4. Enabling a Significant Nuclear Role in China's Decarbonization: Loosening Constraints, Mitigating Risks

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Introduction

Over the next several decades, China faces the immense challenge of expanding energy supply to fuel its growing economy while reducing and ultimately eliminating carbon emissions. It must also drastically reduce local environmental impacts, including the fine particulates that are choking China's cities.

What role could nuclear energy—which emits neither carbon nor other air pollutants—play in decarbonizing China's energy system? China's total final energy consumption in the middle of the 21st century is likely to be in the range of three to four terawatt-years per year, and continue at that level thereafter.[1] Only part of that total will be electricity, though increasing electrification of sectors from industry to transportation will expand the fraction of the total that electricity represents.

Delivering that much energy without carbon emissions will be extraordinarily difficult. For nuclear energy or any other energy source to provide even one-tenth of the total low-carbon energy China will need would require growth to a scale that would deliver 300-400 gigawatt-years per year, which would be a dramatic expansion for either nuclear energy or renewables. Providing a larger share would require even larger-scale growth, and some technologies will certainly have to shoulder more than a tenth of the burden.

Decarbonizing China's energy system is likely to require every low-carbon technology available. Doing it without a major nuclear contribution would be substantially more difficult. But getting a major nuclear contribution will itself be a challenge. Hence, it makes sense to take action today to address enough of the problems that have limited nuclear energy's growth to make it a genuinely expandable option for China's energy future.

Reducing carbon emissions is only one of the reasons to shift away from China's heavy reliance on coal. Reducing air pollution (particularly fine particulates) is politically salient within China and may be an even more important driver of China's energy decisions in the years to come. By some estimates, fine particulates in outdoor air cause over one million premature deaths per year in China, and have a significant negative impact on GDP.[2] China's energy planners also value diversity in the energy mix, partly to strengthen energy security.

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[1] The 3.4 TW-yr of final energy consumed in 2040 in the "current policies" scenario would represent roughly 50 percent growth compared to energy consumption of 2.55 TW-yr in 2016. In a "sustainable development" scenario, final energy consumption in 2040 would be about a third lower, in the range of 2.8 TW-yr/year. See International Energy Agency, *World Energy Outlook 2017* (Paris: IEA, 2017), pp. 700-701. Converted from million tons of oil equivalent. Many other projections are broadly similar.

[2] See, for example, Hu J., Huang L., Chen M., Liao H., Zhang H., Wang S., Zhang Q., and Ying Q., "Premature Mortality Attributable to Particulate Matter in China: Source Contributions and Responses to Reductions," *Environmental Science and Technology,* Vol. 51, No. 17 (2017), pp. 9950-9959. See also IEA, WEO 2017, p. 496. For a discussion of the role coal energy plays in contributing to these particulate concentrations, and of pollution as

This chapter identifies the key constraints on nuclear energy's potential to grow to scales ranging from hundreds of gigawatts to a terawatt or more over the next several decades; the potential risks of such growth; and steps China could take to address these constraints and risks, so as to expand its nuclear energy opportunities. It offers suggestions for policies the Chinese government could implement in the near term (2018-2030) to maximize its nuclear energy options for the long term (2030-2100).

The most important constraints limiting nuclear energy growth at the scale of hundreds of gigawatts to terawatts are public acceptance—essential for siting the large number of facilities that would be needed—and economics. Other constraints are not trivial, but if the central two can be addressed, it is very likely the others can be as well. To address these critical constraints will require:

- *Avoiding catastrophes.* Any Fukushima- or Chernobyl-scale radiation release would likely doom prospects of gaining public acceptance for hundreds of nuclear reactors all over China. Hence, focusing seriously on, and making investments in, both safety and security should be seen as key investments in China's nuclear energy future.
- *Building public trust.* Although China has an authoritarian political system, public opinion matters greatly in siting nuclear facilities. Two proposed fuel cycle facilities have already been canceled (or at least relocated) as a result of public protest, and the government is investing in public outreach efforts in towns where nuclear plants are proposed. A step-by-step process of building public trust, through genuine dialogue with affected publics and fulfilling promises made by nuclear organizations, will be essential to gaining the needed acceptance of nuclear energy.
- *Reducing cost and boosting revenue.* As China shifts toward an energy system where market forces have more influence, the economics of nuclear energy compared with other options will loom large.[3] Steps to reduce the capital cost of reactors, maintain low-cost financing for them, and strengthen their revenues could have a major impact on the scale of future nuclear energy growth.

All three of these goals can be affected by both policy shifts and technological changes. Safety and security, for example, can be improved with rigorous regulation and steps to strengthen organizational cultures at existing facilities—and future reactor designs can offer expanded passive safety, relying less on pumps working or human operators taking the right actions to avoid an accident. This chapter, therefore, discusses both policy and technological approaches to address each issue it identifies.

For the near term, the most critical steps China can take to maximize its long-term nuclear energy options include:

- Expanded efforts to ensure both safety and security;
- Investing in public support for nuclear energy, particularly in step-by-step engagement with local communities;

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a motive for China's efforts to reduce coal use, see Michael Davidson, "From Barrier to Bridge: The Role of Coal in China's Decarbonization," this volume.

[3] For a discussion of China's evolving approach to electricity regulation and markets, see Wang Pu, "Reform China's Electricity Market to Facilitate Low-Carbon Transition," this volume.

- Carrying out research, development, and demonstration (RD&D) to develop new technologies that can be available within a few decades and that help address key constraints; and
- Avoiding near-term technological lock-in on costly, dangerous, and unneeded technologies, such as plutonium reprocessing and plutonium breeder reactors.

Given the importance of avoiding catastrophes, building public trust, and improving economics, those issues receive the most extensive treatment here. The chapter proceeds by focusing, one by one, on each of the most important constraints and risks that might limit nuclear energy's growth in China. The section on each concern discusses how challenging the particular issue is in the Chinese context, and how policy changes, advanced technologies, and, where relevant, changes in business models might help loosen the constraint or mitigate the risk. In addition to avoiding catastrophes, building public trust, and improving economics, the other issues addressed are waste management, proliferation resistance, government and industrial capacity (including human resources), regulatory delays, and integration into China's evolving energy infrastructure. Finally, the chapter concludes with suggestions on near-term steps to keep China's long-term nuclear energy options as open as practicable.

Nuclear energy's future in China matters not only for that country but also for the world. China is making larger investments in nuclear energy than any other country on Earth; as of late 2018, 29 of the 42 reactors brought online during 2013-2018 were in China.[4] Unless nuclear energy can grow enough to play a major role in decarbonizing China's energy supply, it will have little chance of playing a major role in world decarbonization.

China's Current Nuclear Energy Picture and the Scale of the Challenge

In 2017, China's nuclear plants had a capacity of 33.7 GWe.[5] Hence, growth to a scale that would provide even a tenth of the low-carbon energy China will need by mid-century would require scaling up by an order of magnitude—a truly transformational change. This would involve building hundreds of large reactors, or thousands of small modular reactors (SMRs).

A broad spectrum of paths to achieve such growth are possible. At one end of the spectrum, in what might be called a "steady growth" scenario, China could build reactors at a steady pace of perhaps 5-10 GWe per year for decades. At the other end of the spectrum, in a scenario that might be called "later surge," China could deploy current-generation large light-water reactors at only a modest pace, and then accelerate deployments dramatically at some point

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[4] Statistics from International Atomic Energy Agency, "Power Reactor Information System," https://www.iaea.org/pris/.

[5] For a very useful overview of nuclear power in China, see Mark Hibbs, *The Future of Nuclear Power in China* (Washington, D.C.: Carnegie Endowment for International Peace, 2018). For another useful, though optimistic, overview, see World Nuclear Association, "Nuclear Power in China" (London: WNA, October 2017). For more skeptical accounts, see M.V. Ramana and Amy King, "A New Normal? The Changing Future of Nuclear Energy in China," in Peter van Ness and Mel Gurtov, eds., *Lessons From Fukushima* (Canberra: Australia National University Press, 2017), https://press.anu.edu.au/publications/learning-fukushima, pp. 103-132, and Mycle Schneider and Anthony Frogatt, with Julie Hazemann, Tadahiro Katsuta, M.V. Ramana, Juan C. Rodriguez, Andreas Rüdinger, and Agnès Stienne, *World Nuclear Industry Status Report 2017* (Paris: Mycle Schneider Consulting, September 2017), pp. 198-202. For a world overview of the nuclear energy future, see Jacopo Buongiorno, Michael Corradini, and John Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained World* (Cambridge, Mass.: Massachusetts Institute of Technology, 2018).

in the 2030s-2060s, if and when advanced reactors with cost, safety, or other advantages became available. (See Figure 1)

In either of these scenarios, nuclear energy might play a more important role in the second half of the 21st century than the first. In particular, while renewables may outcompete nuclear for low-cost low-carbon energy supply in the near term, achieving deep decarbonization with only intermittent sources and storage could be very costly; having some non-intermittent low-carbon backup would reduce overall system costs.[6] To preserve options for that future nuclear role, however, will require China to take a variety of steps in the nearer term, from avoiding catastrophes to investing in the next generation of technology.

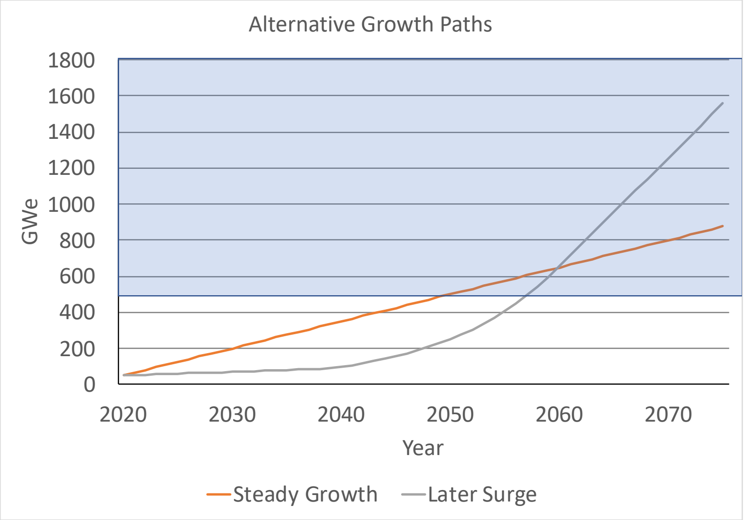

Figure 1

China's current nuclear energy plans are ambitious, but not on the scale described for deep decarbonization. In 2012, following a review after the Fukushima Daichi nuclear accident, China shifted from a policy of "aggressive development" of nuclear energy to one of "safe and efficient development," reducing the nuclear energy target for 2020 from 70 GWe to 58 GWe.[7] That goal has remained unchanged since then, though it will not be met.[8]

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[6] See, for example, Jacopo Buongiorno, Michael Corradini, and John Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained World* (Cambridge, Mass.: Massachusetts Institute of Technology, 2018). Note that other non-intermittent low-carbon sources not examined in the MIT study, such as fossil energy with highly effective carbon capture, could also serve this role.

[7] See discussion and references in Matthew Bunn, Hui Zhang, and Li Kang, *The Cost of Reprocessing in China* (Cambridge, Mass.: Belfer Center for Science and International Affairs, January 2016), pp. 12-13.

[8] "Goals Set for Nuclear Energy Development in Next Five Years," *China Daily,* January 18, 2017, http://www.chinadaily.com.cn/business/2017-01/18/content_27988526.htm

Indeed, nuclear energy growth has been slowing in China. In mid-2019, Chinese authorities approved starting construction on six new reactors – the first approvals in over three years.[9] As of that time, the post-Fukushima hold on building reactors at inland sites had not been lifted. Recent reactor construction has suffered delays and cost overruns (while remaining cheaper and faster than in Western countries), public opposition has been growing since the accident, there is little current need for additional electricity capacity, and China's nuclear industry, centered around a few massive state-owned firms, is suffering financially. As one strongly pro-nuclear Western observer put it, "all the negative factors that have afflicted nuclear programs elsewhere are also equally applicable there."[10]

Recent Chinese plans have not established official targets for longer-term nuclear growth. In 2015, the China Nuclear Energy Association (an industry trade group), projected that nuclear energy would grow to 160 GWe in 2030 and 240 GWe in 2050.[11] These figures now seem very unlikely to be reached.

Some experts believe that nuclear power in China is likely to level off after reaching 100-150 GWe; should that occur, nuclear energy would play only a minor role in reducing China's carbon emissions. The International Energy Agency's "Sustainable Development" scenario, for example, projects only a small role for nuclear energy in decarbonizing the country's energy system over the next few decades. (See Figure 2.) Hence, the questions that are the focus of this chapter—what the key constraints and risks are that limit likely nuclear energy growth, and how could they be addressed—are central to nuclear energy's future as a tool to reduce carbon emissions in China, and, by extension, worldwide.

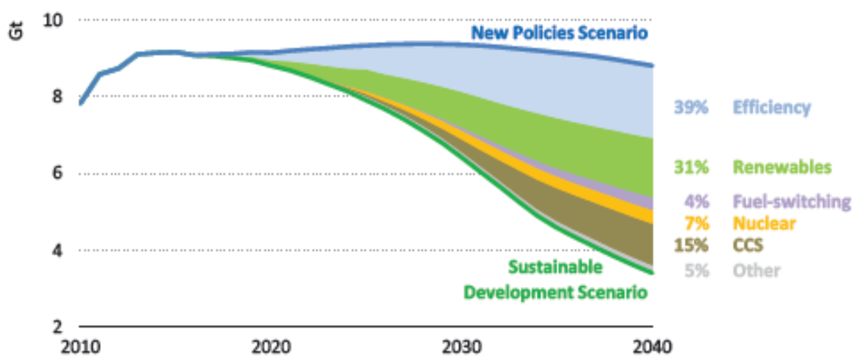

Figure 2

For now, China's nuclear construction program is almost entirely focused on large light-water reactors. A two-unit demonstration pebble-bed plant, one small floating reactor, and one

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[9] Shunsuke Tabeta, "China Approves First New Nuclear Reactors in 3-Plus Years," *Nikkei Asian Review,* August 2, 2019.

[10] See Steven Kidd, "Assessing China's Slowdown," *Nuclear Intelligence Weekly*, November 30, 2018, p. 7.

[11] Cited in WNA, "Nuclear Power in China."

demonstration fast-neutron reactor are also under construction. China is investing in R&D for a number of advanced reactor concepts, and some U.S. or other foreign firms with advanced nuclear proposals—such as the Terrapower concept financed in part by Bill Gates—were considering building their first demonstration units in China, where regulation is more flexible and government support is more available than in the United States.[12] The Trump administration's decision to bar cooperation with China on advanced nuclear technologies, however, is forcing companies to reconsider those plans.[13]

Avoiding Catastrophe: Safety and Security

Avoiding major catastrophes—and convincing the public, relevant government authorities, and relevant investors that the plants will be safe and secure—is perhaps the most fundamental requirement for maintaining China's long-term options for large-scale nuclear energy growth. Increased safety concerns after the Fukushima accident led China to pause nuclear construction, impose new safety requirements, slow its nuclear growth plans, and halt, at least temporarily, plans for inland nuclear reactors. An accident or terrorist attack leading to a substantial radioactive release—particularly one that occurs in China—could make it impossible for nuclear energy to get the support needed to grow at the scale required to play a major part in decarbonizing China's energy system. Safety and security pose somewhat different issues, and this section discusses each in turn.

Safety

The Chinese government has long emphasized its commitment to a "safety first" policy on nuclear energy and has taken substantial actions to improve nuclear safety since Fukushima.[14] Nevertheless, there are clear reasons for concern, including the frequent major industrial accidents that occur elsewhere in China's economy; the quick pace and low cost of nuclear construction in China, which raises questions over whether corners are being cut; a regulator with a smaller, less experienced staff (and lower budget) than its U.S. or European counterparts; the pace of nuclear growth, which has required bringing in construction firms without previous nuclear experience for less sensitive parts of projects, putting stresses on providing sufficient supplies of trained and experienced personnel; and an overall culture of deferring to authority that could pose challenges for maintaining an appropriate "questioning attitude" at nuclear facilities.

Reducing the risk of major accidental releases of radioactivity requires five major categories of action: (a) deploying systems with high levels of built-in safety, including substantial "defense in depth" along each plausible pathway toward a nuclear accident; (b)

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[12] See, for example, Stephen Stapczynski, "Nuclear Experts Head to China to Test Experimental Reactors," *Bloomberg Technology,* September 21, 2017, https://www.bloomberg.com/news/articles/2017-09-21/nuclear-scientists-head-to-china-to-tenst-experimental-reactors. Terrapower reached agreements in 2017 with major Chinese nuclear firms to establish joint ventures to build a demonstration plant for its proposed system and work toward commercialization. See C.F. Yu and Gary Peach, "China: CNNC Commits to TWR Development," *Nuclear Intelligence Weekly,* October 6, 2017.

[13] U.S. Department of Energy, National Nuclear Security Administration, "U.S. Policy Framework on Civil Nuclear Cooperation with China" (Washington, D.C.: NNSA, October 2018); C. F. Yu, "China: U.S. Export Ban Paves Way for Competition," *Nuclear Intelligence Weekly,* October 19, 2018.

[14] For an official account of China's nuclear safety efforts in recent years, see *The People's Republic of China: Seventh National Report Under the Convention on Nuclear Safety (2013-2015)* (Beijing: Ministry

maintaining effective regulation and oversight; (c) maintaining strong "safety cultures" within the organizations building, operating, supporting, and regulating nuclear facilities; (d) ensuring that all personnel in safety-related positions have appropriate training and experience; and (e) advance planning for emergency response. China's approach in each of these areas has been evolving.

China's nuclear regulator, the National Nuclear Safety Administration (NNSA), under the Ministry of Ecology and Environment, has expanded rapidly in recent years in response to both the growth in the number of reactors in China and post-Fukushima safety concerns.[15] A new Nuclear Safety Law entered into force in early 2018. After the Fukushima accident, China undertook a safety review of all its reactors then operating or under construction, paused in authorizing more construction until new safety approaches were agreed upon, and ultimately imposed more stringent safety requirements. By one account, the 2012 nuclear safety plan adopted by the State Council called for spending 80 billion yuan ($12.5-$13 billion at then-current exchange rates, or over $22 billion at PPP rates) on safety upgrades at the Chinese plants that then existed over the following five years.[16] An international review found that China's coastal plants typically have plant heights or seawalls 5-10 meters higher than the highest average historical tsunami in their areas.[17] But for plants close to sea level, China has required a variety of measures, including waterproofing of key equipment and construction of an expanded sea wall at Qinshan. China has been an active participant in international nuclear safety activities, regularly hosting both International Atomic Energy Agency (IAEA) and World Association of Nuclear Operators (WANO) reviews; Chinese reactors typically have one independent safety review per year.[18] Chinese officials have emphasized that China has never had a serious nuclear reactor accident and its plants' ratings on World Association of Nuclear Operators (WANO) safety indicators tend to be average or above average.[19]

Nevertheless, both internally and internationally, the factors already mentioned have raised concerns about nuclear safety in China. The pace of nuclear growth—with operational nuclear reactors tripling between 2010 and 2016—raises concerns over whether the supply of capable and experienced builders and operators, as well as the capability of regulators, will be able to keep up. The number of high-profile accidents in other Chinese industries has heightened questions about whether China can really maintain a very different culture of safety in the nuclear sector. NNSA has discovered welding flaws in safety-significant equipment that the agency attributed to factors such as poor supervision, quality assurance, and personnel skills. The agency also described insufficient equipment testing, inadequate analysis of inspection results, lack of process control, and inadequate approaches to learning from experience. All of this suggests that the safety culture issue may be a deep and difficult one.[20] The wide range of different reactor designs built and operating in China makes the overall nuclear enterprise more

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[15] The Ministry of Environmental Protection was reorganized to become the Ministry of Ecology and Environment in 2018. The director of NNSA is now a Deputy Minister. The Minister, Li Ganjie, is a former head of the nuclear regulatory agency.
[16] See World Nuclear Association, "Nuclear Power in China."
[17] See Philip Y. Lipcsy, Kenji E. Kushida, and Trevor Incerti, "The Fukushima Disaster and Japan's Nuclear Plant Vulnerability in Comparative Perspective," *Environmental Science & Technology,* Vol. 47 (2013), pp. 6082-6088.
[18] World Nuclear Association, "Nuclear Power in China."
[19] See, for example, Yin Dejian, "Nuclear Safety Regulatory Framework and Challenges in China," presentation to the 40th Annual Meeting of the Spanish Nuclear Society, October 2014.
[20] Hibbs, *The Future of Nuclear Power in China,* p. 87.

challenging to operate and regulate. These concerns are exacerbated by the corruption problem in China that President Xi Xingping has targeted, including high-profile cases in the nuclear industry; in 2010, for example, the president of China's largest nuclear company was jailed for life for taking some 6.6 million yuan ($2 million at PPP rates) in bribes.[21]

Finally, while China has taken steps to strengthen and expand NNSA—most recently with the new Nuclear Safety Law—NNSA still has less experience and funding than its counterpart agencies in the United States or Europe. The U.S. Nuclear Regulatory Commission (NRC), for example, has a budget of just under a billion dollars a year, and oversees 99 operating reactors with two more under construction, along with various other materials and facilities. China's NNSA in 2014 had a budget of 350 million yuan (about $100 million if converted at PPP rates) for overseeing, at that time, 20 operating reactors and 24 under construction, along with other materials and facilities. NRC's staff was almost four times larger than NNSA's and typically had substantially more experience.[22]

These factors have led to a range of official and unofficial expressions of concern. In 2010, before Fukushima, China hosted its first IAEA Integrated Regulatory Review Service (IRRS) mission. The mission offered 39 recommendations for action and 40 suggestions—unusually large numbers, including on fundamental issues such as adequate independence and staffing of NNSA. A follow-up mission in 2016, however, found that in the intervening time, China had successfully addressed the vast majority of the concerns raised in 2010. The follow-up mission offered only a handful of new recommendations and suggestions— but one of those was that China should host another full IRRS mission by 2020.[23]

In 2011, after Fukushima, the State Council Research Office (SCRO), which advises China's powerful State Council, issued a report calling for a more cautious approach to nuclear energy, warning that moving too fast "could threaten the long-term healthy development of nuclear power." The SCRO report called for making NNSA an independent body reporting directly to the State Council (rather than being part of MEP), and quadrupling its staff by 2020; strengthening personnel training and efforts to build safety culture; improving quality control in manufacturing nuclear reactor components; and emphasizing safer "Generation III" nuclear reactors over the older-design "Generation II" reactors China (and other countries) have been operating to date.[24]

China's reviews of nuclear safety after Fukushima found a range of issues that needed to be addressed, establishing short-, medium-, and long-term requirements for improvements. In September 2012, following these various reviews—and, strikingly, following a period of public comment—China's State Council approved a sweeping nuclear safety plan (which appears to have included at least some of the SCRO's ideas, including a decision not to build any more

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[21] See "Former China Nuclear Head Jailed for Life Over Bribes," *BBC News,* November 19, 2010. For discussion of a broader set of cases, see Hui Zhang, *China's Nuclear Security: Progress, Challenges, and Next Steps* (Cambridge, Mass.: Project on Managing the Atom, Harvard University, 2016), http://belfercenter.hks.harvard.edu/files/Chinas%20Nuclear%20Security-Web.pdf, pp. 5-7.

[22] For NNSA budget and staff at that time, see Yin Dejian, "Nuclear Safety Regulatory Framework and Challenges in China."

[23] International Atomic Energy Agency, *Integrated Regulatory Review Service (IRRS) Follow-Up Mission to China,* IAEA-NS-IRRS-2016/06

[24] See World Nuclear News, "Maintain Nuclear Perspective, China Told," January 11, 2011, http://www.world-nuclear-news.org/NP_Maintain_nuclear_perspective_China_told_1101112.html

Generation II reactors).[25] By mid-2015, the Chinese government asserted that all the short-term and medium-term actions had been completed, and the longer-term actions were underway.[26]

Prominent individual critics within China's nuclear establishment have also emerged—an unusual phenomenon given that public dissent from major government policies is rarely permitted in China. For example, He Zuoxiu, a physicist who participated in China's nuclear weapons program and has a strongly pro-government record, has described China's rapid nuclear construction as "insane," arguing that "China currently does not have enough experience to make sound judgments on whether there could be accidents." In 2015, He asserted that "there were internal discussions on upgrading [safety] standards in the past four years, but doing so would require a lot more investment, which would affect the competitiveness and profitability of nuclear power… Nuclear energy costs are cheap because we lower our standards."[27] He has been especially opposed to inland reactors, asking: "Imagine if the Fukushima accident had happened on the course of the Yangtze River. Then how many people would have their food and water contaminated?"[28] Similarly, Wang Yinan, a researcher for the Development Research Center under China's State Council (and a protégé of He's), has fiercely opposed inland nuclear plant construction and become a popular anti-nuclear advocate in China.[29] Of course, the overwhelming majority of the country's government and industry experts take a different view, arguing that China is achieving high levels of nuclear safety and nuclear growth should continue.

Strengthening safety: Policies

Both strong policies and new technologies could help strengthen nuclear safety in China and keep open China's long-term options for large-scale nuclear energy growth. Several policy steps could help ensure nuclear safety.

Avoid rushing construction. China's government was wise to slow its nuclear construction plans after the Fukushima accident. A slower pace will allow more time to train builders and operators and let them gain experience, more time for regulators to check and recheck that each step in construction and operation is meeting requirements, less risk that corners will be cut to meet demanding schedules, and more opportunity to build public confidence.

Strengthen nuclear regulation. China's NNSA has expanded, gained experience, and updated some of its key regulations in recent years, but there is more to do to ensure that it has the resources, expertise, authority, culture, and independence needed to oversee nuclear safety in China. The country will need to continue expanding the budget and staff of NNSA and extend its cooperation with other countries' regulators.[30] In particular, while NNSA and the U.S. NRC

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[25] See, for example, Yin Dejian, "Nuclear Safety Regulatory Framework and Challenges in China."

[26] See Chai Guohan, "Safety Enhancement of the NPPs in China After the Fukushima Accident," presentation to the 3rd Regulatory Conference of the European Nuclear Safety Regulators Group, June 29-30, 2015.

[27] Emma Graham-Harrison, "China Warned Over 'Insane' Plans for New Nuclear Power Plants," *Guardian,* May 25, 2015.

[28] Buckley, "China's Nuclear Vision Collides with Villagers' Fears." See also Zhu, "China's Nuclear Expansion Threatened by Public Unease."

[29] See Zhu, "China's Nuclear Expansion Threatened by Public Unease," and Buckley, "China's Nuclear Vision Collides with Villagers' Fears."

[30] For a broader set of recommendations for regulatory reform (though now somewhat dated, as some of the recommendations have since been implemented, at least in part), see Li Jinging, Yang Fuqiang, Jason Portner, Xin

have extensive collaboration focused on their mutual challenge of regulating construction and operation of the AP-1000 reactor design, this cooperation should increase to cover a much broader range of safety (and security) topics. It is also likely to be important to allow more transparency and genuinely independent public discussion. Opening the Nuclear Safety Plan for public comment was a useful step in the right direction.

Establish an effective industry-level nuclear safety organization. In the United States, the Three Mile Island accident provoked the nuclear industry to establish the Institute for Nuclear Power Operations (INPO), which provides in-depth peer reviews and ratings of safety performance.[31] INPO is widely credited with substantially improving the safety focus at U.S. nuclear facilities. While INPO is the U.S. branch of WANO, many see INPO as providing tougher oversight than is typical of WANO. China should establish a comparable body, taking advantage of the industry's common interest in avoiding disasters that would affect all the organizations in the industry.

Strengthen training, incentives, and other programs targeted on safety culture. Since the Chernobyl accident, it has been clear that safety culture—the degree to which everyone in nuclear organizations gives priority to safety and is always looking for ways to improve it—is critical to reducing the dangers of nuclear accidents. Building effective safety cultures is a difficult task, requiring focused, sustained leadership from the top of each major nuclear organization. Asian cultures often include respect for authority and reluctance to question instructions from on high, making a questioning attitude sometimes more difficult to achieve. China has launched a number of efforts to review and improve safety culture, but there is much yet to be done.[32]

Counter nuclear industry corruption. China needs to target additional anti-corruption efforts—and more transparency in everything from major procurement contracts to oversight of on-the-ground construction and operation—to ensure that bribes and kickbacks do not lead officials to look the other way when corners are cut, or to cover up problems, as has occurred in many other industries in China, with sometimes disastrous results. In Russia, for example, Rosatom, the state nuclear corporation, invited Transparency International's Russian branch to take part in the design of a program to address corruption in nuclear procurement, despite the usually strong tensions between the government and anti-corruption non-government groups.[33]

Addressing accident risks: Technologies and business models

Most proposed advanced nuclear reactors are designed for greater levels of passive safety—that is, safety that does not require a human operator to push the right button, or a valve

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Wei, and Alvin Lin, *Recommendation for the Reform of China's Nuclear Safety Regulatory System* (Beijing: Natural Resources Defense Council, December 2013).

[31] For a useful, though dated, account of INPO, see Joseph V. Rees, *Hostages of Each Other: The Transformation of Nuclear Safety Since Three Mile Island* (Chicago: University of Chicago, 1996).

[32] See, for example, Zhang Li, "Nuclear Safety Culture Construction in China," presentation, IAEA Workshop on the Use of a Harmonized Safety Culture Framework, October 23-25, Vienna, 2017.

[33] See, for example, *Public Annual Report-2013: Performance Results of the State Atomic Energy Corporation "Rosatom":* (Moscow: Rosatom, 2014), http://www.rosatom.ru/upload/iblock/f6e/f6eb142a59cc7b93cb8a254ee7dd11a4.pdf. This report includes a preface from Elena Paniflova, director of the Center for Anti-Corruption Research of Transparency International-Russia, briefly describing their work with Rosatom. This is not to say, of course, that the corruption issue in the nuclear sector in Russia is resolved; it remains an ongoing problem.

to work at the appropriate time—than are present in existing reactors. Some would potentially be able to survive a complete cutoff of all cooling for days or weeks without leading to a release of radioactivity. In the case of the fluoride high-temperature reactor (FHR), for example, which involves fuel encased in tiny particles embedded in graphite balls (which are able to withstand very high temperatures), floating in molten salt, one leading U.S. nuclear safety expert remarked: "I cannot figure out how to engineer a release from this reactor."[34] It should be remembered, of course, that initial visions of the advantages of a reactor concept often do not pan out as the concept moves from paper to reality, but a range of approaches do appear to offer the potential for very significant increases in safety compared to current designs, which are already safer than previous designs.

In addition, some advanced systems would be located either underground or well off-shore; in either case, there would be much less potential for large-scale radioactive releases to reach populated areas. Finally, in some cases (such as the underground plants idea, or reactors that could survive even a total loss of cooling) the safety concepts are simpler, easier for non-experts to understand and find convincing, and have more potential for observable real-world demonstrations than the complex safety technologies for large LWRs.

Security

Terrorists or internal saboteurs could also be the cause of a Fukushima-scale disaster. Several terrorist groups have considered or planned attacks on nuclear reactors, and quite a number of sabotage events have already occurred, though none have come close to causing a radioactive release.[35] Terrorists or thieves could also potentially steal weapons-usable nuclear material for a crude nuclear bomb from sites where such material is available. China has experienced increased terrorism in recent years, though most of the incidents have been relatively small-scale and low-tech.[36]

Building more reactors would not necessarily provide more targets for terrorist theft, as long as the reactors were using low-enriched uranium (LEU) fuel, which is not usable in a nuclear bomb. More reactors, however, would mean more targets for potential attacks or sabotage. Spent fuel pools (and transports) are also potential targets; in a densely packed pool where hot, recently discharged fuel assemblies were stored in close proximity to each other, an attack that led to a loss of pool water could potentially cause a spent fuel fire, possibly resulting in a release worse than the Chernobyl disaster.[37]

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[34] Remarks at a workshop on low-carbon energy technologies, MIT, May 2015.

[35] In 2014, for example, an insider at the Doel-4 reactor – as yet unidentified as of 2018 – opened a locked valve and allowed all of the coolant for the turbine to drain away, causing the turbine to overheat and destroy itself. This type of attack could not have led to a radioactive release, and hence appears not to have been intended for terrorism. See discussion in Matthew Bunn, Martin B. Malin, Nickolas Roth, and William H. Tobey, *Preventing Nuclear Terrorism: Continuous Improvement or Dangerous Decline?* (Cambridge, Mass.: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, 2016), http://belfercenter.ksg.harvard.edu/files/PreventingNuclearTerrorism-Web.pdf, p. 29. For a list of relevant incidents, see Thomas Hegghammer and Andreas Daehli, "Insiders and Outsiders: A Survey of Terrorist Threats to Nuclear Facilities," in Matthew Bunn and Scott Sagan, eds., *Insider Threats* (Ithaca: Cornell, 2017), pp. 10-41.

[36] See Zhang, *China's Nuclear Security*, pp. 4-10. See also Robbie Gramer, "The Islamic State Just Pledged to Attack China Next: Here's Why," *Foreign Policy,* March 1, 2017, https://foreignpolicy.com/2017/03/01/the-islamic-state-pledged-to-attack-china-next-heres-why/.

[37] See, for example, Frank von Hippel and Michael Schoeppner, "Reducing the Danger from Fires in Spent Fuel Pools," *Science & Global Security*, Vol. 24, No. 3, pp. 141-173.

China's government takes nuclear security seriously and has identified it as an important area for U.S.-Chinese cooperation.[38] China requires each nuclear operator to have defenses in place against a set of potential threats, with a variety of specific requirements within that overall objective. Reactors are protected by well-armed on-site guard forces, double fences with intrusion detection systems around the site, stringent access control systems, a variety of barriers, and more.[39] Each operator's security arrangements are regularly reviewed by regulators. China's government is considering a draft update of its nuclear security regulations, which, among other things, would require that operators put in place defenses based on a consistent national-level design basis threat (DBT), rather than relying on each operator envisioning the threat it should defend against.[40]

Nevertheless, there are reasons to be concerned. Since China has never acknowledged a significant attempted attack or theft of nuclear material at a nuclear facility, most people in China's nuclear industry do not see terrorism or sabotage as very serious threats, and hence put much lower priority on security as compared with safety. The regulatory effort devoted to security is therefore much smaller than that which is focused on safety. China does not regularly perform realistic tests of whether its nuclear security systems can really defend against intelligent adversaries looking for ways to defeat them—and China's experience of in-depth vulnerability assessment for its nuclear security systems is relatively limited. The country has initiated efforts to strengthen nuclear security culture at its facilities, but little information is available as to how successful those efforts have been. So far, with a few exceptions, U.S.-Chinese cooperation on nuclear security has not involved U.S. expert teams actually visiting major Chinese nuclear sites, so U.S. government understanding of on-the-ground security practices is fairly limited, particularly in the military sector.

Strengthening security: Policies

There are several policy steps China could take to limit the additional security risks from a dramatically larger nuclear fleet, starting with approving the updated nuclear security regulations. Strengthened security rules and practices should address the weaknesses previously noted, including, in particular, establishing regular, realistic "force-on-force" exercises to test the capabilities of security systems, focused programs to strengthen security culture and awareness of the threat, and comprehensive, multi-layered defenses against insider threats.[41]

Most nuclear reactors do not use highly enriched uranium or separated plutonium that could be employed in a bomb—they are potential sabotage targets, but are not locations for potential theft of weapons-usable nuclear material. Minimizing the number of locations and transports with weapons-usable nuclear material, and bulk processing of such material, would be an essential element of managing these risks as China's nuclear fleet grows. Reprocessing and

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[38] For a detailed account of China's nuclear security arrangements, especially for the civil sector, see Hui Zhang and Tuosheng Zhang *Securing China's Nuclear Future* (Cambridge, Mass.: Project on Managing the Atom, Harvard University, 2014), http://belfercenter.ksg.harvard.edu/files/securingchinasnuclearfutureenglish.pdf. For an update, see Zhang, *China's Nuclear Security*.

[39] For an account of a visit to a reactor to understand its security measures, see Yun Zhou, "The Security Implications of China's Nuclear Energy Expansion," *Nonproliferation Review*, Vol. 17, No. 2 (July 2010).

[40] See Wang Liming, "On China's Nuclear Security Regulations," presentation, Harvard-Tsinghua workshop on "Opportunities for Cooperation on Regulating Nuclear Safety and Security," Beijing, China, June 2, 2017.

[41] See the recommendations in Zhang, *China's Nuclear Security*; Zhang and Zhang *Securing China's Nuclear Future*.

recycling plutonium—involving bulk processing and transporting enough plutonium for hundreds or thousands of nuclear weapons every year—would be a major step in the wrong direction.[42]

Strengthening security: Technologies and business models

Advanced nuclear systems could help make effective security easier to achieve. Systems with greater passive safety, making it harder for accidental events to cause a major radioactive release, also make it harder for attackers or saboteurs to cause such a disaster. As noted earlier, reactors located underground or offshore would offer less of a chance of an incident, if it did occur, leading to a major impact on populated areas. Underground reactors might also offer few points of potential attack, making them easier to defend; defending offshore reactors, by contrast, might be somewhat more difficult, though that would depend on the specifics of the arrangement. Reactors that could extend uranium resources without reprocessing would obviate arguments for proceeding with plutonium recycling.

New technologies separate from civilian nuclear energy could also affect future nuclear terrorism risks, for better and for worse. As cyber technologies advance and merge with machine learning and other artificial intelligence approaches, they will create opportunities for more dangerous cyber assaults on nuclear facilities and more effective cyber defenses. Similarly, drones can offer new options for both defenders of nuclear facilities—including a better ability to monitor the areas beyond the fence line, to see attackers before they arrive—and for attackers. Social media now makes it possible for adversaries to identify people who are, for example, guards at a particular facility, and get information about their lives that would be helpful in attempting to recruit or entrap them.

Building Public Trust: Siting and Public Acceptance

Public and government acceptance of siting of nuclear power plants is perhaps the biggest single challenge to the kind of dramatic nuclear growth required for nuclear power to play a major part in China's decarbonization strategy. While China could expand nuclear energy use significantly by adding reactors at existing sites where public support has been established, there are limits to that strategy; for growth to the 0.3-2 TW scale, scores to hundreds of new sites are likely to be needed.

China's government remains sensitive to public opinion and protest, and public concerns about nuclear energy escalated sharply after the Fukushima accident.[43] In August 2016, consideration of one of the possible sites for a large spent nuclear fuel reprocessing facility was canceled after large-scale public protests.[44] Similarly, a 40 billion yuan (approximately $6.5 billion at then-current exchange rates) uranium processing facility, intended to meet half the 2020 demand for nuclear fuel in China, was canceled after mass protests in 2013—though it appears that it will simply be relocated to other sites willing to host it.[45]

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[42] For a brief discussion of the importance of bulk processing as a nuclear security vulnerability, see Bunn et al., *Preventing Nuclear Terrorism*, pp. 59-60.

[43] See, for example, Ramana and King, "A New Normal?" pp. 117-120.

[44] Chris Buckley, "Thousands in Eastern Chinese City Protest Nuclear Waste Project," *New York Times,* August 8, 2016. For an account of these and other protests, see Ramana and King, "A New Normal?" pp. 118-119.

[45] Hui Zhang, *China's Enrichment Capacity: Rapid Expansion to Meet Commercial Needs* (Cambridge, Mass.: Project on Managing the Atom, Harvard Kennedy School, August 2015), pp. 17-18.

In some cases, local government officials have been removed for their failure to control public opposition to other types of unwanted projects. Such demotions have "blown a chill wind through China's regional governments, leading to fears in the nuclear industry that it might have a tougher time attracting local support for nuclear projects."[46] In early 2017, China's largest nuclear companies wrote to the State Council urging additional steps to build public support for nuclear energy and limit the scope of "not in my backyard" (NIMBY) opposition.[47]

China's government has already tried a number of strategies to build local support for nuclear projects, including information campaigns aiming to increase the public's knowledge of nuclear issues and public engagement efforts focused on soliciting and responding to concerns. In 2014, the government published a handbook to guide such efforts.[48]

Public concerns over the possibility of nuclear accidents—sharply heightened after Fukushima—are the biggest driver of the siting issue. Polling research indicates that citizens in many parts of China would be willing to pay substantial sums to avoid having nuclear power plants built near them, though citizens who received even a 10-minute introduction to nuclear energy were somewhat less resistant.[49] Another study, looking specifically at people who lived in towns where new plants were proposed, concluded that the most critical factors affecting local public acceptance were subjective belief in the importance of nuclear energy for China (described as "emotional identification") and trust in the government officials and scientists planning the project, while citizens' perceived level of knowledge about the technology had little impact on their acceptance.[50] In particular, the government's reluctance to approve nuclear power construction at inland sites—which are located along the major rivers that are critical to hundreds of millions of people in China—is based in significant part on concerns over the possibility of accidents that would contaminate those rivers, and concerns about the reactors' use of water in water-scarce regions.[51]

Over the coming decades, as climate change makes the need to reduce carbon emissions ever more apparent, there is a reasonable possibility that "emotional identification" with nuclear energy as an important technology for China's future will grow. But given the degree of opposition that has already begun to build, this should not be left to chance. Finding means to build public support for nuclear energy as a tool for providing energy without local air pollution

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[46] C.F. Yu, "China: Reprocessing Plan Faces New Domestic Challenges," *Nuclear Intelligence Weekly,* August 25, 2017.

[47] Yu, "China: Reprocessing Plan Faces New Domestic Challenges."

[48] This is discussed in Yue Guo and Tao Ren, "When it is Unfamiliar to Me: Local Acceptance of Planned Nuclear Power Plants in China in the Post-Fukushima Era," *Energy Policy,* Vol. 100 (2017), pp. 113-125.

[49] Chuanwang Sun and Xiting Zhu, "Evaluating the Public Perceptions of Nuclear Power in China: Evidence from a Contingent Valuation Survey," *Energy Policy,* Vol. 69 (2014), pp. 397-405. The survey found that the amount respondents were willing to pay to avoid having a nuclear power plant built near them was reduced 15 percent in the group that received the 10-minute introduction to nuclear energy. (The material in the introduction was not described in detail, but presumably presented nuclear energy in a positive light.)

[50] Guo and Ren, "When it is Unfamiliar to Me."

[51] See, for example, Chris Buckley, "China's Nuclear Vision Collides With Villagers' Fears," *New York Times*, November 21, 2015, https://www.nytimes.com/2015/11/22/world/asia/chinas-nuclear-vision-collides-with-villagers-fears.html?_r=0; Zhu Yue, "China's Nuclear Expansion Threatened by Public Unease," *China Dialogue,* September 23, 2014, https://www.chinadialogue.net/article/show/single/en/7336-China-s-nuclear-expansion-threatened-by-public-unease.

or carbon emissions, while addressing public concerns about safety and other issues, is critical to the potential for large-scale nuclear growth in China.

Addressing the siting and public acceptance constraint: Policies

Clearly, the most critical single requirement for maintaining public confidence in nuclear energy in China, and hence in gaining approval for additional sites, is to avoid any major disaster at a nuclear facility—whether by accident or from terrorist action. As already discussed, this will require substantial efforts on both nuclear safety and security.

But building the level of public trust needed for widespread deployment of nuclear energy in China will take more than simply avoiding catastrophes. It is likely to require a level of transparency and engagement with the public that is so far rare in China's nuclear industry, or its rough-and-tumble energy and construction markets more broadly. Both international experience and research suggest that the public's trust in the organizations proposing nuclear facilities is critical and that information provided by the government and industry, often perceived as propaganda, is not enough. Instead, building trust requires a sincere willingness to engage with local publics, listen to and address their concerns, take step-by-step approaches with firmer decisions as more information has been collected and analyzed, and ensure that nuclear organizations consistently follow through on all the promises they make.[52]

In particular, building and sustaining public trust is likely to require a greater tolerance of and support for genuinely independent voices than has generally been the case in China to date. Residents will want to be able to rely on independent experts who are not simply parroting the government line or working for the nuclear industry, and who have the expertise, resources, and access to information to analyze and comment on proposed actions. Open, transparent processes incorporating such independent experts can take more time, but they can also go a long way toward building trust. In the United States, the experience has generally been that rushing projects or trying to push them forward over public objections makes things worse rather than better; proponents of a new nuclear facility have to "go slow to go fast."

Specific policy actions that could help build public acceptance of nuclear energy in China include:

- Scaling up China's existing public engagement efforts at proposed nuclear sites.
- Expanding benefits offered to local communities being considered for, and then hosting, nuclear facilities. In Japan, for example, communities hosting nuclear reactors or fuel cycle facilities receive substantial payments (known as kofu-kin), in addition to jobs and tax revenues.
- Establishing ongoing community engagement activities. In the United States, for example, many reactor companies sponsor regular "town hall" meetings where plant officials and

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[52] See, for example, Juhani Vera, "Winning Public Trust: The Siting of a Nuclear Waste Facility in Eurajoki, Finland," *Innovations: Technology, Governance, Globalization,* Vol. 1, No. 4 (Fall 2006), pp. 67-82. For a discussion of the history and lessons learned from efforts to site nuclear waste facilities in Japan and the United States, see Matthew Bunn, John P. Holdren, Allison Macfarlane, Susan E. Pickett, Atsuyuki Suzuki, Tatsujiro Suzuki, and Jennifer Weeks, *Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Approach to Spent Fuel Management* (Cambridge, MA: Project on Managing the Atom, Harvard University, and Project on Sociotechnics of Nuclear Energy, University of Tokyo, June 2001), pp. 33-56; for recommendations on overcoming obstacles to siting such facilities (most of which are relevant to siting nuclear power plants as well), see pp. 95-116.

workers—who typically also live in or near the host community—answer the public's questions and address concerns. Some plants organize more informal events such as picnics where local citizens can mix with plant staff and get answers to their questions. Some plants also organize citizen advisory boards, which meet regularly to discuss issues related to the plant in a focused and sustained way.

- Expanding local capacity to engage with and oversee the nuclear facilities. Most citizens do not know enough about nuclear technology to draw informed conclusions and must rely on trusted sources for information. It may be useful to provide support to train local representatives to engage with and monitor the nuclear facility in a more expert fashion, so that citizens have local sources of information not directly tied to the industry and government promoting the plant.[53]

Addressing the siting and public acceptance constraint: Technologies and business models

In general, such policy steps are likely to be more important in strengthening public acceptance of nuclear energy than are new technologies. But advanced technologies could also help in several ways.

Increasing demonstrable safety. Some advanced concepts have safety approaches that offer high levels of passive safety, potentially making it much more difficult for an accident or sabotage to lead to a major radioactive release. Moreover, in some cases, the concept may be simple enough to build public confidence that it really would be hard for anything to go seriously wrong. Systems that could survive even a complete loss of cooling and failure to do anything at all to respond, along with reactors located underground, might particularly help convince the public there was little risk of a major radioactive release. Small systems with less radioactive material in their cores and greater inherent safety may require only small zones around them where planning for potential evacuation is needed, making it possible to site them near major populated areas.

Locating plants offshore. The idea of offshore nuclear power plants could make it possible to put plants near the huge coastal cities that are some of the world's largest sources of energy demand; on-shore, the plausible land near such cities is typically heavily used. With the reactors located far enough off-shore to be largely or completely out of view—and with a strong safety case for them—it *might* be possible to greatly reduce public controversies over siting.

Reducing use of scarce water. One of the biggest concerns with the proposed inland sites in China is their potential use of, and threat to, scarce water resources, including major rivers. Already, existing technologies make it possible to locate nuclear power plants far from large

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[53] In the United States, for example, the Department of Energy established citizens' panels near its major nuclear facilities to provide advice, discuss issues at the site, and represent the point of view of local citizens – some of whom are supporters of the facility, while others are critics. Some members of these boards have been experts – in some cases because they once worked in the nuclear industry – or have developed expertise over time through their service on the panels. For a discussion of both the advantages of these boards and the major challenges that still exist in genuinely engaging the public, see Jennifer Weeks, *Advice – and Consent? The Department of Energy's Site-Specific Advisory Boards* (Cambridge, Mass.: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, August 2000), https://www.belfercenter.org/index.php/publication/advice-and-consent-department-energys-site-specific-advisory-boards.

bodies of water, if sources of piped water are available. But some advanced reactor concepts – particularly those that use coolants other than water—offer much greater potential for reduced water use, so they would not need to be sited near oceans, lakes, or rivers.

Overall, if China manages to avoid major incidents, builds public confidence and support, and invests in R&D on concepts that contribute to addressing some of the difficult siting challenges, it may well be possible to successfully site the large number of nuclear plants that would be needed for nuclear to play a significant role in decarbonizing China's energy system.

Improving Economics

Clearly, nuclear energy would grow faster if it were cheaper in comparison to other energy sources. In China, however, the economics of nuclear energy is not as much of a constraint on further deployment as it is in the United States or Europe, for four reasons: (a) nuclear plants are cheaper to build in China; (b) nuclear plants are cheaper to finance in China; (c) the competition from other energy sources is not as stiff, particularly as China does not currently expect to have large quantities of low-cost natural gas; and (d) China's government ha VWWB willing to set feed-in tariffs to provide stable revenue for nuclear plants, or provide other forms of support for what it regards as a strategic industry.

Cheaper to build: It appears that China can build nuclear reactors faster and at lower cost than has been the U.S. or European experience in recent years, though lack of authoritative data and uncertainties in how best to compare prices across currencies create substantial ambiguities in this judgment.[54] The Organization for Economic Cooperation and Development (OECD), for example, reported government estimates in 2015 for the overnight capital cost (OCC) of a generic light-water reactor to come online in 2020 as either $1,807 per kilowatt of installed capacity or $2,615/kW for China. But in the United States, the study concluded that such a reactor, coming on line at the same time, would cost $4,100/kW; cost estimates for European countries were higher still.[55] Similarly, a review of multiple sources over the period 2008-2015 estimated that overnight capital costs in China were $1,500-$2,000/kW less than those in the United States or Europe; the review also concluded that total investment costs (including interest during construction) for the advanced European Pressurized Reactors (EPRs) being built at Tianshan were less than one-half those of the EPRs being built at Olkiluoto in Finland or Flamanville in France. The reason for the differences was that the delays and cost growth experienced in China were much less than those in Europe.[56] The review noted that other

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[54] For projects where most of the costs relate to internationally traded goods and services, currency exchange rates are the best way to compare costs between different currencies, while for projects with mostly domestic content, "purchasing power parity" (PPP) exchange rates are more useful. In China's case, the two are quite different: the average market exchange rate for the 3 years leading up to 2018 was in the range of 6.6 yuan/$, while the PPP exchange rate for those years was in the range of 3.5 yuan/$. See Organization for Economic Cooperation and Development, "Purchasing Power Parities (PPP)," https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm. For nuclear projects, which combine international and domestic content, a realistic comparison is probably between these two exchange rates. Both are reported in this chapter.

[55] Organization for Economic Cooperation and Development, International Energy Agency and Nuclear Energy Agency, *Projected Costs of Generating Electricity* (Paris: OECD/IEA/NEA, 2015), p. 41.

[56] Nadira Barkatullah and Ali Ahmad, "Current Status and Emerging Trends in Financing Nuclear Power Projects," *Energy Strategy Reviews*, Vol. 18 (2017), pp. 127-40. These conclusions from Barkatullah are also featured prominently in World Nuclear Association, "The Economics of Nuclear Power" (London: WNA, version updated

reasons for reduced costs would include ongoing recent experience in reactor construction; lower costs for materials, equipment, and labor; and high levels of localization of manufacturing.[57]

Overall, in 2017, the China Nuclear Energy Association, an industry trade group, estimated that building 30 GWe of new nuclear energy in the 13th 5-year plan would cost 100 billion yuan per year, amounting to over 16,600 yuan/kW. That would be $2,520/kWe if converted at currency exchange rates, or $4,750/kWe if converted at PPP rates.[58] By comparison, by 2017, the estimated overnight capital cost of the two AP-1000 reactors still under construction in the United States had risen to more than $19 billion, amounting to over $8,500/kW.[59] Recent U.S. estimates of what such reactors might cost after several had been built and first-of-a-kind costs had been eliminated are just under $6,000/kW.[60]

These are overnight costs, not including the costs of interest during construction. Those costs are lower in China as well, since (a) Chinese state-owned nuclear companies are able to access capital at low cost, and (b) China typically builds reactors somewhat faster than has been the case in the United States and Europe. In mid-2018, for example, despite years of delays, China brought the first units of the AP-1000 and EPR designs online, even though their counterparts in the United States and Europe had started construction years earlier.[61]

Cheaper to finance. Nuclear plants in China are also cheaper to finance, as China's state-owned nuclear firms are able to finance nuclear plants at lower costs of money than are typically available to purely private firms. For an energy source where two-thirds to four-fifths of the total cost of electricity is the cost of building the plant, how much the owner has to pay for the money invested in construction can make all the difference between a profitable plant and a failing one. In other words, *the same reactor, costing the same amount to build, can be economic in one market and completely uneconomic in another, depending on the financing arrangements.*

Limited competition from natural gas. The competition is not as steep for nuclear energy because China does not yet enjoy the very low natural gas prices that currently pertain in the United States. So far, natural gas production in China is modest, leaving the country heavily dependent on imported liquefied natural gas (LNG), which has been expensive. Plans for scaling up the use of natural gas electricity in China are also comparatively modest. Natural gas provides roughly half as much electricity as nuclear power does in China today, and in the IEA's

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August 2017), http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

[57] Localization often reduces costs in China, where manufacturing is typically managed more efficiently, with lower labor costs, than it is in other locations where such nuclear equipment would be manufactured.

[58] China Nuclear Energy Association, *China Nuclear Energy Guide 2017* (Beijing: CNEA, 2017), https://www.niauk.org/wp-content/uploads/2018/04/CNEA-China-Nuclear-Energy-Guide.pdf.

[59] With financing during construction included, the cost of the two reactors is estimated at $26 billion. See "Direct Testimony and Exhibits of Tom Newsome, PE, CFA, Philip Hayet, and Lane Kollen," *In the Matter of: Georgia Power Company's Seventeenth Semi-Annual Vogtle Construction Monitoring Report,* Docket No. 29849 (Augusta, Ga.: Georgia Public Service Commission, December 1, 2017). Georgia Power owns only 45.7 percent of the reactors, so the costs in this report represent only 45.7 percent of the total.

[60] See, for example, U.S. Energy Information Administration, "Capital Cost Estimates for Utility Scale Electricity Generating Plants" (Washington, DC.: EIA, November 2016), https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf; Lazard, "Lazard's Levelized Cost of Energy Analysis – Version 11.0" (New York: Lazard, November 2017).

[61] Data from International Atomic Energy Agency, "Power Reactor Information System," https://www.iaea.org/pris/. These were all Generation II plants.

"New Policies Scenario," gas would still be providing only 75 percent as much power as nuclear in 2040.[62]

Availability of feed-in tariffs or other support. As discussed elsewhere in this volume, China is debating plans to introduce greater market competition in its electricity sector in the future, but for now, nuclear and renewable electricity sources typically enjoy fixed feed-in tariffs, allowing them to make a reliable profit.[63]

In short, until recently, the financial environment for nuclear investment in China was excellent, with strong state support, rapidly rising demand, low-cost second-generation reactors, low-cost government-backed financing, and certain, steady revenues from high and fixed feed-in tariffs. In the last few years, however, the environment has become much more uncertain, with excess capacity, state-owned companies exposed to more market forces, curtailment and future load-following reducing revenues, and cuts in tariffs. In 2017, for example, the Chinese government imposed reduced rates on some nuclear plants and indicated that future nuclear tariffs would be tied to the price of coal electricity.[64] In 2019, the Chinese government set the feed-in tariffs for the AP-1000 and EPR plants that had recently been completed in the range of 0.42-0.44 yuan/kw-hr, well below what industry had hoped for, comparable to the tariffs for cheaper Generation II facilities. With these tariffs, the firms that built these plants will probably see little profit from them, potentially reducing investors' enthusiasm for nuclear projects.[65] Major Chinese nuclear firms are now also investing heavily in renewables, which currently appear to offer greater profit opportunities.[66] In the long term, as China moves toward deep decarbonization, there will presumably be strong state support for low-carbon energy sources, including nuclear energy. However, if China moves toward more market competition in the electricity sector, there is likely to be considerable competition among these sources, creating more uncertainty for investors. Ultimately, there may be tensions between deep decarbonization goals and government efforts to keep electricity prices low.

Addressing the economic constraint: Policies

Policy choices, new technologies, and different business models could all contribute to (or undermine) the economics of nuclear energy. On the policy side, the most important step would be to maintain the availability of low-cost financing. A second key step would be to continue at least a moderate pace of nuclear construction, to maintain a competitive nuclear construction industry and supply chain as well as a workforce with experience in nuclear construction and operations.

A third step would be to maintain strong and stable prices for nuclear energy, even if China moves toward more competitive electricity markets. This would make nuclear energy a more attractive and lower-risk target for private investment.

Finally, a fourth important move would be to maintain cooperative regulator-industry relationships. On the one hand, Chinese regulators need to be critical and independent enough to

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[62] IEA, *WEO 2017*, p. 702. The difference between nuclear and natural gas would be even greater in the Sustainable Development Scenario, p. 703.

[63] See Wang Pu, "Reform China's Electricity Market," this volume.

[64] Yu, "NEA Codifies Nuclear Load-Following."

[65] C.F. Yu, "China: Lower-Than-Expected Tariffs for First AP1000s and EPRs," *Nuclear Intelligence Weekly,* April 5, 2019.

[66] C.F Yu, "China: Nuclear Players Shift to Renewables," *Nuclear Intelligence Weekly,* April 6, 2018.

ensure safety. On the other hand, having a flexible approach that minimizes regulatory uncertainty and delays can also contribute to reducing nuclear energy costs, and to nuclear energy growth overall.

Addressing the economic constraint: Technologies and business models

A variety of approaches to modular design and construction, simplified systems, and enhanced passive safety could reduce construction costs and times, as well as the number of people needed to operate plants.[67] Smaller plant footprints and greater passive safety could also reduce the costs of security.

These potentials, however, remain to be realized. It is worth remembering that the Generation III plants were initially said to be cheaper to build than Generation II facilities, and proved to be still more expensive. One survey of experts in the early 2010s found that, on average, U.S. and European experts expected that the costs of both small modular reactors (SMRs) and Generation IV reactors would be slightly *more expensive* in 2030 than the costs of Generation III reactors were at the time of the survey.[68] All of the envisioned advantages of advanced reactors should be considered as possibilities that *may* come to pass, not as confirmed realities.

Modified business models might also improve nuclear energy economics. For example, if a reactor could provide electricity when the price was high and use its energy for other purposes (such as industrial process heat) when the price was low, the reactor could make more money. (By contrast, load-following as practiced at existing plants just means lowering output some of the time, meaning less electricity sold and less revenue.) In one approach, some high-temperature advanced reactors envision using the facility's energy to produce hydrogen or store heat when electricity prices are low and using hydrogen, natural gas, or stored heat to increase the plant's power output when prices are high and peaking power is needed.[69] Reactors that could go beyond the steady electricity baseload role of traditional nuclear power plants may become more important in a future world with grids incorporating large portions of intermittent renewables.

Some other concepts envision changing business models to reduce construction costs and deployment times. Engineers at the Massachusetts Institute of Technology (MIT), for example, have proposed both small and large reactors on offshore platforms similar to oil rigs.[70] These could be built in large numbers in factories (benefiting from economies of manufacturing scale) and towed to the sites where they would be used, greatly shortening construction times; they would eliminate the need to purchase land and drastically reduce the amount of nuclear-grade concrete that would have to be poured, also potentially reducing cost.

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[67] See, for example, the discussion in Buongiorno, Corradini, and Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained World,* pp. 31-58.

[68] Laura Diaz Anadon, Valentina Bosetti, Matthew Bunn, Michela Catenacci, and Audrey Lee, "Expert Judgments about RD&D and the Future of Nuclear Energy," *Environmental Science & Technology*, Vol. 46, No. 21 (November 2012), pp. 11497-11504.

[69] See, for example, Charles Forsberg, Lin-Wen Hu, Per Peterson, and Kumar Sridharan, *Fluoride-Salt-Cooled High-Temperature Reactor (FHR) for Power and Process Heat: Final Project Report,* MIT-ANP-TR-157 (Cambridge, Mass.: Massachusetts Institute of Technology, December 2014).

[70] J. Buongiorno, J. Jurewicz, M. Golay, N. Todreas, "The Offshore Floating Nuclear Plant (OFNP) Concept," *Nuclear Technology*, Vol. 194 (April 2016), pp. 1–14.

More Modest Constraints

Waste Management

Effective waste management is vital to any nuclear power program, both for protecting the environment and for maintaining public confidence. If nuclear wastes are managed appropriately, however, the cost of doing so is a small part of the overall cost of nuclear energy, and the impact on human health and the environment per kilowatt-hour is quite small compared with other energy sources. This is partly because of nuclear energy's ability to generate an enormous amount of energy from a small amount of fuel: for example, while a one-gigawatt coal plant needs an 80-car train of fuel every day, a one-gigawatt nuclear plant needs half of one train car once a year.

In nuclear waste management, China may have the opportunity to succeed where the United States and others have so far failed. China has the following in its favor: large, sparsely populated areas for siting nuclear waste repositories; a unified and authoritarian government capable of making and sustaining decisions over time; nascent approaches to public engagement that seem to be showing positive effects; and the luxury of time to get waste management right, since dry cask storage of spent nuclear fuel provides a cheap and safe option for decades. Dry casks can offer time for the technology, politics, and economics of final spent fuel disposition to evolve.[71] It should be both politically and technically possible for China to provide large-scale spent fuel storage as nuclear power grows, and eventually one or more deep geologic repositories capable of containing all the spent fuel and other high-level radioactive wastes a growing nuclear program might generate.

Proliferation Resistance

Since China is already a nuclear weapon state, many in China (and elsewhere) believe that its nuclear energy choices have little impact on the spread of nuclear weapons. But there are at least three important elements of proliferation risk, even when systems are deployed in nuclear weapon states: the risk of nuclear theft if weapons-usable nuclear material is available in the fuel cycle; the risk of technology leakage; and the "example effect," increasing the probability that non-nuclear weapon states will pursue technologies such as enrichment and reprocessing that could increase their ability to build weapons if they chose to do so.[72]

While the number of reactors China decides to build is not likely to have much effect on the spread of nuclear weapons, the specific technological choices it makes might have an effect. Hence, limiting proliferation risks should be an important consideration as China moves forward with its nuclear program. Enrichment and reprocessing—the two technologies that make it possible to produce bomb material—are the key intersections between civilian and military nuclear technologies, and decisions about them will have an outsized impact on proliferation risk. In particular, if China, as the country that will probably become the world's nuclear energy

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[71] Matthew Bunn, John P. Holdren, Allison Macfarlane, Susan E. Pickett, Atsuyuki Suzuki, Tatsujiro Suzuki, and Jennifer Weeks, *Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Approach to Spent Fuel Management* (Cambridge, MA: Project on Managing the Atom, Harvard University, and Project on Sociotechnics of Nuclear Energy, University of Tokyo, June 2001).

[72] See Matthew Bunn, "Proliferation-Resistance (and Terror-Resistance) of Nuclear Energy: How to Think About the Problem," presentation, Engineering and Public Policy Seminar, Carnegie-Mellon University, December 12, 2014, https://www.belfercenter.org/sites/default/files/legacy/files/prolif-resist-talk-2014.pdf.

leader in the 21st century, chooses to rely on fuel cycles based on reprocessing and recycling plutonium, it will be more difficult to convince non-nuclear-weapon states not to do the same.

In addition to these nuclear energy choices, it will be important for China to strengthen its enforcement of strategic trade controls, to limit proliferators' ability to acquire the nuclear and dual-use technologies they seek (many of which come from industries far afield from the nuclear industry).[73]

Government and Industrial Capacity

Dramatically increasing China's nuclear energy enterprise would require similarly substantial increases in governmental capacity to regulate and oversee nuclear plants and in industrial capacity to design, build, operate, and decommission them. This would require dramatically increasing the number of trained, experienced personnel in all of these areas.

Serious investments and training programs will be needed to avoid having these capacity issues constrain China's nuclear growth. But over time, it appears likely that if nuclear energy were to become a significant element of China's decarbonization strategy, the market would adjust, with the demand for nuclear experts (and resulting salaries) drawing more people into the field to fill the need. If institutional structures in government and industry can adjust as well, it should be possible to address the industry and government capacity constraints. Over the longer term, advanced reactor systems with increased passive safety and expanded modularity and automation in construction may require substantially fewer trained people per gigawatt of installed capacity.

Regulatory Delays

Regulatory delays and uncertainties—from approving construction of a new reactor to getting approval for a new design or a modified operating approach—have slowed nuclear growth in a number of countries, and may well do so in the future. By affecting investor confidence in whether and when a reactor or new design will generate revenue, such delays can have reverberating effects.

China has already experienced unexpected regulatory delays— such as the extended pause in approvals for construction after Fukushima, and the ongoing (as of late 2019) hold on approval of inland sites. Overall, however, China's regulators have generally had a more cooperative relationship with industry than pertains, for example, in the United States. If China's government decides to make nuclear energy a major part of its decarbonization strategy, it is likely to be able to ensure that regulatory delays do not unduly constrain the necessary nuclear growth. Avoiding regulatory delays while maintaining the highest achievable standards of safety and security will be a major challenge, however.

Integrating Nuclear Energy into China's Evolving Energy Infrastructure

As China moves toward deep decarbonization, intermittent renewables are likely to play a fundamental role in electricity supply. Non-intermittent low-carbon backup sources could be quite important to achieving 80-100 percent decarbonization at a reasonable cost.[74] Ideally,

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[73] See, for example, Matthew Bunn, Martin B. Malin, William C. Potter, and Leonard S. Spector, eds, *Preventing Black-Market Trae in Nuclear Technology* (Cambrudge, UK: Cambridge University Press, 2018).

[74] See, for example, the analysis in Buongiorno, Corradini, and Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained World,* pp. 5-29.

however, such backup sources would not simply provide steady power all the time, as nuclear plants typically do today, but would behave more like natural gas plants—offering steady power if desired, but also having the ability to shift output rapidly to follow requirements and offer peaking power when needed. Nuclear plants could generate more revenue and play a larger role in the overall energy system if they could go beyond providing baseload electricity. As noted earlier in this chapter, some existing nuclear designs already do significant load following, and some advanced designs envision being able to expand output for peaking power when prices are high, and use the reactor's heat for other purposes (ranging from storage to production of liquid fuels) when the grid has little need for the reactor's power. Even in a heavily electrified future, there will be many energy demands beyond baseload electricity.

Unlikely to Be a Major Constraint: Uranium Supply

Advocates of China's pursuit of plutonium reprocessing and fast-neutron "breeder" reactors have argued that such a "closed" fuel cycle is necessary because China has scarce uranium resources that will soon run out. These concerns have proven to be overblown. China has access to plenty of uranium to fuel even a greatly expanded nuclear enterprise for many decades to come, if not longer.

Domestically, by 2016 China had identified over 366,000 metric tons of uranium (tU); studies indicate that the total likely to be available in China is in the range of 2 MtU, though much of this may only be available at fairly high costs.[75] That would be enough, even if no more were found and none purchased overseas, to fuel even half a terawatt of nuclear power for decades.

But estimates of the total uranium available will not remain fixed. China has been finding more uranium at a much faster pace than it has been using it; the previously reported estimate of China's identified resources, from only two years earlier, included only 265,500 tU, a 100,000-ton increase in just two years.[76]

In part because much of China's uranium is costly to mine (though much less costly than reprocessing and breeder reactors are likely to be), China has also been buying uranium abroad—both on the open market and by purchasing foreign mines. In recent years, China has pursued a "three thirds" policy, getting a third of its uranium from each of these sources. To ensure that supply could not be cut off, China has built up a stockpile of roughly 10 years of fuel supply, ready for use when needed.[77]

Globally, uranium is abundant. As of 2016, the IAEA estimated total available resources of some 15 million tU, enough to fuel current consumption rates for over 250 years.[78] Over time, these numbers have been going up, not down, as the world has generally found uranium faster than it has been used.

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[75] Nuclear Energy Agency, Organization for Economic Cooperation and Development, and International Atomic Energy Agency, *Uranium 2016: Resources, Production, and Demand* (Paris: NEA/OECD, 2016), http://www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf, pp. 201-204.

[76] Hui Zhang and Yunsheng Bai, *China's Access to Uranium Resources* (Cambridge, Mass: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, May 2015), https://www.belfercenter.org/sites/default/files/legacy/files/chinasaccesstouraniumresources.pdf.

[77] Zhang and Bai, *China's Access to Uranium Resources*; Hibbs, *The Future of Nuclear Power in China*.

[78] NEA/OECD and IAEA, *Uranium 2016*.

Some have projected that uranium prices would inexorably rise as the lowest-cost resources were mined out. This projection, however, ignores the parallel improvements in technology. On average, the real price of mined minerals declined rather than increasing over the 20th century.[79] This trend is continuing, and there is little indication that uranium will be different. Indeed, the abundance of world uranium resources and the flexibility that abundance offered for fuel cycle choices was one of the key conclusions of MIT's 2009 study on *The Future of the Nuclear Fuel Cycle.*[80]

In short, lack of uranium is not likely to be a significant constraint on even large-scale growth of nuclear energy in China. China can continue to ensure an adequate supply through both policy and technology choices.

China's Investments in Advanced Nuclear Systems

To address some of these risks and constraints, China is investing in research, development, and demonstration (RD&D) programs on advanced nuclear energy systems for the future. These include both near-term and long-term options.

There are good reasons to be optimistic about innovation in nuclear energy technologies. Many groups are developing new ideas; new materials, technologies, and construction approaches are opening fresh avenues of possibility; and advanced computer simulation accelerates the process of designing and assessing new concepts.

But there are also reasons to be pessimistic. No reactor concept other than an LWR has been successfully commercialized in over half a century. As noted earlier, the Generation III reactors were intended to be cheaper than Generation II systems but proved to be more expensive. The heat or electrons that reactors provide are commodities, the same as the heat or electrons from other technologies, so they cannot compete on the basis of unique features in the way a new smartphone can. The utilities that would buy a reactor are in the business of operating plants reliably for decades at costs slightly less than the price of the electricity, and they are deeply conservative, only wanting to buy systems that are reliable, tried, and true. As designs move from concepts to practical reactors, unexpected challenges appear, and they tend to become more expensive and problematic. In particular, everyone should be skeptical of claims of very low costs for advanced reactors, which have not proven out in the past; the recent MIT study of the future of nuclear energy concluded that "without design standardization and innovations in construction approaches, we do not believe the inherent technological features of any of the advanced reactors will produce the level of cost reductions needed to make nuclear electricity competitive with other generation options."[81]

Thus, in considering the *potential* benefits of advanced reactors, it is worth remembering the warning offered decades ago by Admiral Hyman Rickover, founder of the U.S. nuclear navy, that an "academic reactor" would always have a huge number of advantages that a "practical

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[79] Erich Schneider and William Sailor, "Long-term Uranium Supply Estimates," *Nuclear Technology*, Vol. 162, No. 3 (June 2008), p. 379–87.

[80] Mujid Kazimi and Ernest J. Moniz, co-chairs, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (Cambridge, Massachusetts: MIT, 2011), http://web.mit.edu/mitei/research/studies/documents nuclear-fuel-cycle/The_Nuclear_Fuel_Cycle-all.pdf.

[81] Buongiorno, Corradini, and Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained-World,* p. xii.

reactor," one that was actually being built, would not have.[82] That, unfortunately, often remains the case today.

Chinese-designed sodium-cooled fast reactors

China has started construction on a 600 MWe sodium-cooled fast-neutron "breeder" reactor called the China Demonstration Fast Reactor (CDFR), and envisions building larger commercial reactors based on this design in the future.[83] These systems would rely on reprocessing and recycling the plutonium they produce, creating large flows of plutonium. Traditionally, fast reactors have had even higher capital costs than LWRs, and at present, it appears unlikely that these designs will be commercially successful.[84]

High-temperature pebble-bed reactors

China is completing construction of a two-unit demonstration "pebble bed" high-temperature gas-cooled reactor (HTGR) at the Shidaowan site in Shandong province.[85] These systems involve fuel in tiny particles coated in layers of carbon and silicon, which are embedded in tennis-ball-sized balls of graphite; the core, filled with these graphite balls, is cooled with helium. This offers high levels of passive safety, greater electricity production efficiency, and high-temperature heat usable for industrial applications. The reactors have proved to be more expensive than expected, however, and whether additional units will be built remains in doubt.

Molten salt reactors

For the longer term, China is funding R&D on molten salt reactor (MSR) concepts.[86] These include solid-fuel versions with pebbles essentially identical to those in the HTGR system, floating in molten salts rather than cooled by helium gas, and liquid-fueled versions in which the fuel would be dissolved in the salts. MSRs face a number of technical challenges, but could potentially offer very high levels of passive safety, high-temperature operation for efficiency and industrial process heat, and, in the liquid-fueled concepts, more efficient use of the uranium resource. Whether they will prove to be economically viable remains to be seen, however.

Terrapower

Terrapower is a private U.S. company funded in part by Bill Gates, which is pursuing a sodium-cooled fast reactor that would breed fuel and burn it without reprocessing. In late 2017, Terrapower reached an agreement with Chinese firms to build a prototype facility in China, perhaps as soon as the mid-2020s. The Trump administration's decision to bar advanced nuclear reactor exports to China, however, has forced Terrapower to drop that plan.[87] Nevertheless,

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[82] Admiral Hyman Rickover, memorandum, June 5, 1953, http://ecolo.org/documents/documents_in_english/Rickover.pdf.

[83] For discussions, see Bunn, Zhang, and Kang, *The Cost of Reprocessing in China,* pp. 32-34; and Hibbs, *The Future of Nuclear Power in China,* pp. 30-38.

[84] Collectively, developed countries have spent over $50 billion on research, development, and demonstration of fast reactors and reprocessing without ever producing a viable commercial system. See Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki, and Frank von Hippel, *Fast Breeder Reactor Programs: History and Status* (Princeton, N.J.: International Panel on Fissile Materials, February 2010), http://fissilematerials.org/library/rr08.pdf.

[85] See, for example, the discussion in Hibbs, *The Future of Nuclear Power in China,* p. 72.

[86] For brief discussions, see Hibbs, *The Future of Nuclear Power in China,* pp. 51-53.

[87] C.F. Yu, "China: CNNC Commits to TWR Development," *Nuclear Intelligence Weekly,* October 6, 2017; Jay Greene, "Trump's Tech Battle With China Roils Bill Gates Nuclear Venture," *Wall Street Journal,* January 1, 2019.

should U.S.-Chinese disputes be resolved, Terrapower and other U.S.-origin advanced reactor technologies remain options for China's nuclear energy future. Terrapower, like other proposed "breed and burn" systems, would make it possible to extend uranium resources without reprocessing, and would also reduce volumes of nuclear waste. If successful, Terrapower might displace China's own fast neutron reactor designs.

Lead-cooled fast reactors

China is also pursuing early R&D on fast-neutron breeder reactors cooled with molten lead, rather than molten sodium, though these do not have priority similar to better-understood sodium-cooled systems.[88] Such reactors might have a number of advantages, including strengthened passive safety. Lead, unlike sodium, does not catch fire when exposed to moist air. Lead-cooled reactors are a longer-term possibility for China.

Accelerator-driven systems

China is continuing basic research on accelerator-driven systems, in which a reactor that is not quite able to sustain an ongoing chain reaction is driven by an accelerator supplying additional neutrons. Such systems might have advantages in safety and transmuting waste to shorter-lived species, but face daunting technical and economic challenges. These, too, appear to be a possibility only for the very long term.[89]

Fusion reactors

For the long term, fusion—generating nuclear energy by putting small atoms together, rather than splitting big atoms apart—represents a potentially important alternative to fission. Fusion systems would have very low safety, security, and proliferation risks, greatly reduced nuclear waste, and essentially unlimited fuel supplies. Like many other countries, China is making modest investments in fusion R&D. While there are companies attempting to find near-term solutions to fusion's technical and economic challenges, many experts believe those challenges will put commercial fusion energy systems at 2050 or beyond – if they ever are commercially successful.[90]

Conclusions

Like other energy sources, nuclear energy would have to grow dramatically to play a major part in decarbonizing China's energy system. As this chapter has described, doing so would require overcoming a variety of challenging constraints, and addressing important safety, security, and proliferation risks. Because of the immense challenges of decarbonization, and the role nuclear energy could play in meeting those challenges, it is worth doing what is practical to address the constraints on nuclear power growth, so that it could be a readily expandable option for the future.

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[88] Hibbs, *The Future of Nuclear Power in China,* p. 53.

[89] Hibbs, *The Future of Nuclear Power in China,* p. 53.

[90] See, for example, Edwin Cartlidge, "Fusion Energy Pushed Back Beyond 2050," *BBC News,* July 11, 2017, http://www.bbc.com/news/science-environment-40558758. For a brief account of China's fusion efforts, see Hibbs, *The Future of Nuclear Power in China,* pp. 57-58.

China can take several steps in the next 10 to 20 years to maximize the nuclear energy options it would have available in 30-70 years. The most important of these steps are described briefly below.

Avoiding catastrophes

Any large-scale nuclear accident or terrorist incident in China could effectively make significant nuclear growth politically impossible. Hence, the most fundamental steps China can take to keep its future nuclear options open are investments in safety and security to avoid such catastrophes.

As described earlier, China should strengthen its nuclear regulatory agencies and create an industry-level group similar to INPO in the U.S. to establish best practices, conduct peer reviews, and track trends. It should also boost training, incentives, and other steps to strengthen both safety and security culture in its nuclear organizations. China should continue its decision not to start construction of additional Generation II reactors, emphasizing instead reactors with the greater passive safety features of Generation III and beyond. And it should avoid rushing reactor construction, giving builders, operators, and regulators time to do their work carefully, without cutting corners, and expanding their efforts at a moderate pace. On the security side, China should ensure that all major nuclear facilities are effectively protected against the full spectrum of plausible adversary threats, and carry out regular, realistic tests of its nuclear security systems' performance. High degrees of passive safety—making it very difficult for either accidents or human action to cause large releases of radioactivity—should be a fundamental goal of China's advanced reactor development.

Building public trust

Public opposition to nuclear facilities is likely to be among the most substantial constraints to be addressed to achieve large-scale nuclear growth in China. China's nuclear organizations will have to invest in the slow, painstaking work of building trust with local communities, step-by-step—engaging with local residents, understanding and responding to their concerns, and building a reputation for following through on their promises. As noted earlier, this is likely to require more transparency and a bigger role for genuinely independent expert voices than has previously been the norm in China. The country should incorporate surveys and other data collection on the effectiveness of its public engagement efforts on nuclear energy, so that these support-building efforts can learn over time about what works and what does not.

Improving economics

As it maps out its future energy and power generation approaches, decarbonization supports, and market reforms, China should ensure that it maintains a financial environment in which nuclear and other low-carbon sources can attract investment. This includes low-cost financing, strong construction management to minimize construction costs, and revenues that are at least reasonably predictable. Further cost reductions and revenue opportunities (such as using the energy from nuclear plants for more than just providing baseload electricity) should be a major focus of development of advanced nuclear energy systems.[91]

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[91] Similarly, the recent MIT report on the future of nuclear energy recommends that: "Future research, development, and demonstration (RD&D) funding should prioritize reactor designs that are optimized to substantially lower capital costs, including construction costs. Innovations in fast reactors that are advertised on the basis of fuel cycle

Avoiding technological lock-in on dangerous and unneeded technologies

Just as China decided not to invest further in Generation II reactors, it should avoid major investments in technologies that are expensive, dangerous, and do little for the long-term future of nuclear energy. This includes plutonium reprocessing and breeder reactors that depend on reprocessing. Reprocessing is far more expensive than not doing so, and the capital cost—the main cost of nuclear energy—of breeder reactors has traditionally been significantly higher than the cost of light-water reactors.[92] Processing spent fuel at high temperatures in volatile chemicals creates a variety of new safety risks. The large spent fuel pools, processing operations, liquid high-level waste storage, and plutonium storage and transport create potential targets for terrorist sabotage or nuclear material theft. A Chinese decision to rely on plutonium reprocessing and recycling would likely make it more difficult to stop the spread of reprocessing to additional non-nuclear-weapon states, increasing proliferation risks. There is no need for China to accept these costs and risks, since, as noted earlier, China has access to plenty of uranium to fuel its nuclear growth, and options for storage and disposal of spent fuel can provide safe nuclear waste management with lower costs and risks than reprocessing.[93]

Developing options for the future

Finally, to maximize its future nuclear energy options, China should continue to invest in and facilitate research, development, and demonstration (RD&D) on selected advanced nuclear systems. This includes RD&D in China, cooperative RD&D with institutions in other countries, and monitoring of the promising results of foreign RD&D that China might adopt or adapt. The goal should not be to rush ahead, focusing only on those technologies ready for almost immediate demonstration and deployment, but to find technologies that could address key problems that have limited nuclear energy's growth in the past. China should seek to ensure that at least a small number of these advanced technologies are brought through the demonstration phase and ready for commercial deployment by mid-century.[94]

China should focus its nuclear RD&D efforts on those advanced systems most likely to help overcome the key obstacles and risks described in this chapter, including systems that could offer improved economics; increased passive, demonstrable, and understandable safety; broader siting options; strong security and proliferation resistance; and better ability to integrate with intermittent renewables and meet energy needs in addition to baseload electricity. To achieve such goals, China should build institutions for deciding on and implementing these RD&D efforts which are able to set priorities, allow different approaches to compete fairly, ensure goals are being met—and cut less promising projects, allowing resources to be reallocated to those that show the most promise for nuclear energy's future.

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metrics are unlikely to advance commercial deployment." Buongiorno, Corradini, and Parsons, co-chairs, *The Future of Nuclear Energy in a Carbon-Constrained World,* p. 83.

[92] See Bunn, Zhang, and Kang, *The Cost of Reprocessing in China.* For the global experience with breeder reactors, see Cochran et al, *Fast Breeder Reactor Programs.*

[93] For overviews of the issues with reprocessing in the U.S. case, see Matthew Bunn, "Assessing the Benefits, Costs, and Risks of Near-Term Reprocessing and Alternatives," testimony before the Subcommittee on Energy and Water, Committee on Appropriations, U.S. Senate, 14 September 2006, and Frank von Hippel, *Managing Spent Fuel in the United States: The Illogic of Reprocessing* (Princeton, N.J.: International Panel on Fissile Materials, January 2007).

[94] For an argument for a similar approach by the United States, see Michael J. Ford and Daniel P. Schrag, "A Tortoise Approach for Nuclear Research and Development," *Nature Energy,* July 30, 2018, https://www.nature.com/articles/s41560-018-0221-1.pdf.

The path ahead

Achieving nuclear growth on the scale needed for nuclear energy to play a significant part in decarbonizing China’s energy system will be a major challenge. There is no certainty today that the obstacles can be overcome. But with an approach that combines determination and care, China can maximize the nuclear energy choices it will have in the future, and have a chance to turn nuclear energy into a genuinely expandable element of the portfolio for mitigating climate change – for China, and for the world.