Testimony before the U.S.-China Economic and Security Review Commission

Hearing on Technology, Trade, and Military-Civil Fusion:
China's Pursuit of Artificial Intelligence, New Materials, and New Energy

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Good afternoon Vice Chairman Cleveland and Commissioner Lee, and other esteemed members of the Commission. I would like to thank the Commission for the opportunity to testify about China's export ambitions in advanced nuclear energy. It is an honor to participate in this hearing.

My remarks today will cover the decline of the US in global nuclear power markets and the rising ambitions of China, particularly with respect to new and advanced nuclear technologies. China has the largest number of nuclear reactors under construction today, and will soon surpass France to have the second largest operating reactor fleet. Beyond their short-term plans for large-scale light-water reactors, China is also investing significant resources in small modular reactors (SMRs), offshore nuclear, molten salt reactors, and high-temperature gas-cooled reactors.

This comes at a time when the US nuclear industry has stagnated domestically and struggles to win new export projects. The risk from a decline of U.S. dominance in the global nuclear market is about much more than economics. Historically, the US has used trade in commercial nuclear technologies to require stricter safety and security standards in host countries. There has been growing concern among US policymakers that with the decline of nuclear exports, the US is losing a strong tool of influence in regions of strategic importance like the Middle East, sub-Saharan Africa, and southeast asia.

While the lack of strong state support for nuclear power in the US is often seen as a competitive disadvantage on the global market, I will argue that this weakness is actually a strength. The US maintains a robust nuclear power industry with dozens of companies, both small and large, working on commercializing advanced nuclear designs. With smarter federal policies, US companies can develop nuclear technologies that are actually better suited for deployment in competitive markets abroad and at home.

While my remarks today are focused on China, many of these arguments apply to competition with Russian nuclear exports as well.

China's Role in Advanced Nuclear Development

Around the world today, most of the 450 commercial nuclear power reactors are light-water technology, burning uranium oxide fuel and using regular water as both a coolant and neutron moderator. There are also about 50 heavy-water reactors, particularly in Canada and India, and 15 gas-cooled reactors, mostly in the UK.

There is a broad group of technologies that we refer to as "advanced nuclear" that are under development by national governments and companies around the world. The US and China both have devoted significant funding to advanced nuclear designs. At the most basic level, advanced nuclear is anything other than the large-scale water-cooled reactors that we operate today. The term can also include light-water small modular reactors (SMRs), which are essentially scaled down models of traditional reactors, but with the ability to be factory produced and with enhanced safety and performance features.

Beyond light-water SMRs, there are several broad categories of advanced nuclear reactors that are in development. These include molten salt reactors, gas-cooled reactors, and fast breeder reactors. Their attributes differ, but most advanced reactors are pursuing passive safety features, smaller sizes and modular fabrication, with the goals of reduced capital costs and improved performance.[1]

Most of these designs were originally developed and tested in the U.S. starting in the 1960s, but struggled to find commercial success. Factors including improved materials, manufacturing techniques, and computer modeling capabilities have led to a renewed push to commercialize these technologies. In addition, growing concerns around climate change have spurred a new generation of engineers to work on improving the economics and performance of nuclear power.

Over 50 companies in the US are developing advanced reactor technologies, and several hope to construct their first commercial demonstration in the 2020s.[2] While some of these companies were spun out of university and national laboratory programs, many have been successful at raising private funding.

As federal funding for nuclear development has declined over the last few decades, China has scaled-up investment across the board in both traditional and advanced nuclear. China has two state-owned enterprises developing SMRs. Construction of their first commercial demonstration of a 125MW SMR will begin in late 2019 with completion expected in 2025. They also have plans to demonstrate a floating barge-based version of this reactor, for deployment in the South China Sea. China has a pair of 200MW high-temperature gas-cooled

[1] Nordhaus, T., Lovering, J. & Shellenberger, M. *How to Make Nuclear Cheap*. The Breakthrough Institute (2013). https://www.thebreakthrough.org/articles/how-to-make-nuclear-cheap

[2] Third Way. "The Advanced Nuclear Industry: 2016 Update" December 12, 2016 https://www.thirdway.org/infographic/the-advanced-nuclear-industry-2016-update

reactors under construction in Shidaowan, originally based on a German technology, with expected grid-connection in 2019. China has also invested over $300 million in molten salt technology over the last few years, with plans to build small-scale demonstrations of both a solid-fueled and liquid-fueled design in the 2020s, with commercial demonstration in the 2030s. The most prominent international collaboration was a Chinese partnership with the Bill Gates-funded company Terrapower to demonstrate a metal-cooled fast breeder reactor near Beijing. Due to increased nuclear trade restrictions, Gates announced this project would be cancelled in early 2019. However, Terrapower is still moving forward with a molten salt design in the US.

China's Transition to Indigenous Reactor Technology and Domestic Supply Chain

China currently has the world's third largest fleet (46) of operating commercial nuclear reactors, and the largest number of reactors under construction (11). After a pause in approvals for new construction following Fukushima, China looks likely to fall short of their target for 58 gigawatts (GW) of installed nuclear capacity by 2020. But as they've begun approving the first new construction projects in three years, they are re-committing to strong growth, predicting 120-150 GW of installed capacity by 2030, which would mean they surpass the US as the world's largest producer of nuclear power.[3]

While China's nuclear power sector initially succeeded with a suite of imported designs from France, Canada, Russia, and the US, there has been a major effort to localize the supply chain and develop indigenous reactor technology. When the first reactor was supplied by France in 1987, only 1% of the components and equipment were manufactured in China. In 2006, the Chinese government set a goal to localize 75% of the supply chain, and by 2014 they had surpassed that goal with a reported 80% of components and equipment manufactured in China. Now the government is pushing manufacturers to export these components to nuclear projects abroad.[4]

Over the last decade, the Chinese government asked its two main nuclear developers to coordinate on a 1000 MW indigenous reactor design that could be exported starting in the 2020s. The result was the Hualong-1, which is a derivative of a French design.[5] Pakistan is planning to build five Hualong-1 reactors at two power plant sites. In 2017, the UK began Generic Design Review of the reactor for a potential project there, and there are also plans for export to Argentina.

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[3] Reuters. "China likely to more than triple nuclear power capacity by 2030 - official." November 8th, 2018. https://www.reuters.com/article/china-nuclearpower/china-likely-to-more-than-triple-nuclear-power-capacity-by-2030-official-idUSL4N1XJ3AR

[4] Nuclear Business Platform. "China's Nuclear Supply Chain Movement: From Localization To Globalization" http://www.nuclearbusiness-platform.com/nuclear-industry/chinas-nuclear-supply-chain-movement-from-localization-to-globalization/

[5] Hibbs, M. *The Future of Nuclear Power in China*. (Carnegie Endowment for International Peace, 2018). pg. 56

China pursuing nuclear exports for political influence in addition to economics

Nuclear vendors recognize that there is a large and growing potential export market for commercial reactors. Over thirty countries are pursuing their first nuclear power plants, according to the IAEA.[6] And the IEA predicts that global nuclear capacity will need to double by 2050 to meet aggressive decarbonization targets.

China is not alone in recognizing the size of the future nuclear power market, but they also recognize the important geostrategic goals that nuclear exports facilitate. Building a nuclear power plant in a foreign country establishes a 60-100 year business and political relationship that goes beyond supplying fuel and components for the physical plant. Nuclear supplier countries have in the past used nuclear exports as a gateway product to facilitate other trade deals,[7] and also to establish influence in the fuel cycle, regulation, and power sector of the foreign country.

China is pursuing a diverse campaign of influence through its Belt and Road initiative. For nuclear power in particular, China's overseas ambitions fall broadly into three categories: 1) marketing its domestic Hualong reactor for export, 2) investing in existing nuclear projects, such as Hinkley C in the UK, and 3) partnering with Canada and the U.S. to develop advanced reactor concepts. Additionally, China has invested heavily in nuclear innovation, including developing small modular reactors (SMR), molten salt reactors, and high-temperature gas reactors.[8]

From 2000-2015, China signed over 50 nuclear cooperation agreements with 20 countries including: Egypt, Jordan, Saudi Arabia, Algeria, and Turkey in the Middle East and North Africa; Pakistan, Thailand, Taiwan, Japan, and Korea in Asia; the UK, France, Russia, Belarus, and Romania in Europe; along with Australia, Argentina, and the U.S. In about half of these agreements, China acted as the supplier, providing concrete technological support for things like nuclear power plants, reactors, or fuel cycle facilities or services.[9]

In sub-Saharan Africa, China has recently signed nuclear agreements with Kenya, Sudan, and Uganda, and appears keen on increasing its scope of nuclear influence on the African continent more broadly. In 2014, partnerships were signed between the Nuclear Energy Corporation of South Africa (Necsa) and both the China Nuclear Engineering Group and China's State Nuclear Power Technology Corporation. Both agreements were focused on training for nuclear power plant construction and NPP project management. China General Nuclear owns and operates the world's second largest uranium mine in Namibia, as well as submitting a proposal for a small nuclear power plant there. China has also built research reactors in Ghana and Nigeria.

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[6] World Nuclear Association. Emerging Nuclear Energy Countries. Updated March 2019. http://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx

[7] Bratt, D. *The Politics of CANDU Exports*. (University of Toronto Press, 2006).

[8] Ichord, R. F. *US Nuclear-Power Leadership and the Chinese and Russian Challenge*. (2018).

[9] Data from: Jewell, J., Vetier, M. & Garcia-Cabrera, D. The international technological nuclear cooperation landscape: A new dataset and network analysis. *Energy Policy* 128, 838–852 (2019).

Chinese reactors half the cost of western designs

It has been difficult to get accurate costs of nuclear power plants from China, but limited evidence suggests they are roughly half the cost of reactors in the US or Europe. A 2015 study from the OECD estimated that average overnight capital costs for new nuclear in China were $2,200/kW, compared with $4,100/kW in the US.[10] Financing costs add about 100% to the overnight capital costs, which brings the total cost to $5,000/kW for China, compared with $9,300/kW for the US. For context, this implies that a typical 1,000 MW reactor under construction today would cost $9.3 billion in the US but only $5 billion in China.

One can also compare levelized costs, which puts all lifetime costs into present day value per unit of energy produced. According to the same OECD report, the levelized cost of electricity for a new nuclear plant built in China today is about $42/MWh, whereas it's estimated at $78/MWh in the US. More importantly, the levelized cost of electricity from nuclear in China is cheaper than from coal, gas, wind, or solar. Only hydroelectric produces cheaper electricity in the long run. By contrast, in the US the levelized cost of electricity from nuclear is more expensive than natural gas and onshore wind. This can help to explain why China continues to invest heavily in new nuclear power plants whereas the US has built relatively few in the last thirty years.

Cheap financing from the state helps bring the costs down for these projects, and lower labor costs also help, but the most important factor is reduced component cost through economies of scale and series. There are a number of key components involved in a nuclear project that are both expensive and nuclear specific. China has worked to localize manufacturing of these key components, while also sourcing the raw materials nearby, allowing them to reduce the cost up to 80%. Investing in the manufacturing facilities, which are often imported, to produce these key components would not be economical unless China was building a lot of nuclear power. Similar factors are at play in South Korea, which is why an American advanced nuclear firm, NuScale, recently partnered with a Korean manufacturing firm, Doosan, to produce their pressure vessels.

The biggest limitations of China's domestic nuclear industry and future exports are project management and quality control. For China's ongoing international builds, like the EPR and AP1000, they have chosen to partner with US and French architect-engineering firms for overall project management. It is unclear how well this skill can be localized, and may represent an ongoing opportunity for US firms to stay competitive in China. Similarly, despite strong government pressure to localize production, China's state-owned nuclear firms often prefer to source components from foreign firms when they worry a domestic contractor will outsource production to a low-quality supplier who is unfamiliar with nuclear facilities.[11]

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[10] IEA. Projected Costs of Generating Electricity (2015 Edition). (2015).

[11] Metzler, F. & Steinfeld, E. S. *Sustaining Global Competitiveness in the Provision of Complex Products and Systems: The Case of Civilian Nuclear Power Technology*. MIT Political Science Department (2013).

U.S. Risks Losing Influence in Global Nuclear Governance

In the last ten years, there have been several prominent reports arguing that the U.S. is at risk of losing its significant influence in international nuclear governance regimes if the domestic industry continues to struggle to build and export commercial nuclear technology. In reports from 2013 and 2018, the Center for Strategic and International Studies made the case that success of the Non-Proliferation Treaty has been dependent on the dominance of U.S. nuclear technology in the global market.[12,13] Specifically, the US has leveraged the attractiveness of US nuclear technology to require countries to sign bilateral trade agreements that included much stricter proliferation controls than other countries required. Indeed, even countries like France, West Germany, and Canada tended to be much looser on such controls to secure nuclear export deals.

Motivated by these concerns, my doctoral advisors - Granger Morgan at Carnegie Mellon University and Ahmed Abdulla at UC San Diego - convened a workshop in September 2018 that was titled "Evaluating Strategies to Restore US Leadership in the International Nuclear Market and Control Regimes." We brought together experts from both national security and the nuclear energy industry to discuss the role of commercial trade in international governance and to evaluate potential strategies to strengthen US influence.

Most experts in our workshop thought the US still maintained strong influence through its legacy dominance of nuclear trade and technologies, but that this influence would certainly wane going forward, particularly as more countries build designs not originating in the US. Another concern was that the International Atomic Energy Agency, the international safety and security regulator, depends on expertise from the US, and the US has gained that expertise from decades of working with LWR technology.

Enduring Challenges for U.S. Nuclear Exports

While the higher costs of US technology is a challenge, the main reason the US is not competitive as an exporter is the lack of a successful domestic market. When newcomer nuclear countries take bids for their first commercial nuclear plants, they look for vendors with a recent track record of building reactors on-time and on-budget. This is how South Korea won the bid for the first four 1400 MW reactors under construction now in the United Arab Emirates.

By almost any metric, the U.S. civilian nuclear industry is on the decline. Of the 54 reactors under construction worldwide, only two are in the U.S. Research and Development funding for nuclear has also been on the decline since the 1970s, although has seen increases in the last few years. Likely as a result of reduced R&D spending, nuclear patents from the U.S. have also

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[12] Wallace, M. et al. Restoring U.S. Leadership in Nuclear Energy: A National Security Imperative. CSIS (2013).
[13] Wallace, M., Roma, A. & Desai, S. Back from the Brink. CSIS (2018).

been on the decline, averaging over 100 nuclear patents per year from 1960-2000, but falling to less than 20 per year in the last decade. In contrast, China has grown from almost zero patenting in the 1990s, to over 200 per year in the last decade.[14]

The US still retains strong influence from its legacy of LWR exports and former dominance of the global market. For example, a study of nuclear cooperation agreements by Jewell et al. (2019) found that the US still dominates these agreements for supportive technological cooperation, including areas such as knowledge exchange and training, safety and security, planning, regulation, and supportive infrastructure. But these agreements likely rest on past US experience building and exporting LWR technology.[15]

Therefore, the future market for advanced reactors provides a dual opportunity for the US to regain market power and influence in the next wave of nuclear governance. Luckily, there are over 50 companies working on advanced nuclear technologies in the US,[16] many with significant private investment and funding from the Department of Energy. Several are beginning pre-licensing activities with the Nuclear Regulatory Commission. Those that are farthest along are aiming for commercial demonstration in the 2020s.

While many express frustration that private US nuclear companies have to compete with state-owned enterprises in China, this can actually be to the U.S. advantage. In the 1960s and 70s, the U.S. spent significantly more money on advanced reactor research and development, even funding prototypes and commercial demonstrations. What was lacking was a market for such technologies. To have government agencies pick and choose technologies and then push them onto the market is a recipe for failure. A better role for federal investment is creating market demand and supporting the innovation infrastructure, such as testing facilities at national labs. This is exactly what NASA did starting in 2005 for commercial spaceflight. Rather than invest $25 billion to develop a new space shuttle to deliver cargo and crew to the International Space Station, NASA decided to stimulate the emerging commercial industry, accelerating technical readiness of launch vehicles that NASA could later contract with for launch services. This model proved cheaper and faster, but also encouraged more companies to compete with a variety of designs on the international market, making the U.S. a leader in global launch services in the space of 10 years.[17]

[14] Lovering, J., King, L. & Nordhaus, T. *How To Make Nuclear Innovative: Lessons From Other Advanced Industries*. (2017).
[15] Jewell, J., Vetier, M. & Garcia-Cabrera, D. The international technological nuclear cooperation landscape: A new dataset and network analysis. Energy Policy 128, 838–852 (2019).
[16] Third Way. "The Advanced Nuclear Industry: 2016 Update" December 12, 2016 https://www.thirdway.org/infographic/the-advanced-nuclear-industry-2016-update
[17] Lovering, J., King, L. & Nordhaus, T. "Commercial Spaceflight: Case Study No. 1 in How to Make Nuclear Innovative." The Breakthrough Institute (2017) https://www.thebreakthrough.org/issues/energy/commercial-spaceflight

Policy Recommendations

At our 2018 workshop, experts evaluated potential strategies for both regaining U.S. market competitiveness as well as strengthening direct U.S. influence in international nuclear governance. The results from our expert evaluation concluded that three policies look promising from both an efficacy and feasibility perspective. The first is partnering with South Korea to build nuclear power plants in third countries. This would take advantage of Korea's manufacturing strengths and success at recent nuclear builds, paired with U.S. diplomatic strength and reputation in nuclear safety. The next policy is what we called the "NASA model", which is to move commercial development of advanced nuclear into the private sector, and use federal investment to build out a supportive infrastructure and create demand.[18] Lastly, the participants thought that the U.S. moving forward on a solution to nuclear waste could actually improve our ability to compete with nuclear vendors like Russia that offer fuel take-back.

These are not as improbable as they might seem at first. Recently passed legislation like the Nuclear Energy Innovation Capabilities Act and the Nuclear Energy Innovation Modernization Act,[19] are helping to accelerate commercialization of advanced reactors, but we need significantly more policy changes. The Nuclear Energy Leadership Act, introduced in the Senate in April 2019, goes much further in investing in innovation infrastructure and supporting commercial demonstrations. Mandates for procurement of nuclear electricity, similar to federal and state mandates for renewables procurement, could also stimulate demand for nuclear and revitalize the domestic market.[20]

Domestic success could help the U.S. be more competitive in the export market, but financing remains a major obstacle. Policies to expand funding for nuclear projects through the Export-Import Bank could help, but having a fully functioning EXIM board of directors is a good first start.[21] Going further, the U.S. government could pressure international financial institutions like the World Bank to change their long-standing prohibitions on funding nuclear projects. Such restrictions on funding push newcomer nuclear countries toward state-owned nuclear vendors that offer generous financing packages.

Ultimately, federal policies should recognize both the environmental and national security benefits of commercial nuclear power. With more targeted government investment, private companies can commercialize advanced nuclear technologies that could be competitive both in domestic markets and globally, strengthening U.S. influence in emerging nuclear countries.

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[18] Lovering, J., King, L. & Nordhaus, T. *How To Make Nuclear Innovative: Lessons From Other Advanced Industries*. (2017).

[19] Nuclear Energy Innovation Capabilities Act of 2017. https://www.congress.gov/bill/115th-congress/senate-bill/97 Nuclear Energy Innovation and Modernization Act https://www.congress.gov/bill/115th-congress/senate-bill/512

[20] Clean Energy Standards: How More States Can Become Climate Leaders. The Breakthrough Institute and Third Way. https://www.thebreakthrough.org/articles/clean-energy-standards

[21] NEI. https://www.nei.org/advocacy/compete-globally/export-import-bank