hibbs, "Rethinking China's Fast Reactor," Carnegie Endowment for International Peace, 17 February 2017, https://carnegieendowment.org/2017/02/17/rethinking-china-s-fast-reactor-pub-68079.
[128] "TVEL ships testing equipment for China's fast reactor," Nuclear Engineering International, 30 December 2021, https://www.neimagazine.com/news/newstvel-ships-testing-equipment-for-chinas-fast-reactor-9354390; Kamen Kraev, "Russian Company Starts Fuel Facility For China's CFR-600 Fast Neutron Reactor," NucNet, 3 March 2021, https://www.nucnet.org/news/russian-company-starts-fuel-facility-for-china-s-cfr-600-fast-neutron-reactor-3-3-2021.
[129] "Russia completes fuel deliveries for China's CFR-600 fast reactor", Nuclear Engineering International, 3 January 2023, https://www.neimagazine.com/news/newsrussia-completes-fuel-deliveries-for-chinas-cfr-600-fast-reactor-10486493.
[130] Darya Dolzikova, "Atoms for Sale: Developments in Russian Nuclear Energy Exports," RUSI, 14 February 2023, https://rusi.org/explore-our-research/publications/special-resources/atoms-sale-developments-russian-nuclear-energy-exports.
[131] "Rosatom and the PRC Atomic Energy Agency signed a program of cooperation in the field of fast neutron reactors" [Росатом и Агентство по атомной энергии КНР подписали программу сотрудничества в области реакторов на быстрых нейтронах], Rosatom, 22 March 2023, https://rosatom.ru/journalist/arkhiv-novostey/rosatom-i-agentstvo-po-atomnoy-energii-knr-podpisali-programmu-dolgosrochnogo-sotrudnichestva-v-obla/.
[132] "Ukraine may return to 100% dependence on Russia in the supply of nuclear fuel if China builds a plant for its fabrication" [Украина может вернуться к 100% зависимости от России в поставках ядерного топлива в случае строительства Китаем завода по его фабрикации], Atomic Energy, 24 July 2018, https://www.atomic-energy.ru/news/2018/07/24/87623.
[133] "Westinghouse to Continue Nuclear Fuel Delivery to Ukraine Through 2025," Westinghouse, 29 January 2018, https://info.westinghousenuclear.com/news/westinghouse-to-continue-nuclear-fuel-delivery-to-ukraine-through-2025; Charles Digges, "Ukraine inks deal to fuel older reactors with Westinghouse fuel," Bellona, 2 October 2020, https://bellona.org/news/nuclear-issues/2020-10-ukraine-inks-deal-to-fuel-older-reactors-with-westinghouse-fuel.
[134] Yang Mingjuan [楊明娟], "Xi Jinping Visit to Kazakhstan Amidst the Pandemic, Nuclear Energy Strategy is the Key" [習近平疫情下首訪哈薩克 核能源戰略是關鍵], Radio Taiwan International, 27 September 2022, https://www.rti.org.tw/news/view/id/2145689.
[135] "Russia brings Chinese funding into uranium mining," World Nuclear News, 13 March 2018, https://world-nuclear-news.org/UF-Russia-brings-Chinese-funding-into-uranium-mining-13031801.html; "Uranium production in Russia and major projects," Mining Technology, 28 June 2023, https://www.mining-technology.com/data-insights/uranium-in-russia/?cf-view.
[136] Svetlana Burmistrova, "China descends into the mines: China invests in uranium mining in Transbaikalia" [Китай спускается в рудники КНР инвестирует в добычу урана в Забайкалье], RBC Daily, https://www.rbc.ru/newspaper/2018/03/13/5aa6833b9a794747854c99b1.
[137] "Russia brings Chinese funding into uranium mining," World Nuclear News, 13 March 2018, https://world-nuclear-news.org/UF-Russia-brings-Chinese-funding-into-uranium-mining-13031801.html.
[138] Ekaterina Borisova, "Russian scholars will participate in Chinese tokamak research" [俄罗斯学者将参加中国托卡马克研究工作], Sputnik News, 26 March 2021, https://sputniknews.cn/20210326/1033348984.html.
[139] "Russia to undertake graphite research for China's HTGR," Nuclear Engineering International, 5 February 2020, https://www.neimagazine.com/news/newsrussia-to-undertake-graphite-research-for-chinas-htgr-7753849.
[140] Yang Hao [杨浩], "Research based on the cooperation model of China and Russia in the third country to carry out VVER nuclear power projects" [基于中俄在第三国开展 VVER 核电项目合作模式的研究], Industrial & Science Tribune, 2020, https://oversea.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2020&filename=CYYT202006050&uniplatform=OVERSEAS_EN&v=pWjIL2JF5EMj6_hxOUg0lwqpfHwt2JXoWrnw9IEhQd4lwrr9QdNbj_MB5SMEUite.
[141] Katya Golubkova and Gleb Stolyarov, "Russia's Rosatom sees foreign revenues, new products fuelling rapid growth," Reuters, 24 June 2019, https://www.reuters.com/article/us-russia-rosatom-strategy/russias-rosatom-sees-foreign-revenues-new-products-fuelling-rapid-growth-idUSKCN1TP1LI.
[142] Joe Deaux, Will Wade, and Ari Natter, "Russian Sanctions Pose Risks to U.S. Nuclear Power Industry," Bloomberg, 3 March 2022, https://www.bloomberg.com/news/articles/2022-03-03/russian-sanctions-pose-risks-to-u-s-nuclear-power-industry.
[143] "2021 PERFORMANCE OF STATE ATOMIC ENERGY CORPORATION ROSATOM IN 2021"," Rosatom, 2021, https://www.report.rosatom.ru/go_eng/go_rosatom_eng_2021/rosatom_2021_eng.pdf; Nevine Schepers, "Russia's Nuclear Energy Exports: Status, Prospects, and Implications," SIPRI, February 2019, https://www.sipri.org/sites/default/files/2019-02/eunpdc_no_61_final.pdf.
[144] Jonathan Tirone, "Russia's Grip on Nuclear-Power Trade Is Only Getting Stronger," Bloomberg, 14 February 2023, https://www.bloomberg.com/news/features/2023-02-14/russia-s-grip-on-nuclear-power-trade-is-only-getting-stronger?leadSource=uverify%20wall.
[145] "China 'to build third Hualong One nuclear reactor' in Pakistan," South China Morning Post, 25 November 2017, https://www.scmp.com/news/china/diplomacy-defence/article/2121532/china-build-third-hualong-one-nuclear-reactor-pakistan.
[146] "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.

[147] "Civil Nuclear Strategies," Enerdata, 11 March 2021, https://www.enerdata.net/publications/executive-briefing/world-civil-nuclear-strategies.html.
[148] Jonathan Tirone, "China Nuclear Deal Held Up Over Argentina's Reactor Fuel Demand," Bloomberg, 19 September 2022, https://www.bloomberg.com/news/articles/2022-09-19/china-nuclear-deal-held-up-over-argentina-s-reactor-fuel-demand.
[149] Dan Yurman, "Argentina Signs $8B Deal for China's Hualong One PWR," Neutron Bytes, 12 February 2022, https://neutronbytes.com/2022/02/12/argentina-signs-8b-deal-for-chinas-hualong-one-pwr/.
[150] "Argentina to postpone joint nuclear power plant construction with Russia" [Аргентина отложит совместное с Россией строительство АЭС], Neftegaz.ru, 10 August 2020, https://neftegaz.ru/news/nuclear/625209-argentina-otlozhit-sovmestnoe-s-rossiey-stroitelstvo-aes/.
[151] Hüseyin Erdoğan, "Turkey to build 3rd nuclear plant with China: Erdogan," Anadolu Agency, 19 June 2018, https://www.aa.com.tr/en/energy/nuclear/turkey-to-build-3rd-nuclear-plant-with-china-erdogan/20544.
[152] "Chinese Companies Lobby for Contract to Build Bangladesh's Second Nuclear Plant," RFA, 9 May 2019, https://www.rfa.org/english/news/china/bangladesh-nuclear-05092019173654.html; "Russia Completes Welding Of Upper Half Of Rooppur-2 RPV," Nucnet, 8 July 2020, https://www.nucnet.org/news/russia-completes-welding-of-upper-half-of-rooppur-2-rpv-7-3-2020.
[153] "China drafts new nuclear energy law, focus on international market," Reuters, 21 September 2018, https://www.reuters.com/article/us-china-nuclear-law/china-drafts-new-nuclear-energy-law-focus-on-international-market-idUSKCN1M2024.
[154] Dan Yurman, "Argentina Signs $8B Deal for China's Hualong One PWR," Neutron Bytes, 12 February 2022, https://neutronbytes.com/2022/02/12/argentina-signs-8b-deal-for-chinas-hualong-one-pwr/.
[155] Ivan Nechepurenko and Andrew Higgins, "Coming to a Country Near You: A Russian Nuclear Power Plant," New York Times, 21 March 2020, https://www.nytimes.com/2020/03/21/world/europe/belarus-russia-nuclear.html.
[156] Suriya Jayanti, "Russia Is Still Winning the Energy War," Time Magazine, 29 April 2022, https://time.com/6172292/russia-ukraine-invasion-energy/.
[157] Aram Ekin Duran, "Akkuyu nuclear plant: Turkey and Russia's atomic connection," DW, 3 April 2018, https://www.dw.com/en/akkuyu-nuclear-plant-turkey-and-russias-atomic-connection/a-43241154; Ivan Nechepurenko and Andrew Higgins, "Coming to a Country Near You: A Russian Nuclear Power Plant," New York Times, 21 March 2020, https://www.nytimes.com/2020/03/21/world/europe/belarus-russia-nuclear.html.
[158] "Westinghouse signs expanded Ukraine nuclear fuel deal," Reuters, 30 September 2020, https://www.reuters.com/business/energy/ukraine-signs-deal-with-westinghouse-end-russian-nuclear-fuel-needs-2022-06-03/; "Ukraine signs deal with Westinghouse to end Russian nuclear fuel needs," Reuters, 3 June 2022, https://www.reuters.com/article/us-ukraine-energy-westinghouse-idUSKBN26L25B.
[159] "Finnish group scraps nuclear plant deal with Russia's Rosatom," France24, 2 May 2022, https://www.france24.com/en/live-news/20220502-finnish-group-scraps-nuclear-plant-deal-with-russia-s-rosatom.
[160] "Czech energy company CEZ switches away from Russian nuclear fuel," BNE.eu, 29 June 2022, https://www.bne.eu/czech-energy-company-cez-switches-away-from-russian-nuclear-fuel-248913/.
[161] David Dalton, "Sweden's Vattenfall Says 'No Deliveries From Russia' Until Further Notice," NucNet, 24 February 2022, https://www.nucnet.org/news/sweden-s-vattenfall-says-no-further-deliveries-from-russia-until-further-notice-2-4-2022.
[162] David W. Yellen, "The trade war we want China to win: China's nuclear exports can challenge Russian dominance," Atlantic Council, 26 February 2020, https://www.atlanticcouncil.org/blogs/energysource/the-trade-war-we-want-china-to-win-chinas-nuclear-exports-can-challenge-russian-dominance/.
[163] "'Existential danger': Romania switches from China to US for help in building reactors," Global Construction Review, 10 December 2020, https://www.globalconstructionreview.com/existential-danger-romania-switches-china-us-help/.
[164] Stanley Reed, "U.K. Backs Giant Nuclear Plant, Squeezing Out China," New York Times, 29 November 2022, https://www.nytimes.com/2022/11/29/business/uk-nuclear-plant-china.html.
[165] "2021 PERFORMANCE OF STATE ATOMIC ENERGY CORPORATION ROSATOM IN 2021"," Rosatom, 2021, https://www.report.rosatom.ru/go_eng/go_rosatom_eng_2021/rosatom_2021_eng.pdf.
[166] Steve Holland and Kanishka Singh, "U.S. mulls sanctions on Russian atomic energy company Rosatom - U.S. official," Reuters, 9 March 2022, https://www.reuters.com/world/europe/us-weighs-sanctions-russian-nuclear-power-supplier-rosatom-bloomberg-2022-03-09/.
[167] John Quiggin, "Atomic disruption: how Russia's war on Ukraine has rattled the nuclear world order," The Conversation, 23 March 2022, https://theconversation.com/atomic-disruption-how-russias-war-on-ukraine-has-rattled-the-nuclear-world-order-179939.
[168] "The localization rate of nuclear power equipment ranges from 1% to 86.7%, and my country's nuclear power equipment industry develops by leaps and bounds" [核电设备国产化率从 1%到 86.7%，我国核电装备产业跨越式发展], National Nuclear Safety Administration, 6 June 2018, https://nnsa.mee.gov.cn/ywdt/yjzx/201806/t20180606_442659.html.
[169] William Laurance, "The Dark Legacy of China's Drive for Global Resources," Yale E360, 28 March 2017, https://e360.yale.edu/features/the-dark-legacy-of-chinas-drive-for-global-resources.
[170] Ian Tiseo, "Largest global emitters of carbon dioxide by country 2020," Statista, 5 November 2021, https://www.statista.com/statistics/271748/the-largest-emitters-of-co2-in-the-world/.
[171] Hanna Ritchie, "What are the safest and cleanest sources of energy?," Our World in Data, 10 February 2020, https://ourworldindata.org/safest-sources-of-energy.
[172] "China," Climate Action Tracker, October 2021, https://climateactiontracker.org/countries/china/; "Russian Federation," Climate Action Tracker, October 2021, https://climateactiontracker.org/countries/russian-federation/.
[173] "China Nuclear Power," World Nuclear Association, accessed 28 April 2022, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx; "China Nuclear Fuel Cycle," World Nuclear Association, accessed 6 March 2023, https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.
[174] "Factbox: China-Russia trade has surged as countries grow closer," Reuters, 1 March 2022, https://www.reuters.com/markets/europe/china-russia-trade-has-surged-countries-grow-closer-2022-03-01/.
[175] Jessica Lovering and M. Granger Morgan, "As US nuclear exports decline, experts fear international safeguards will too," The Bulletin of Atomic Scientists, 27 August 2021, https://thebulletin.org/2021/08/as_us_nuclear_exports_decline_experts_fear_international_safeguards_will_too/.

[176] "Civil nuclear strategies," Enerdata, 11 March 2021, https://www.enerdata.net/publications/executive-briefing/world-civil-nuclear-strategies.html; "Restoring America's Competitive Nuclear Energy Advantage: A strategy to U.S. National Security," U.S. Department of Energy, April 2020, https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage_1.pdf; M. Granger Morgan et al., "US nuclear power: The vanishing low-carbon wedge," PNAS, 2 July 2018, https://www.pnas.org/doi/10.1073/pnas.1804655115.

[177] Vladimir Mukhin, "China's nuclear potential threatens not only the United States, but also Russia" [Ядерный потенциал Китая угрожает не только США, но и России], Nezavisimaya Gazeta, 16 July 2019, https://www.ng.ru/world/2019-07-16/2_7624_threat.html.

[178] David W. Yellen, "The trade war we want China to win: China's nuclear exports can challenge Russian dominance," Atlantic Council, 26 February 2020, https://www.atlanticcouncil.org/blogs/energysource/the-trade-war-we-want-china-to-win-chinas-nuclear-exports-can-challenge-russian-dominance/.