PART II

TECHNOLOGY AND CONSUMER PRODUCT OPPORTUNITIES AND RISKS

CHAPTER 3: U.S.-CHINA COMPETITION IN EMERGING TECHNOLOGIES

Abstract

The United States is locked in a long-term strategic competition with China to shape the rapidly evolving global technological landscape. Innovation in emerging technologies could transform society, create new industries, foster new dependencies, and alter the character of warfare. Whichever country secures a lead in key technologies—particularly those with first mover advantages—will tip the balance of power in its favor and reap economic benefits far into the 21st century. China under General Secretary of the Chinese Communist Party (CCP) Xi Jinping has recognized the potential advantages of seizing the innovation "high ground" in this competition and has aggressively designed, implemented, and funded programs to dominate technologies of the future. In doing so, Beijing hopes its efforts will underpin national rejuvenation, making the country powerful, self-sufficient, and impervious to perceived technological "containment" from the United States and its allies and partners. China has focused on developing emerging technologies such as artificial intelligence (AI), quantum technologies, biotechnology, and battery energy storage systems. The United States has similarly realized the importance of technology competition with China and has significantly altered the policy environment around key technologies, particularly semiconductors, advanced computing, and clean energy. China faces many challenges, including these U.S. policies, a faltering domestic economy, and inefficiencies inherent in its state-directed innovation system. However, if China manages to overcome these challenges, its rapid technological progress threatens U.S. economic and military leadership and may erode deterrence and stability in the Pacific, as well as tip the global balance of power.

Key Findings

- The CCP is prioritizing research in key emerging technology areas such as AI, quantum technology, biotechnology, and batteries with the goal of becoming a world leader in science and technology. Xi is placing a bet that China's investments in high-tech industries will unleash "new quality productive forces," transcend an old growth model reliant on infrastructure and lower-technology exports, and help China to achieve

its goal of becoming a superpower in the 21st century. China's focus on emerging technologies is also motivated by its desire to attain self-sufficiency in what its leaders describe as "chokepoint" technologies amid an international environment they perceive as increasingly hostile and to better prepare for a potential conflict with the United States over Taiwan or in other contingencies.

- China's state-centric approach and heavy investments in domestic innovation reflect similar techno-nationalist initiatives dating back to the Mao Zedong era. Under Xi, these efforts have intensified as the Party has sought to impose tighter top-down control in the innovation ecosystem to make breaking dependencies on foreign technologies a focal point.
- The United States and China are neck-and-neck, with one being ahead or behind depending on the specific critical and emerging technology. On certain manufacturing-intensive technologies, like advanced batteries and electric vehicles (EVs), China's various efforts have enabled its companies to obtain a clear advantage.
- ***Artificial intelligence:*** China is making rapid advancements and noteworthy investments in its AI capabilities. It is developing AI not only to advance China's economic growth more broadly but also for military applications, such as autonomous unmanned systems, data processing, decision-making, and cognitive warfare. Across key aspects of AI competition, however, China is having mixed success.
  - ***Advanced semiconductors:*** The United States and like-minded countries currently have an advantage in the advanced semiconductors needed to power AI technologies. China is aggressively working to address this deficit.
  - ***Compute and cloud:*** The United States leads in total compute and cloud, but several Chinese companies have notable cloud capabilities. Further, the nature of cloud computing creates a heightened threat of "leakage" into China of advanced compute capabilities located outside of China.
  - ***AI models:*** The United States currently leads the world in developing robust AI models, but China is pursuing numerous government-led and ostensibly private efforts to develop advanced AI models.
  - ***Data:*** Data are critical to AI capabilities. Each country has certain advantages in terms of collection, use, and availability of data for AI systems. China understands the value of data to AI and has taken active measures to increase the availability of quality data within its AI ecosystem.
- ***Quantum technologies:*** Both the United States and China are heavily funding research in quantum computing, sensing, and communications, the three subdomains that together make up quantum information science (QIS). While QIS is still in an early stage of development, it will have significant competitive and military impacts if it becomes commercially viable. China's Par-

ty-state drives quantum research through support to a major state laboratory in Anhui Province as well as a growing roster of state-backed startup companies. China appears to be an early leader in quantum communications, launching the world's first quantum communications satellite and connecting two ground stations with quantum key distribution. In other areas, China appears to be lagging behind the United States, though its scientists have claimed breakthroughs in cracking encrypted communications systems and developing advanced radar technology, claims that are difficult to confirm.

- ***Biotechnology:*** Biotechnology is another key emerging technology with the potential for transforming many industries. China aims to use biotechnologies to make itself less dependent on U.S. agriculture while embedding Chinese firms in U.S. food production and supply chains in genomic, pharmaceutical, and other biotechnologies. The major research and market presence of Chinese genomic and biotech services companies in the United States gives these companies access to key technologies and data.
- ***Advanced batteries:*** China has attained a sizable advantage at each stage of the battery supply chain, ushering in rapid global market share increases for Chinese EV and battery makers. China's near monopoly on battery manufacturing creates dependencies for U.S. auto manufacturers reliant on upstream suppliers as well as potential latent threats to U.S. critical infrastructure from the ongoing installation of Chinese-made battery energy storage systems throughout U.S. electrical grids and backup systems for industrial users.

Recommendations

The Commission recommends:

- Congress establish and fund a Manhattan Project-like program dedicated to racing to and acquiring an Artificial General Intelligence (AGI) capability. AGI is generally defined as systems that are as good as or better than human capabilities across all cognitive domains and would surpass the sharpest human minds at every task. Among the specific actions the Commission recommends for Congress:
  - Provide broad multiyear contracting authority to the executive branch and associated funding for leading artificial intelligence, cloud, and data center companies and others to advance the stated policy at a pace and scale consistent with the goal of U.S. AGI leadership; and
  - Direct the U.S. secretary of defense to provide a Defense Priorities and Allocations System "DX Rating" to items in the artificial intelligence ecosystem to ensure this project receives national priority.
- Congress consider legislation to:
  - Require prior approval and ongoing oversight of Chinese involvement in biotechnology companies engaged in operations

in the United States, including research or other related transactions. Such approval and oversight operations shall be conducted by the U.S. Department of Health and Human Services in consultation with other appropriate governmental entities. In identifying the involvement of Chinese entities or interests in the U.S. biotechnology sector, Congress should include firms and persons:

- Engaged in genomic research;
- Evaluating and/or reporting on genetic data, including for medical or therapeutic purposes or ancestral documentation;
- Participating in pharmaceutical development;
- Involved with U.S. colleges and universities; and
- Involved with federal, state, or local governments or agencies and departments.

- Support significant Federal Government investments in biotechnology in the United States and with U.S. entities at every level of the technology development cycle and supply chain, from basic research through product development and market deployment, including investments in intermediate services capacity and equipment manufacturing capacity.

- To protect U.S. economic and national security interests, Congress consider legislation to restrict or ban the importation of certain technologies and services controlled by Chinese entities, including:
  - Autonomous humanoid robots with advanced capabilities of (i) dexterity, (ii) locomotion, and (iii) intelligence; and
  - Energy infrastructure products that involve remote servicing, maintenance, or monitoring capabilities, such as load balancing and other batteries supporting the electrical grid, batteries used as backup systems for industrial facilities and/or critical infrastructure, and transformers and associated equipment.
- Congress encourage the Administration's ongoing rulemaking efforts regarding "connected vehicles" to cover industrial machinery, Internet of Things devices, appliances, and other connected devices produced by Chinese entities or including Chinese technologies that can be accessed, serviced, maintained, or updated remotely or through physical updates.
- Congress enact legislation prohibiting granting seats on boards of directors and information rights to China-based investors in strategic technology sectors. Allowing foreign investors to hold seats and observer seats on the boards of U.S. technology startups provides them with sensitive strategic information, which could be leveraged to gain competitive advantages. Prohibiting this practice would protect intellectual property and ensure that U.S. technological advances are not compromised. It would also reduce the risk of corporate espionage, safeguarding America's leadership in emerging technologies.

- Congress establish that:
  - The U.S. government will unilaterally or with key international partners seek to vertically integrate in the development and commercialization of quantum technology.
  - Federal Government investments in quantum technology support every level of the technology development cycle and supply chain from basic research through product development and market deployment, including investments in intermediate services capacity.
  - The Office of Science and Technology Policy, in consultation with appropriate agencies and experts, develop a Quantum Technology Supply Chain Roadmap to ensure that the United States coordinates outbound investment, U.S. critical supply chain assessments, the activities of the Committee on Foreign Investment in the United States (CFIUS), and federally supported research activities to ensure that the United States, along with key allies and partners, will lead in this critical technology and not advance Chinese capabilities and development.

Introduction

This chapter examines U.S.-China technology competition from the standpoint of economic and national security. Beijing hopes its efforts to gain leadership in emerging technology will underpin national rejuvenation, making the country powerful, self-sufficient, and impervious to perceived technological "containment" from the United States and its allies and partners.[1] This chapter first provides context, noting a recent shift in U.S. policy across multiple administrations to address the challenges of technology competition with China and China's efforts to lead in key technologies. It then focuses on U.S.-China technology competition in four key emerging technology areas: AI, QIS, biotechnology, and advanced battery technology. For each technology, the chapter highlights commercial and national security implications of the technology, compares relative capabilities of China and the United States, examines China's policies and investments, and analyzes China's exploration of such technologies for military and national security uses. Lastly, the chapter discusses the implications of U.S.-China technology competition for the national security and economic prosperity of the United States. The chapter draws on the Commission's February 2024 hearing on "Current and Emerging Technologies in U.S.-China Economic and National Security Competition," consultations with experts, and open source research and analysis.

Securing U.S. Advantage in Emerging Technologies

The policy environment around U.S.-China technology competition has shifted significantly. For years, Chinese companies and the Party-state have sought to acquire U.S. cutting-edge technology, intellectual property (IP), and know-how through licit and illicit means. For much of that time, outside of narrow export controls and occasional foreign investment reviews, U.S. policy was inadequately responsive to China's technology policies and ambitions. A large

constraint on technology transfer to China in many areas came from the reluctance of U.S. companies to transfer their best technology to China out of concerns over IP theft rather than U.S. law.[2] In recent years, however, successive administrations and Congress have identified emerging technologies as central to the U.S.-China strategic competition.

As attitudes in the United States have shifted, the United States has taken a number of steps in recent years to better protect U.S. national security and shore up U.S. advantages in the development, production, and protection of these technologies. U.S. policymakers have identified certain "critical and emerging technologies" or "foundational" technologies as vital to economic and national security, including advanced semiconductors, quantum information systems, and AI; biotechnologies and biomanufacturing; and clean energy generation and storage technology.[3] Each of these families of technologies carries the potential to be a "force multiplier" across the various fields of technology, accelerating the broader pace of innovation and adoption, and serving as a bedrock upon which to ground future industries.[4] Each also has significant national security implications.

U.S. policy has begun to shift to recognize the importance of competition with China over these critical technologies. In recent years, the United States has made investments to help ensure it retains an edge in key foundational technologies; it has also expanded use of export controls relating to advanced semiconductors and AI and tightened up other avenues that adversaries use to gain access to sensitive U.S. technology. Now that U.S. policymakers have realized the stakes, U.S.-China technology competition will continue to be a key issue in the U.S.-China economic and security policy space for years to come.

China Has Long Sought Dominance in Emerging Technologies

China has long sought to spur domestic science and technology innovation to enhance its military and commercial progress, but it is intensifying its efforts in light of disruptive global events and heightened competition with the United States. China is seeking to dominate emerging technology industries to sustain economic growth as traditional sectors atrophy and to exert greater global influence via the trade and economic leverage that come with these technologies.

The CCP has clearly articulated and publicly stated its priorities in emerging technologies, and it leverages a variety of assets to direct attention, effort, and resources toward these priorities. In contrast to the more market-oriented innovation landscape in the United States, the state takes on a much more prominent role in China's technology ecosystem, with the government strategically allocating funding and resources to industries and research areas deemed a priority.[5] The results of abundant and sustained state support have been mixed, creating expected inefficiencies commonly associated with centrally planned economies and yet also enabling tremendous returns to scale for fledgling industries that have resulted in clear comparative advantages for Chinese producers of certain technolo-

gies.[6] Despite the traction of some of these efforts, China faces challenges, including a shortage of highly skilled workers and economic headwinds.[7] Additionally, while China has increased its scientific research and patent output, translating these findings into groundbreaking innovations and economic benefits remains a hurdle.[8]

China under the CCP has a long history of techno-nationalism, often rooted in fear of being dominated by technologically superior foreign powers.[9] For example, China successfully developed the atomic bomb in 1964 through "Project 596," a national initiative that aimed to build nuclear weapons.[10] Similar national innovation programs have been used to achieve advancement in targeted technology areas, such as the National High-Tech R&D Program (863 Program) established in 1986 and the National Basic Research Program (973 Program) established in 1997.[11] These large government-funded initiatives channeled financing and resources to scientists and entrepreneurs credited with producing the world's first quantum telephone network, improved solar technology, and the Tianhe-1A supercomputer, which for a time was the world's fastest computer.[12]

In the mid-2000s, China made explicit its intention to use technology policy to move up the value chain of global production, increase its indigenous capacity, and become a global leader in certain technology areas. The 2006 Medium- to Long-Term Program (MLP) for the Development of Science and Technology articulated the need to facilitate indigenous innovation and set specific goals to be achieved by 2020. These included targets in research and development (R&D) spending, patent filing, and publication of academic articles.[13] China implemented numerous policies under the MLP in the ensuing years, many of which ran counter to the letter and spirit of WTO rules.[14]

Techno-Nationalism Accelerates under Xi

General Secretary Xi has continued—and in recent years, accelerated—these techno-nationalist policies, focusing efforts on technologies he believes are transformative and can propel China into dominance this century by leapfrogging the United States. Seeking to accelerate progress under the MLP, in 2015, China rolled out "Made in China (MIC) 2025," a more comprehensive industrial policy intended to improve manufacturing processes and achieve breakthroughs in ten high-value sectors.*[15] MIC set ambitious domestic market share targets in the identified priority sectors for Chinese-made products, including 80 percent for EVs and batteries, 70 percent for industrial robotics, and 40 percent for mobile phone chips.[16] The *South China Morning Post* claimed in April 2024 that 86 percent of these targets had been met or exceeded.[17]

Xi has doubled down on the state-centric approach in order to seize the "high ground" of innovation, rhetorically highlighting its importance and promulgating further iterations to industrial policy.[18] In speeches and policy documents, Xi and other top Chinese

*The ten high-value sectors highlighted in Made in China 2025 are advanced railway transportation equipment, aerospace, agricultural machines, biopharma and high-tech medical devices, energy equipment, high-end computerized machines and robots, maritime equipment and high-tech ships, new energy and energy-saving vehicles, new generation information technology, and new materials. Karen M. Sutter, "'Made in China 2025' Industrial Policies: Issues for Congress," *Congressional Research Service* IF10964, March 10, 2023.

leaders have emphasized the need to reduce reliance on so-called "chokepoint" technologies, particularly those controlled by Western countries, by achieving breakthroughs in domestic innovation and developing alternative sources of supply.*[19] In March 2023, the State Council asserted that global competition and external "containment" necessitated the acceleration of "high-level scientific and technological self-reliance and self-improvement."[20]

China's 14th Five-Year Plan (2021–2025) built on previous initiatives to advance high-priority sectors like AI, QIS, biotechnology, and advanced batteries.[21] It also indicated a response to what the CCP perceives as an increasingly hostile and disruptive global environment by incorporating the "dual-circulation"† development model and placing an emphasis on obtaining foreign technologies through pathways that remain open, such as research partnerships, establishing R&D centers abroad, and providing incentives for technological talent to work in China.[22]

More recently, Xi has introduced the concept of "new quality productive forces," which the National People's Congress elevated as its top policy priority during its annual meeting in March 2024 and adopted at the Third Plenum held a few months later in July.[23] This slogan, now being widely disseminated in Chinese political discourse, indicates that China is focusing its state-led economic efforts to enhance competitiveness in emerging technologies like AI and clean energy to ensure continued economic growth and global economic leverage through dominance in key technologies of the future.[24] In doing so, China hopes to eclipse the United States across the full spectrum of national power.[25]

Under Xi, the CCP regime has also moved to assert greater control over science and technology innovation efforts, aiming to enhance Party control and ensure alignment with Party priorities.[26] After the reform and opening up era in the 1980s, China facilitated research and capital linkages through a system of hundreds of publicly funded laboratories—often integrated into universities and private companies—and by clustering research facilities and businesses in development zones.[27] This decentralized approach was intended to harness private efforts and allow for localized policy experimentation.[28] In 2016, the Party under Xi moved to reform the system of state labs and development zones under the "Innova-

*While publicly available official policy documents describe "key and core technologies" controlled by "others" as an area of concern, Chinese leadership rarely delineates these technologies. In a 2021 speech before the Chinese Academy of Sciences, Xi called on the scientific community to "resolutely win the battle over key core technologies" by focusing efforts on basic research that can "break through bottlenecks" and "understand the basic theories and technical principles of 'chokepoint' technologies." In 2018, the Chinese state media newspaper *Science and Technology Daily* published a list of 35 chokepoint technologies reviewed and approved by the Ministry of Science and Technology, among them machinery to fabricate semiconductors such as photo-lithography machines and vacuum evaporators, specialized steel alloys, and aviation software. Ben Murphy, "Chokepoints: China's Self-Identified Strategic Technology Import Dependencies," *Center for Security and Emerging Technology*, May 2022, 1, 3; Xi Jinping, "Accelerate the Construction of a Scientific and Technological Power to Achieve High-Level Scientific and Technological Self-Reliance and Self Improvement" (习近平:加快建设科技强国 实现高水平科技自立自强), *Qiushi*, April 30, 2022. Translation.

†Dual circulation consists of achieving a largely self-reliant domestic economy by relying on the production base and massive consumer market to vertically integrate important industries, while simultaneously deepening dependencies on Chinese high-quality exports around the world. Karen M. Sutter and Michael D. Sutherland, "China's 14th Five-Year Plan: A First Look," *Congressional Research Service* IF11684, January 5, 2021; Center for Strategic and International Studies, "Will the Dual Circulation Strategy Enable China to Compete in a Post-Pandemic World?" December 15, 2021.

tion-Driven Development Strategy."[29] A key objective of this strategy is to consolidate what was determined to be a fragmented innovation landscape with an overabundance of research funding for underperforming efforts into higher-performing equivalent institutions more directly controlled by the CCP and focused on achieving self-sufficiency in key "bottleneck" technologies.[30] In March 2023, China also announced plans to restructure its Ministry of Science and Technology to reduce its responsibilities and centralize Party control through the establishment of a decision-making body called the Central Commission on Science and Technology.[31]

Funding Mechanisms Buttress China's Science and Technology Ambitions

The United States has long led the world in both public and private sector funding for R&D,* though China is closing the gap. The Chinese government has prioritized R&D funding to accelerate its ambitions to innovate in science and technology and better compete with the United States.[32] According to data from the Organisation for Economic Co-operation and Development (OECD) that compare R&D spending across countries using purchasing power parity, in 2021 the United States continues to outpace China on total R&D, spending $806 billion (3.46 percent of gross domestic product [GDP]) compared to China's $667.6 billion (2.43 percent of GDP).[33] In this dataset, government funding represented roughly 20 percent of total R&D spending in both countries.[34] However, a 2023 estimate from Rhodium Group found that approximately 60 percent of all financing within China's science and technology ecosystem came from government-related sources of funding after accounting for tax incentives and off-budget financing, distinguishing it from other large and technologically advanced economies.[35] In total dollars spent, U.S. multinational enterprises in high-tech industries spent 240 percent more on R&D than Chinese firms in 2021, spending $529 billion and $154 billion, respectively.[36] However, when adjusted for wage differences, U.S. companies only spent 80 percent more than their Chinese counterparts.[37] In her written testimony before the Commission, Ngor Luong, a senior research analyst at the Center for Security and Emerging Technology (CSET), noted that in 2022 the Chinese National Bureau of Statistics reported that the country's R&D investment increased by 10 percent from 2021, outpacing its goal of 7 percent annual increases outlined in the 14th Five-Year Plan.[38]

In addition to direct government funding, traditionally, China has utilized an array of state-owned enterprises (SOEs) to direct

*R&D is typically subdivided into three components: (1) basic research, which is experimental or theoretical and attempts to generate new knowledge devoid of a particular application; (2) applied research, which seeks to acquire new knowledge that can be directed toward a practical objective; and (3) experimental development, which is the systematic approach to utilize knowledge gained through research to produce new products or services or improve existing products or services. Together, basic research and applied research comprise "fundamental research." In medical and life sciences, the more common term "translational research," sometimes used synonymously with applied research, is the process of moving discoveries from basic research into medical applications for patients and populations. National Institutes of Health, "About Translational Science," April 19, 2024; Organisation for Economic Co-operation and Development, "Research and Development (R&D)," 2024; Marco Zarbin, "What Constitutes Translational Research? Implications for the Scope of Translational Vision Science and Technology," *Translational Vision Science & Technology*, July 14, 2020; U.S. Department of Defense, Defense Advanced Research Projects Agency, *Fundamental Research*.

capital to key sectors and advance national innovation goals. China's Minister of Science and Technology Wang Zhigang has called on SOEs to be "pillars" in the country's whole-of-nation approach to achieve self-sufficiency and high-technology innovation.[39] China's state-owned banks have been instrumental in directing capital to national priorities, exemplified by six state-owned investors together providing one-third of the investment in the latest $47 billion semiconductor fund alongside other SOEs and the Ministry of Finance.[40] China's central government is expected to continue to provide robust support to SOEs involved in national security priorities, including aerospace and defense and policy banks, while support for those in disfavored sectors, such as real estate and even consumer goods, is less assured.[41] Beyond providing funding, SOEs have been directed to increase their own levels of R&D spending and seek opportunities to integrate more agile high-tech small and medium enterprises into their supply chains.[42]

Beijing also uses government guidance funds—public-private funding mechanisms that blend state capital with Chinese private equity and venture capital—to steer capital toward strategic industries such as AI.[43] However, Ms. Luong, along with research fellow Zachary Arnold and Chinese translation manager Ben Murphy at CSET, find that in practice "most guidance funds fail to live up to their ambitions, weakened by unrealistic goals, bureaucratic constraints, incompetent management, risk aversion, and a lack of market discipline."[44]

The Reshaping of Beijing's Innovation Drive to Utilize Small and Medium-Sized Enterprises

Over the past decade, China has pivoted its innovation-oriented policies to refocus on supporting small and medium-sized (SMEs), developing a whole-of-nation approach to fostering small but highly innovative firms. As emphasized in 2023 by Premier Li Qiang, Beijing now believes that "supporting early tech startups should be a top priority."[45] This shift reflects both Beijing's acknowledgement of the success of "hidden" champions* in China's startup ecosystem and its desire to curtail the "disorderly expansion of capital," seeking to avoid what the Party-state viewed as an excessive concentration of investment in e-platforms, including services like video gaming and online tutoring.[46]

The Little Giants program, officially launched in 2018, forms the core of Beijing's efforts to develop a multi-tiered system to help SMEs compete in emerging technologies or occupy niche but critical segments of global supply chains.[47] The Ministry of Industry and Information Technology (MIIT) certified the first batch of companies as "Little Giants" in 2019, and tens of thousands of SMEs have since received support from the initiative.[48] This system encompasses a broad array of tools to foster innovation, from direct subsidies to initiatives enhancing SME-university collaboration.[49] However, the most important element is the broadened

*Technology analyst Dan Wang argues that many outside observers underestimate China's innovation capacity in part due to China's innovative firms being concentrated in "less flashy" manufacturing capabilities and products sold at lower price points in lower-income countries. Dan Wang, "China's Hidden Tech Revolution: How Beijing Threatens U.S. Dominance," *Foreign Affairs*, February 28, 2023.

access to capital markets for Little Giants.[50] SMEs have historically struggled to access financing within China's bank-dominated financial system where lenders prioritize credit to SOEs and large non-state firms.[51] This acts as a barrier to innovation for many non-state enterprises, one that Beijing aims to ameliorate through the Little Giants program.[52]

China has created a series of new financing mechanisms over the past several years for small firms operating in priority industries, with varying degrees of success. In 2019, the Shanghai-based Science and Technology Innovation Board, or STAR Market, was launched to expand equity investment in smaller Chinese technology companies.[53] The exchange hosts over 500 companies with a combined market cap of $716.7 billion as of June 2024, and it predominately fast-tracks initial public offerings (IPOs) for companies in high-tech fields, including new materials, biomedicine, and information technology.[54] The STAR Market initially outperformed China's other major indices, but as of August 2024 it has fallen 59.7 percent since its peak in July 2020.[55] Following lackluster performance of the index in recent years, the China Securities Regulatory Commission has since raised the requirements for companies seeking to list.[56] The Beijing Stock Exchange also opened in 2021 for even smaller enterprises (with a minimum market value of $30 million, relative to the $140 million required to list on the STAR Market).[57] Little Giants accounted for around 40 percent of listings across all stock exchanges in China in 2022.[58]

Additionally, China is guiding its banking sector to provide easy access to credit, with the People's Bank of China (PBOC) creating a special purpose lending facility that enables innovative SMEs in science and technology areas to refinance loans well below market rates.[59] At the end of 2023, total lending to sci-tech SMEs reached $340 billion (renminbi [RMB] 2.45 trillion),* an increase of 21.9 percent relative to 2022 and outpacing overall loan growth by 11.8 percentage points.[60] Leaderdrive, a non-state SME that produces components for industrial robots, is an illustrative example of the financial support firms gain access to under the program.[61] After it was awarded the Little Giant title in 2019, Leaderdrive benefited from both government guidance fund investments and a listing on the STAR Market in 2020.[62] Large domestic industrial robotics manufacturers also provide a source of ongoing demand for Leaderdrive's production.[63]

Case Studies in U.S.-China Technology Competition

Both the United States and China view AI, QIS, biotechnology, and advanced battery technology as some of the key strategic emerging industries of the future.[64] As outlined in the 14th Five Year Plan (2021–2025), China views these technologies as integral to strengthening its national defense in tandem with driving innovation.[65] The following sections will assess U.S.-China technology competition in these four technologies.

*Unless noted otherwise, this section uses the following exchange rate throughout: $1 = RMB 7.25.

Artificial Intelligence: A Revolutionary Technology with Significant Military Implications

In the broader geostrategic competition between the United States and China, leadership in Artificial Intelligence (AI) has the potential to reshape the global balance of power.[66] AI is the science and engineering of machines that use complex "algorithms, modeled after the decision-making processes of the human brain, that can 'learn' from available data and make increasingly more accurate classifications and predictions over time."*[67] In recent years, AI has been used to solve complex problems, provide predictive analytics, recognize and interpret visual information, engage in natural language processing to create high-quality content and "understand" and analyze written and verbal language, and speed the development of robotics.[68] The country that leads in AI has the potential to reap economic benefits including productivity enhancement and the ability to innovate new products and services and enable insights for business leaders through data analysis.[69] The full extent to which AI will transform and underpin various industries is still unfolding, but its estimated impact is massive. McKinsey & Company estimates that AI could add up to $4.4 trillion annually to the global economy.[70] As discussed below, AI also has numerous military applications that may provide a strategic advantage to the United States or China in an Indo-Pacific conflict.[71]

The United States and China Vie for AI Supremacy

China recognizes the transformational potential of AI and is positioning itself to capitalize on technological breakthroughs. Chinese commentators point to the defeat of the top Chinese player in the boardgame Go by Google's AlphaGo in May 2017 as a "Sputnik moment" for the country, which kicked off an effort to channel attention and resources from entrepreneurs, tech talent, and policymakers.[72] Two months later, the State Council issued an AI strategy titled the "New Generation Artificial Intelligence Development Plan," which called for increased funding and support to make China a leader in AI theory, technology, application, and innovation by 2030.[73] Then, in late 2022, the powerful demonstration of OpenAI's generative model ChatGPT-3 again surprised China's AI industry, exemplifying a clear advantage for the United States.[74] At the annual meeting of China's rubber-stamp legislature, Premier Li announced an "AI+" initiative in his work report intended to "actively develop the digital industry, transform traditional industries with digital technologies, and fully integrate digital technology into the real economy."[75] Beijing is making noteworthy investments in its AI capabilities, utilizing government funding mechanisms and leveraging the non-state sector for its economic development and efforts to "leapfrog" the United States militarily.[76]

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*There are numerous subtypes of AI that serve various uses. One of the major types of AI is machine learning, in which a computer algorithm is developed to analyze and make predictions from data that are provided in a system. Deep learning, a form of machine learning, uses complex layers of computation to form a deep neural network, which is capable of learning from large amounts of unstructured data. IBM, "Understanding the Different Types of Artificial Intelligence," October 12, 2023; National Institute of Biomedical Imaging and Bioengineering, *Artificial Intelligence (AI)*.

The race for superior AI across industries relies on successfully bringing together enabling technologies and building blocks, including advanced chips; computational power, including cloud services; well-designed algorithmic models; and vast and rich data to train models. Currently, the United States has a lead in most of these technologies and building blocks.

Semiconductors Underpin U.S.-China AI Competition

Semiconductors are integral to U.S.-China competition in AI. Advanced semiconductors are key to AI capabilities due to their role in accelerating processing speeds and harnessing the computational power needed for complicated AI-related computing tasks.[77] The United States currently has a lead in advanced semiconductors.[78] According to an August 2024 report by the Information Technology and Innovation Foundation, Chinese competitors are around "five years behind global leaders in high-volume manufacturing of leading-edge logic semiconductor chips" and trail in memory chips and semiconductor manufacturing equipment.[79] U.S. companies like NVIDIA and AMD dominate the design of advanced chips, and they are fabricated almost exclusively by Taiwan Semiconductor Manufacturing Company (TSMC).[80] The United States has sought to protect that lead through export controls and domestic investments.[81] The U.S. government and its partners and allies have introduced targeted export controls that have undercut China's ability to access high-end chips and to fabricate them domestically.[82] At the same time, the United States has made substantial investments in growing domestic production capacity through the CHIPS and Science Act.[83]

China has been investing heavily in its domestic semiconductor industry to boost its AI capabilities and overcome its dependence on global supply chains, but it still faces numerous hurdles to overtaking the United States. The export controls by the United States and its allies against China, coupled with China's desire to boost its AI capacities, have spurred China's domestic chip industry to develop more rapidly, leading to significant additional spending and experimentation.[84] In March 2024, the Economist Intelligence Unit estimated that since 2014, China's state-led investment into its semiconductor industry exceeded $150 billion, including central and provincial government support.[85] That estimate came prior to the May 2024 announcement that the third phase of the Chinese government-supported Integrated Circuit Industry Investment Fund (often called "the Big Fund") had raised $47.5 billion of investment to support China's semiconductor industry.[86] If this is all new money, it would bring the total since 2014 to $197.5 billion. At the local level, there are numerous provinces and municipalities that have issued subsidies for local semiconductor-related firms or to support the buildout of the local semiconductor industry.*[87] Specific to AI-focused chips, Beijing's municipal government has also provided new subsidies for firms that purchase domestically produced AI chips.[88] In April 2024, the Beijing Municipal Bureau of Economy and Infor-

*Other instances where subsidies at the local level have been provided include Beijing, Shanghai, Suzhou, Nanjing, Shenzhen, Qingdao, Hefei, Tianjin, Changsha, Wuhan, Chengdu, Wuxi, Hunan Province, Jiangsu Province, and Guangdong Province. See endnote 87 for sourcing.

mation Technology announced that it would give companies a percentage of their investment for purchases of domestically controlled graphic processing unit (GPU) chips used in intelligent computing services, with the city seeking to become fully self-reliant in smart computing infrastructure hardware and software by 2027 under the initiative.[89]

China has made some strides in closing the gap on cutting-edge GPU semiconductors used to train AI models. Wang Tao, Huawei's chief operating officer of its Ascend and Kunpeng ecosystem, claims that Huawei's Ascend 910B AI chip is capable of up to 80 percent of the performance of NVIDIA's A100 GPU when training large language models (LLMs), and in "some other tests" surpasses the A100 by 20 percent.[90] Analysts and sources quoted by *Reuters* claim that the 910B chips are comparable to NVIDIA's in terms of raw computing power but lag in performance.*[91] According to a detailed analysis by CSET, "the performance increase is smaller than advertised; only 75 percent of the theoretical maximum performance increase can be attributed to an actual increase in hardware performance" and "Huawei reduced the number of active AI cores between the 910 and 910B series—likely either due to poor yields or limited capacity on SMIC's 7nm fabrication process."[92] In August 2024, the *Wall Street Journal* reported that Huawei is close to introducing a new chip for AI use, the Ascend 910C, which the company claims is comparable to NVIDIA's H100.[93] However, it has faced production delays with these chips, and further U.S. restrictions may prevent access to machine components and memory chips for its AI hardware.[94] Additionally, some experts have argued that the underlying technology being used to produce Huawei's chips has significantly lower "yield," meaning that a significant portion of the chips produced are flawed and do not function effectively, resulting in appreciably higher total costs to manufacture at scale.[95]

It's Not Just Chips: How Huawei Seeks to Compete across the AI "Stack"

To date, U.S. concerns around AI and China have focused largely on access to advanced semiconductors. Similar to many other advanced technologies, however, AI is powered by a "stack" of enabling hardware, software, and services. Policymakers have paid much less attention to other elements of the AI stack.

NVIDIA is a leader in the AI space not only because of GPUs but also its CUDA software.† Known as its "secret sauce" or "moat," CUDA is NVIDIA's closed-source "AI software ecosystem" that allows programmers to utilize the parallel computing power

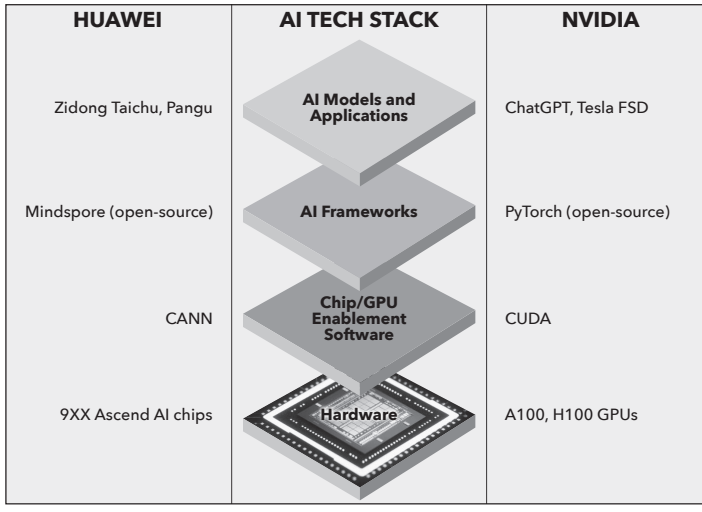
*According to a report by AI Now Institute, a New York-based policy institute, computational power, also known as compute, is measured in floating point operations, or FLOP, which is a mathematical operation that enables the representation of extremely large numbers with greater precision. Compute performance, on the other hand, is measured in floating point operations per second, or FLOP/s. This is essentially the number of computations a given resource can carry out in a second. Jai Vipra and Sarah Myers West, "Computational Power and AI," *AI Now Institute*, September 27, 2023.

†CUDA stands for Compute Unified Device Architecture. Related to CUDA is cuDNN (CUDA deep neural network), a library built on top of CUDA containing tools and routines specific to deep neural networks such as AI. 1kg, "cuDNN: What Is cuDNN?" *Medium*, May 4, 2024; Rakesh Rajpurohit, "Understanding CUDA for GPU Computing," *Medium*, August 15, 2023; Deep Lizard, "CUDA Explained - Why Deep Learning Uses GPUs," September 9, 2018; Fred Oh, "What is Cuda?" NVIDIA, September 10, 2012; NVIDIA, "NVIDIA cuDNN."

It's Not Just Chips: How Huawei Seeks to Compete across the AI "Stack"—*Continued*

of NVIDIA's GPUs for building AI applications.*[96] As NVIDIA has been developing CUDA since 2004, it has a lead over both domestic and foreign AI chip design firms in the resources it can offer AI programmers.†[97] The symbiosis within NVIDIA's AI stack has led to a "flywheel effect" that makes the company essential for many AI developers. As companies purchase more NVIDIA GPUs for AI development, more developers use CUDA; as more developers use CUDA, they increase their dependency on NVIDIA's GPUs.[98]

Figure 1: A Comparison of NVIDIA and Huawei's AI Tech Stacks



Note: The diagram indicates the various software technologies (mid-to-upper layers) that are either directly controlled or best optimized for NVIDIA or Huawei's chip-based hardware (bottom layer), respectively. CANN and CUDA are Huawei and NVIDIA's respective proprietary software frameworks required to manage the parallel processing power of their chips. MindSpore (Huawei) and PyTorch (PyTorch Foundation) are open source AI frameworks that rely on or are best optimized for CANN and CUDA, respectively. Finally, Pangu (Huawei) and ChatGPT (OpenAI) are examples of technologies built or iterated using these AI frameworks.
Source: Various.[99]

*CUDA allows for the optimization, speeding up, and programming of NVIDIA GPU's CUDA core and machine learning-focused Tensor core sub-processing units necessary for parallel computing and the deep learning associated with building AI models. For more, see 1kg, "cuDNN: Common Challenges and Their Practical Solutions," *Medium*, June 26, 2024; Jeremy Appleyard and Scott Yokim, "Programming Tensor Cores in CUDA 9," *NVIDIA Developer*, October 17, 2017; Ravi Rao, "Tensor Cores vs CUDA Cores: The Powerhouses of GPU Computing from NVIDIA," *Wevolver*, July 25, 2024.

†PyTorch and TensorFlow are the most popular AI frameworks for building AI models (though PyTorch is more widely used). This is evolving slightly as Google (which designed and oversees TensorFlow) continues building out its Tensor Processing Unit (TPU) hardware/software AI stack. For now, CUDA is widely seen as the de facto choice for AI frameworks. As the cofounder of PyTorch Soumith Chintala put it in 2023, "The CUDA monopoly is nowhere close to being broken and CUDA will continue to be the key dependency for PyTorch." For more, see Soumith Chintala, *X.com*, Jan 17, 2023. For more on PyTorch popularity compared to TensorFlow, see Valantis K, "Battle of the Giants: TensorFlow vs PyTorch 2023," *Medium*, January 28, 2023. For possible future domestic challenges to NVIDIA and CUDA, see Dylan Patel, "How Nvidia's CUDA Monopoly in Machine Learning Is Breaking - OpenAI Triton and PyTorch 2.0," *SemiAnalysis*, January 16, 2023; Kevin Jackson and Doug Eadline, "Spelunking the HPC and AI GPU Software Stacks," *HPC Wire*, June 21, 2024.

It's Not Just Chips: How Huawei Seeks to Compete across the AI "Stack"—*Continued*

Huawei is not just targeting advanced semiconductors but is also seeking to establish its own "flywheel" to displace NVIDIA's dominance.[100] Like NVIDIA, Huawei's AI "tech stack" starts with its hardware (the Ascend family of AI chips) atop of which is a CUDA-like layer of software known as CANN (Compute Architecture for Neural Networks).[101] Atop of CANN, Huawei has also released MindSpore, an open source AI framework of software similar to the popular PyTorch and TensorFlow AI framework software used to create LLMs and other AI technologies.[102] Though PyTorch and TensorFlow are also open source, Huawei needs an alternative because PyTorch and TensorFlow are largely integrated with CUDA and as a contingency should the U.S. government ever block access to PyTorch and Tensorflow.* [103]

In the short term, Huawei still trails NVIDIA and its AI hardware/software "stack." NVIDIA alone has developed 600 AI models; and four million developers currently use CUDA software for training AI.[104] Programmers in China also have concerns about Huawei's CANN, reporting large-scale issues with bugs, software glitches, and general inferiority to NVIDIA's CUDA.† [105] MindSpore also trails more popular open source AI frameworks such as PyTorch. While the Chinese Academy of Information and Communications Technology (CAICT) has noted that MindSpore is the most popular AI framework domestically within China, it admits that PyTorch and TensorFlow are a "duopoly" internationally.[106]

However, in the long run, Huawei's attempts to recreate NVIDIA's "flywheel" via an integrated AI hardware/software stack bears close attention. As of July 2023, Huawei claimed that the number of Ascend and CANN developers had doubled from a year prior and reached 1.8 million.[107] Huawei has also stated that nearly half of all large language models in China are currently trained on its Ascend (hardware)/CANN (software) AI ecosystem.‡ [108]

Mobile technology provides an instructive example of how Huawei has leveraged privileged access to China's massive domestic market and various types of state support to overcome technological hurdles, accelerate adoption, and continue to pur-

*Though there are other layers of the AI stack, the relationship between hardware (chips) and software (CUDA/CANN) to AI frameworks (PyTorch/MindSpore) that rely on them is critical for understanding NVIDIA and Huawei's "flywheels".

†China's own developers are still heavily reliant on CUDA, with prominent Chinese chip startups like Moore Threads and Denglin using or accessing CUDA. Jeff Pao, "'China's NVIDIA' Collapsing in a Heated Funding Dispute," *Asia Times*, September 3, 2024; Che Pan, "Tech War: NVIDIA's Move to Curb Use of CUDA Exposes China's Weak Link in Chip Software," *South China Morning Post*, March 6, 2024; Simon Sharwood, "China's GPU Contender Moore Threads Reveals Card That Can Cope with NVIDIA's CUDA," *Register*, December 20, 2023.

‡Based on the most recent filings from the Cyberspace Administration of China's Algorithmic Registry, as of August 5, there are 487 algorithms registered within China. This includes a mix of generative AI models, recommendation engines, and other algorithm/AI applications. Cyberspace Administration of China, Announcement of the Cyberspace Administration of China on the Release of the Seventh Batch of Deep Synthesis Service Algorithm Registration Information (国家互联网信息办公室关于发布第七批深度合成服务算法备案信息的公告), August 5, 2024. Translation; Qiheng Chen, "China's Emerging Approach to Regulating General-Purpose Artificial Intelligence: Balancing Innovation and Control," *Asia Society Policy Institute*, February 7, 2024; Matt Sheehan, "What China's Algorithm Registry Reveals about AI Governance," *Carnegie Endowment for Peace*, December 8, 2022.

It's Not Just Chips: How Huawei Seeks to Compete across the AI "Stack"—*Continued*

sue technological leadership.* The United States added Huawei to the Entity List in May 2019, restricting access of Huawei to various products and technologies, including semiconductors, the licensed version of Android (which was the operating system [OS] underlying Huawei's handsets), Android OS updates, and access to Google apps and services.[109] Leading U.S. tech publications that saw Huawei as a leading manufacturer of low-cost hardware were concerned that the Android ban, in particular, would irreparably harm the company moving forward.[110] Huawei's domestic Android alternative, Harmony OS (HongMeng), was dismissed by Western critics as a glorified "fork" that relied on Android's open source software, which would face myriad challenges in becoming a viable rival to Android.[111]

Five years later, however, the pairing of Harmony OS with China's export control-defying hardware (the Kirin 9000 chip) has been a key reason Huawei has continued to remain competitive in the handset space.[112] Harmony OS currently is used on over 900 million devices globally; 2.5 million developers are working on apps for the Harmony OS platform, and Huawei targets one million apps for the OS in the near future.[113] The company's next mobile operating system, HarmonyOS NEXT, scheduled to debut October 2024, will remove its Android open source code, making it a fully independent mobile operating system.[114]

China has made progress in expanding "legacy" or "mature node" semiconductor production. Semiconductor Manufacturing International Corporation (SMIC) has become the world's third-largest foundry and is prominent in "mature node," or 28 nm and above chip production.[115] These chips are less demanding in wafer production and are made with older-generation deep ultraviolet lithography equipment.[116] China is rapidly expanding production capacity for these semiconductors, which are crucial to a wide range of commercial products. According to one estimate, China is on pace to add more than 18 new chip fabs in 2024 alone.[117] The Information Technology and Innovation Foundation estimates that between 2022 and 2026, China will bring 26 new fabs online, a majority of which will build legacy chips.[118] According to Silverado Policy Accelerator, "China has the most fabs expected to come online during 2022–26, which will result in it having the most both 200 mm and 300 mm wafer capacity in the world" and "as of March 2023, [China] accounted for 32 percent [the world's largest share] of current and planned capacity for 20 to 180 nm semiconductors (excluding memory)."[119]

*On a related point, Huawei's continued status as the global leader in 5G technology—as of 2023 it is still the number one provider globally—suggests limits to U.S. technology controls and related efforts to limit the spread of national security-sensitive Chinese technology. 5G has some important differences, however, given that Huawei was already the global leader in this technology before the imposition of U.S. controls. Daniel Chiang and Vyra Wu, "Huawei vs. Samsung: Who Leads the Global Communication Equipment Race?" *DigiTimes*, April 17, 2024.

The Silverado production capacity estimates were made in October 2023; since then, China's imports of semiconductor manufacturing equipment surged to new highs for calendar year 2023 and are on pace to surpass that in 2024. In 2023, China was the largest global importer of semiconductor manufacturing equipment, importing $42.5 billion, almost $15 billion more than Taiwan, the second-largest importer.[120] According to data from China's General Administration of Customs, Chinese imports of chip equipment in the first seven months of 2024 hit a new high, totaling $26 billion.[121] Lithography tools, in particular, are a key piece of semiconductor manufacturing equipment for which China currently has no significant domestic alternative, with only an estimated 1 to 1.2 percent of lithography tools manufactured domestically.[122] In the past five years, China has imported 444 lithography machines from EU trading partners (predominantly the Netherlands) and $27.4 billion dollars' worth of semiconductor manufacturing equipment in 2023, an increase of nearly 50 percent from the prior year.*[123]

Given limitations on advanced semiconductor manufacturing equipment sales, China is constantly pursuing legal and illegal means to acquire semiconductor manufacturing equipment.[124] On its own, China is not likely to catch up at scale on high-end AI chips, at least not using current technology.[125] SMIC and Yangtze Memory Technologies Corp (YMTC) are still dependent on Western equipment, especially for making more high-end semiconductors.[126] Unless China can solve the "yield" problem inherent in using older equipment to produce more advanced semiconductors, it is not likely to be able to produce AI-caliber chips in quantities needed for the massive expansion in AI demand that is projected.[127] It is worth noting, though, that total AI infrastructure demands for national security uses are likely a fraction of those needed for the broader commercial market.

Legacy Semiconductors Underpin Wide Variety of Modern Technologies; Significant Risk of Overcapacity Glut from China

Although the world's most cutting-edge semiconductors are at the forefront of advancements in AI, "legacy" semiconductors are critical for a whole host of other technologies.† Legacy chips are pervasive and essential, as they can be found in nearly every electronic device ranging from automobiles, fighter jets, drones, medical devices, smartphones, computers, industrial equipment, scientific equipment, communications devices, sensors, and more.[128]

*The complexity of these machines cannot be overstated. The latest extreme ultraviolet lithography machines produced by ASML are "the size of a bus, but so accurate they could direct a laser to hit a golf ball as far away as the Moon." Lucy Rodgers et al., "Inside the Miracle of Modern Chip Manufacturing," *Financial Times*, February 28, 2024,

†Chips are categorized based on their function. Analog chips are used to capture real-world wave signals such as those used in sound amplification, energy regulation, some sensors, and surveillance equipment. The most sophisticated category is logic chips, which process data and conduct computing functions, with applications in smartphones, AI and advanced computing, and the automotive industry. Logic chips are differentiated further based on performance, which is related to the distance between circuits, or nodes. Generally, chips below the 10-nanometer node threshold are considered advanced, with smaller nodes allowing for more transistors to be packed onto a chip to increase computational speed and power. Lin Jones et al., "U.S. Exposure to the Taiwanese Semiconductor Industry," *U.S. International Trade Commission*, November 2023, 5.

Legacy Semiconductors Underpin Wide Variety of Modern Technologies; Significant Risk of Overcapacity Glut from China—*Continued*

In some cases, mature node chips are used alongside leading-edge processors to power these technologies; in others, only "legacy" chips are needed.[129]

Currently, the legacy semiconductor supply chain is fairly diversified, but China already plays an important role in it. China accounted for 31 percent of global legacy chip production at the end of 2023, and in a few years it is projected to become the leading global producer of 200 mm to 300 mm semiconductors.[130] According to a May 2024 report by Rhodium Group, China not only has more capacity than any other country in analog, discrete, mixed-signal, and power chips, it is also expanding production capacity in those chips faster and at a larger scale than any other country.[131]

Legacy chips have also been an important source of technological power bolstering Russia's war against Ukraine. According to a June 2024 *New York Times* report, an expansive network of illicit exporters operating in China and several other countries has managed to ship an estimated $4 billion worth of restricted integrated circuits to Russia since its invasion of Ukraine. Many of these come from Chinese companies shipping via shell companies in Hong Kong, helping "China emerg[e] as the dominant chip supplier to Russia."[132] Despite not being suitable for advanced military technologies such as AI, legacy semiconductors have been found in a host of Russian weapons and are a critical dual-use technology for Russia's war efforts. (For more information on China's sales of integrated circuits to Russia, see Chapter 1, "U.S.-China Economic and Trade Relations (Year in Review).")

If past is prologue, once China's massive new semiconductor fabrication capacity comes online, China may flood the world with cheap legacy semiconductors, forcing prices down.[133] In turn, this could threaten the viability of other countries' legacy semiconductor industries and provide China significant global economic leverage.[134] According to Jimmy Goodrich, nonresident fellow at the University of California's Institute on Global Conflict and Cooperation, "Already, Chinese foundries are engaged in a price war with their domestic competitors that has spilled over to impact similar firms in Taiwan and South Korea."[135] This scenario echoes the first "China shock" and highlights rising concerns that China's economic model is premised on investing in excess capacity and relying on global markets to absorb the exports.[136]

China Seeks to Close the Gap with the United States in Total Compute Power

The rise in demand for AI has come with a corresponding need for greater compute power, as training models require a substantial amount of data and compute-intensive resources provided by

advanced semiconductors.*[137] In this context, compute power, computing power, or "compute" generally refers to national-level or company-level infrastructure, capabilities, and resources dedicated to computational power and data processing.[138] These may include the development and use of computing systems, data centers, cloud computing facilities, and networks that support high-end computational tasks.[139] The United States currently has a lead in compute power over China. Experts assess that one of the factors contributing to the status of U.S.-based companies—including OpenAI, Google, and Meta—as some of the dominant players in the global AI landscape is their preferential access to compute.[140] In particular, these three companies are building compute infrastructure using tens or even hundreds of thousands of advanced NVIDIA GPUs, including the cutting-edge GH100.[141] According to Paul Triolo, the senior vice president for China and technology policy lead at Albright Stonebridge Group, and Kendra Schaefer, a partner at Trivium China and nonresident fellow at the National Bureau of Asian Research, "Amassing so many advanced GPUs is largely out of reach for Chinese technology platforms and start-ups," and in contrast to their U.S. counterparts, many Chinese AI players struggle to find access to investment and compute.[142] The U.S. export controls on advanced semiconductors will help the United States maintain its compute power lead because such semiconductors allow for new systems with significantly faster and larger total compute loads necessary for the demands of AI. As such, U.S. export controls have complicated China's long-term capacity to keep up with the United States in compute.[143]

Chinese government efforts to expand national computing power networks and optimize resource efficiency are key to China's AI self-reliance drive, and Beijing has taken multiple policy actions in recent years to improve its computing capabilities. In 2021, China's National Development and Reform Commission announced plans to optimize and integrate computing resources across the country through the (still under construction) National Integrated Computing Power Network.†[144] Chinese government departments set a target in October 2023 to increase the country's aggregate computing power from 197 EFLOPs (a measure of computing speed equal to 1 quintillion floating-point operations per second) to 300 EFLOPs between 2023 and 2025, constituting a 50 percent increase.[145] MIIT claimed in October 2023 that China's compute power ranked second behind the United States, but it did not provide a number for its estimate of U.S. computing power.[146] In May 2024, China launched a three-year action plan to strengthen standards in cutting-edge

*Technologies like high bandwidth memory also allow for faster transfers of data within chips. China has also acknowledged that it lacks a fully indigenous high-bandwidth memory supply chain. Aside from two U.S.-sanctioned companies, China does not have any large-scale high-bandwidth memory producers. Boston Consulting Group, "The Race for Advanced AI Chips," April 17, 2024; Brocade, "The War for AI National Power: GPUs Are the Obvious Thread, but HBM Is the Hidden Thread" (AI国力战争:GPU是明线，HBM是暗线), *CSET Emerging Technology Observatory*, March 28, 2024. Translation.

†The National Integrated Computing Power Network is an integrated and optimized network of computing resources, such as data centers, that aims to boost China's overall computing power and broaden access to computing power nationwide for a variety of applications. For more, see "The EDWC and China's Data Center Buildout" textbox below. *Global Times*, "China Vows to Establish Integrated Computing Power Network, Boosting Digital Economy: NDB Chief," March 25, 2024.

technologies, including national computing power, which will in part focus on enhancing computing power infrastructure standards and strengthening basic standards for data resources.[147]

A critical aspect of compute is cloud computing. The United States leads on cloud computing, but China has made it a priority to catch up. Cloud computing allows computing power to be made available to a wider range of users remotely.* It is a "crucial behind-the-scenes engine of the digital economy… allowing companies to run artificial intelligence programs."[148] It is also a major driver of economic activity and technological innovation in both the United States and China. Domestically, the United States is the world's largest cloud market, with its public cloud market expected to exceed $430 billion in 2024.†[149] U.S. companies currently lead the global cloud computing market, with Amazon (32 percent), Microsoft (23 percent), and Google (12 percent) on their own making up a 67 percent global market share.[150]

Within China, Alibaba, Huawei, and Tencent control 72 percent of China's protected domestic cloud market.‡[151] China's cloud market is the world's second-largest market, with the Chinese government-backed think tank CAICT calculating China's 2023 domestic cloud market size at $85 billion and predicting it will reach $293 billion by 2027.[152] Currently, both Microsoft and Amazon AWS operate cloud services in China, with Microsoft offering services under a wholly owned subsidiary of local company 21Vianet and AWS China partnering with local companies Sinnet and NWCD to offer data center services.[153] An Amazon executive for Greater China reportedly stated in June 2024 that AWS "is committed to long-term investments in China, and will focus on offering generative artificial intelligence technology and helping Chinese enterprises in their digital transformation."[154]

In terms of international presence, China's cloud providers currently trail U.S. firms by a significant margin. China's big three cloud companies only make up roughly 8 percent of global cloud market share, led by Alibaba (4 percent global market share), Tencent (2 percent), and Huawei (2 percent).[155] Chinese companies are seeking to make significant inroads, however, in expanding cloud presence in developing and lower-income countries. Though Chinese companies do not publish their total data center figures, China's three largest cloud providers have listed their international (non-China) "availability zones": clusters of data centers offering cloud service. Between Huawei (33), Alibaba (28), and Tencent (22), China's cloud leaders operate 81 data center cluster "availability zones" outside of China.[156] Southeast Asia is currently where Alibaba (10) and Tencent (8) have the most availability zones, with Huawei's leading con-

*The National Institute of Standards and Technology defines cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Peter Mell and Tim Grance, "SP 800-145: The NIST Definition of Cloud Computing," *U.S. Department of Commerce National Institute of Standards and Technology*, September 2011.

†The term "public cloud" is an industry term generally defined as "computing services offered by third-party providers over the public Internet, making them available to anyone who wants to use or purchase them." Microsoft Azure, "What Is a Public Cloud?".

‡Alibaba controls 37 percent, Huawei controls 19 percent, and Tencent controls 16 percent of China's total domestic cloud market. Canalys, "Mainland China's Cloud Service Spend Grew by 20% in Q1 2024—Canalys," June 27, 2024.

centration of availability zones in Mexico and South America (12), followed closely by Southeast Asia (10).*[157] With Southeast Asia's cloud computing market predicted to hit $40.3 billion by 2025, U.S. and Chinese cloud firms are positioning to battle over market share throughout the region.[158] As Bridge Song, the VP of Alibaba Cloud Intelligence International, publicly stated September 2024, "The primary strategic market of Alibaba Cloud has always been Southeast Asia."[159] China tech analyst Kevin Xu pointed out in July 2023 that in this "battle," the data center buildout of Chinese companies at that time far outpaced U.S. cloud providers, with Amazon having data centers only in Indonesia and Malaysia; Google only offering data centers in Singapore and Indonesia; and Microsoft offering cloud services only in Singapore, with plans to build data centers in Indonesia and Malaysia.[160]

Data storage will be increasingly important as both the United States and China are set to produce more and more data. By 2025, China is predicted to generate more data than the United States, producing 48.6 zettabytes to an estimated 30.6 zettabytes for the United States.[161] Managing and storing this amount of data for both the United States and China will require an enormous amount of physical infrastructure and energy. China is seeking to address these challenges by simultaneously building out data storage and optimizing electrical infrastructure layout for data centers. (For more on this, please see the textbox on "The Eastern Data Western Computing (EDWC) and China's Data Center Buildout" later in this chapter.)

This growth coincides with a Party-state push that sees cloud as essential to China's national security, technological, and economic goals. Leading government organizations such as the State Council and MIIT have highlighted cloud adoption as a key component of strategic "five-year plans" involving the long-term direction of technology and the economy.†[162] Cloud is also crucial to state-led goals for increasing compute through infrastructure as a service (IaaS), with the construction of cloud facilities and data center nodes as the backbone of China's massive "Eastern Data Western Computing" (EDWC) project.[163] Besides the EDWC, China's state asset manager, the State-Owned Assets Supervision and Administration Commission of the State Council (SASAC), has launched a "national cloud" available for use by China's state-owned enterprises.[164] Finally, at the provincial level, companies like Alicloud have been partnering with key municipalities such as Hangzhou, Tianjin, and Shenzhen in efforts to strengthen their local cloud computing infrastructure for data exchanges that China sees as essential to its "new digital economy."‡[165]

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*Until recently, Alibaba also operated cloud data centers in Australia and India (two zones each for four zones total); however, as of 2024, these plants are planning to cease operation. Muhammad Zulhusni, "Alibaba Cloud Shutters Australian and Indian Data Centres, Contradicting Earlier Claims," *CloudTech*, July 2, 2024.

†China's tech firms are not the only players in its cloud computing market; as of July 2024, at least 16 local governments in China have offered companies coupons to access processing power at subsidized prices at large state-run data centers where scarce supplies of advanced chips have been pooled. Also, U.S. tech companies like Amazon and Microsoft continue to provide cloud services in China. Liza Lin, "China Puts Power of State behind AI—and Risks Strangling It," *Wall Street Journal*, July 16, 2024; *Reuters*, "List of Chinese Entities Who Have Turned to the Cloud for Access to Restricted US Tech," August 23, 2024.

‡China's data exchanges are state-supervised sites for the purchase, sale, or "exchange" of data across a wide variety of state and economic sectors. China sees them as critical for utilizing data as a "new factor of production" and strengthening its digital economy. Qiheng Chen, "China Wants

Eastern Data Western Computing (EDWC) and China's Data Center Buildout

China is reshaping a significant part of its domestic development program in order to create the infrastructure for the compute, data center capacity, and electrical power requirements necessary for advanced technologies such as AI. Current estimates indicate China's domestic data centers consume roughly 200 terawatt hours (TWh) of electricity now, set to grow to roughly 300 TWh by 2025 and 380 TWh by 2030.*[166] China's Ministry of Ecology and Environment has estimated that the share of national energy consumption by data centers will rise from 1.5–1.9 percent circa 2020 to over 5 percent by 2030.[167]

China has developed a plan to meet the growing demand for data center compute while potentially contributing to regional development needs. China's eastern regions, where current data centers are concentrated, already face high electricity prices and strained electrical grids.†[168] These problems in Eastern China contrast sharply to the situation of Western China, which has severely underdeveloped data center infrastructure but abundant and cheap energy as well as land.[169] (For more on China's energy needs and constraints, see Chapter 7, "China's New Measures for Control, Mobilization, and Resilience.")

To solve this imbalance of data center power needs and relative cost structures, China has spent the past several years implementing a grand realignment plan for its digital infrastructure: the Eastern Data Western Computing (EDWC) project. The EDWC envisions a massive buildout of data centers and cloud facilities in western provinces with abundant (green, low-carbon) energy resources, such as Inner Mongolia, Ningxia, and Guizhou.‡[170] Since being formally codified as national-level policy in 2021, the National Development Reform Commission issued a joint order along with numerous other government entities to accelerate the EDWC implementation and buildout.[171]

The EDWC also is intended to advance China's long-term goal of increasing the availability of computing power through a "nationally integrated computing power network," or NICPN, that is

to Put Data to Work as an Economic Resource—But How?" *Digichina*, February 9, 2022; Julia Lu, "China's Data Exchanges, Explained," *Technode*, August 17, 2021.

*A terrawatt hour is the amount of power generated by a 1-terawatt generator (or multiple lower-power generators equivalent to a 1-terawatt generator) for one hour. To put these terms on a human scale, 1 gigawatt is enough to power approximately 750,000 U.S. homes for one year. 1,000 Gigawatts = 1 Terrawatt. Zach Stein, "What Is a Terawatt Hour (TWh)?," *Carbon Collective*, October 1, 2024; Caleb Harding and Lily Ottinger, "Powering China's Data Centers: Batteries or Nukes?" *ChinaTalk*, September 12, 2024.

†Power consumption is a major concern for data center operators, with some academics placing power consumption at 70 percent of a data center's operational expenses. For a general sense of China's power consumption and generation at a national level, a useful comparison comes from Reuter's market analyst John Kemp: "Ten provincial-level areas in the east and south (Liaoning, Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong) accounted for 50% of national consumption but only 40% of generation in 2022. By contrast, six remote and sparsely populated northern and western areas (Inner Mongolia, Xinjiang, Shanxi, Shaanxi, Gansu and Ningxia) accounted for 18% of consumption but 25% of generation." Ning Zhang et al., "The 'Eastern Data and Western Computing' Initiative in China Contributes to Its Net-Zero Target," *Engineering*, August, 2024; John Kemp, "China's Rapid Renewables Rollout Hits Grid Limits," *Reuters*, July 4, 2024.

‡There are several translations of the project's name with slight variants. We have chosen to use "Eastern Data Western Computing," as it is one of the most widely reported translations.

Eastern Data Western Computing (EDWC) and China's Data Center Buildout—*Continued*

currently under construction.[172] The NICPN seeks to pool and allocate compute from the EDWC's interconnected data centers as well as existing data centers in order to boost China's overall computing power and increase the effectiveness of how it is allocated.[173] Newly appointed head of the National Data Administration (NDA) Liu Liehong cites the NICPN as crucial for meeting the computing power needs of advanced technologies like generative AI.[174]

As of June 2024, Liu Liehong announced that China's government had invested roughly $6.2 billion in the project, with additional funding of more than $28.4 billion from other sources, including the private sector.[175] Early analysis reveals the data centers' "primary operators" will be China's big three state-owned telecoms, with China Mobile investing $6.4 billion, China Telecom investing $4.9 billion, and China Unicom investing $3 billion.[176] China tech champions Huawei and Alibaba have also made major investments in the project, with estimated financing of $4.7 billion and $3 billion, respectively.[177]

While the EDWC program faces some challenges over demand, cost, and latency, China's government believes the EDWC and NICPN can boost China's capacity in data center technology, computing power, and the digital economy, particularly as energy demands from data centers for AI increase.[178] The United States is now making efforts to ensure that it maintains a strategic lead in compute by meeting with leading AI, AI GPU, and data center companies to discuss how the United States can rapidly build out its data center infrastructure and provide energy resources to meet the needs of these technologies.[179]

Access to compute via cloud computing complicates and internationalizes U.S.-China AI-related competition. Cloud computing can be an effective way to circumvent export controls on advanced chips, as it allows remote access to the computing power enabled by such chips.* Since the chips themselves are not exported in a cloud computing service, export controls are not necessarily implicated at all.[180] For example, Chinese companies targeted by U.S. sanctions have found workarounds to obtain access to restricted U.S. AI technology by using third-party cloud providers and rental arrangements.[181] iFlytek, a state-backed voice recognition company blacklisted by Washington in 2019, has been renting access to NVIDIA's A100 chips.[182] According to an investigative report by Reuters in August 2024, Chinese state-linked entities were accessing

*Remote access to compute power is also a potential issue for quantum computing. According to Edward Parker with RAND Corporation, "Many quantum computing companies do not sell hardware but instead operate under a cloud-access model whereby customers submit tasks remotely and the companies perform the actual computations in-house. Any export controls on quantum computing should clearly address the permissibility of selling computing services to foreign customers, even if no physical hardware ever leaves the United States." Edward Parker, written response to question for the record for U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024.

controlled NVIDIA chips for AI training via AWS and other cloud providers.[183] Also in August 2024, the *Wall Street Journal* reported on a company in Australia which, with the help of investors from Dubai and the United States, set up a cloud service powered by NVIDIA's advanced H100 chips at least in part to process AI algorithms for Chinese-based companies.[184] An executive at the company explained the decision to target China: "There is demand. There is profit. Naturally someone will provide the supply."[185]

The United States has begun to explore how to combat China's use of cloud computing for access to AI technologies, but solutions to date all have significant limitations. First, to prevent Chinese companies from simply setting up AI infrastructure outside of China and using it there (or making it available in China), existing export controls on advanced semiconductors apply to Chinese entities even when they are operating overseas.[186] Second, so-called "U.S. persons" authority would prevent U.S. cloud providers from knowingly providing services that contribute to certain specified national security risks, including helping Chinese entities obtain access to advanced semiconductor technology.*[187] Third, on an ad hoc basis, the U.S. government appears to be using various points of leverage to persuade domestic technology providers and their potential foreign partners that want access to the most advanced semiconductor technology to take measures to exclude Chinese entities.[188] Fourth, the United States has proposed "know your customer" rules and reporting requirements for domestic cloud providers when their services are used by foreign entities to train large AI models.[189] Each of these rules or proposals, however, has some limitations in scope, coverage, and/or comprehensiveness—for example, applying only to Chinese companies, only to U.S. companies, or only on an ad hoc basis.† There is currently no comprehensive authority akin to export controls for broadly restricting access to cloud services reliant on U.S. technology.

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*Originally, the "U.S persons" authority only applied to limit activities of U.S. persons that contribute to proliferation of weapons of mass destruction. ECRA expanded the coverage to include support for "foreign military intelligence services." Congress significantly expanded this authority again in 2022 to allow BIS to prohibit U.S. persons from knowingly providing support to adversarial foreign military services, intelligence services, and security services. In July 2024, BIS proposed a rule to implement the new authority that would significantly expand the scope of "U.S. persons" restrictions to cover a broad class of "foreign security end users." According to Gibson, Dunn, & Crutcher LLP, a multinational law firm, the breadth of the restrictions will likely necessitate the enhancement of company diligence efforts to better understand end users, with cloud service providers potentially needing to ensure that U.S. persons are not providing prohibited services or support for restricted parties. U.S. Department of Commerce Bureau of Industry and Security, "Export Administration Regulations: Crime Controls and Expansion/Update of U.S. Persons Controls," *Federal Register* 89:145 (July 29, 2024); Restrictions on Specific Activities of "U.S. Persons," 15 C.F.R. § 744.6, 2024; National Defense Authorization Act for 2023, Pub. L. No. 117-263, 2023; 50 U.S.C. § 4812(a)(2)(F); Gibson, Dunn, and Crutcher LLP, "Proposed Rules Call for Significant Restrictions on Facial Recognition Technologies, Defense Services, U.S. Persons Activities, and New Classes of Foreign End-Users," August 13, 2024; Export Control Reform Act (ECRA) §1741(2), Pub. L. No. 115-232, August 13, 2018, codified as amended at 50 U.S.C. §4801(2).

†The United States has used sanctions as a tool to limit certain types of technology-related transactions with an adversary, including the provision of certain cloud services. Specifically, in response to Russia's war of aggression against Ukraine, the U.S. Department of the Treasury's Office of Foreign Assets Control prohibited "U.S. persons" located anywhere in the world from exportation, reexportation, sale, or supply, directly or indirectly, of quantum computing services to any person located in Russia. This action prohibits U.S. cloud services companies from supporting Russia's quantum computing sector. Stefan H. Reisinger and Mikkaela Salamatin, "New US Sanctions and Export Restrictions on Russia and Belarus," *Norton Rose Fulbright*, September 2022; U.S. Department of the Treasury, Office of Foreign Assets Control, Determination Pursuant to Section 1(a)(ii) of Executive Order 14071: Prohibitions Related to Certain Quantum Computing Services, September 15, 2022.

CCP Control and Xi Jinping Thought May Constrain China's AI Models

China risks inhibiting its AI ambitions by its tight regulations on LLMs. Heavily censored datasets can lead to biases in AI models and limit their ability to handle certain tasks.[190] In April 2023, the Cyberspace Administration of China (CAC) unveiled its draft measures on generative AI services.[191] The CAC will require companies to go through a government security review process and make companies responsible for the content their AI services generate, such as prohibiting content the CCP views as politically sensitive, including arbitrary and broad definitions of subverting state power, inciting secession, or disrupting social order.[192] Additionally, the CAC requires companies to test whether the models can provide "safe" answers to users by preparing between 20,000 and 70,000 questions.[193] Companies must also submit a dataset of 5,000 to 10,000 questions the model will decline to answer, roughly half of which relate to political ideology and criticism of the Communist Party.[194] Xu Chenggang, a senior research scholar at the Stanford Center on China's Economy and Institutions, has asserted that China's strict censorship rules could inhibit the quality of data and the development of chatbots, stating that "if there are restrictions everywhere in the setup of your algorithms, of course its ability will be restricted."[195]

China is also developing a closed-source LLM based on Xi Jinping's political philosophy in a move that demonstrates the CCP's desire to experiment with centralized control over AI as a strategic asset. The machine learning language model was launched by the China Cyberspace Research Institute, which operates under the CAC.[196] Answers are sourced from a fixed pool of Chinese official documents and outlets.[197] The model is still undergoing internal testing and was not yet available for public use, but it is open to "designated users by invitation," according to the CAC.[198]

China Seeks to Create Advanced Generative AI Models to Outcompete the United States

The third element of AI competition is the quality of generative AI models. Generative AI models can transmit algorithms into text, images, audio, video, and code, enabling the creation of new content.[199] Although assessing AI models "is an art, not a science . . . making it difficult to compare Chinese models with global leaders," most experts believe the United States currently leads China in this space.[200] China's demonstrations of its generative AI models in early 2023 failed to outperform U.S. models like ChatGPT.[201] Baidu's ERNIE Bot launch, which relied on prerecorded examples rather than a live demonstration, was largely seen as a flop.[202] Erniebot and Alibaba's Tongyi Qianwen also both performed worse than ChatGPT in writing computer code.*[203] More than a dozen tech industry in-

*For example, Robin Li, Baidu's chief executive, admitted halfway through a "live" demonstration of Ernie that it was prerecorded. In June 2023, however, Baidu claimed that its Ernie 3.5 model outperformed OpenAI's ChatGPT and GPT-4 across numerous metrics, such as answering over 13,000 multiple-choice questions across 50 different subjects in Chinese more correctly. However, when the model took a separate test that was developed by a group of U.S. universities, the

siders and leading engineers interviewed by the *New York Times* in February 2024 said the generative AI capabilities of Chinese companies still lag behind those of U.S. companies by at least a year, with the article claiming that Chinese companies rely almost entirely on underlying systems from the United States.[204] In April 2024, Alibaba chairman Joe Tsai said that Chinese firms lag behind U.S. peers in AI development by at least two years.[205]

Chinese companies are making a concerted effort to develop generative AI models similar in sophistication to those of U.S. companies.[206] China's AI development landscape is diverse, with approximately 50 Chinese companies developing AI models as of June 2024, compared to the relatively small number of large companies in the United States that focus on developing models such as OpenAI, Google, and others.[207] As of late September 2023, China accounted for 40 percent of all LLMs in the world (while the United States has 50 percent), according to brokerage and investment group CLSA.[208] By June 2024, analysts asserted that by some metrics, Baidu's ERNIE Bot and Zhipu AI's GLM-4 had reached a similar level of quality as Open AI's GPT-4 model. Due to the evolution of leading-edge models and soon-to-be-released models like GPT-5, these analysts assert that benchmarking remains a moving target, which may also pose challenges for Chinese AI firms in developing metrics to assess their own capabilities.[209] Baidu's CEO Robin Li said in July 2024 that there are "too many" LLMs in China, which he says have resulted in a "significant waste of resources, particularly computing power"; he also questioned how many of these have provided real-world applications that are beneficial.[210]

The Open vs. Closed Debate and U.S.-China Competition

As the United States and China compete for technological leadership in AI, there have been concerns raised as to whether open source AI models may be providing Chinese companies access to advanced AI capabilities that would not otherwise be available, allowing them to catch up to the United States more quickly.

The debate surrounding the use of open source models and closed source models is a vigorous one within the industry, even apart from issues around China's access to the technology. Advocates of the open source approach argue that it promotes fast-

Ernie 3.5 model performed behind ChatGPT and GPT-4. Yasheng Huang, a professor of management at the Massachusetts Institute of Technology, said of China's efforts to build ChatGPT-level chatbots that "China is incredibly good at scaling an existing invention, but it is not very good at making breakthroughs." The Ernie bot has still become a popular option for generative AI use, as Baidu claimed in April 2024 that its platform has over 200 million users. Additionally, the Beijing Academy of Artificial Intelligence's WuDao 2.0, released in the summer of 2021, was touted by *Forbes* as a "bigger, stronger, faster AI" due to having ten times more parameters (the numbers inside an AI model that determine how it processes information) than GPT-3. However, AI experts Helen Toner, Jenny Xiao, and Jeffrey Ding assert that having more parameters "does not make one AI system better than another" if it is not matched with corresponding increases in data and computing power, and they also argue that the Chinese researchers who posed questions to the model helped boost its performance to appear stronger. Tracy Qu, "Baidu Says Ernie AI Chatbot Now Has 200 Million Users," *Wall Street Journal*, April 16, 2024; Arjun Kharpal, "China's Baidu Claims Its Ernie Bot Beats ChatGPT on Key Tests as A.I. Race Heats Up," *CNBC*, June 27, 2023; Helen Toner, Jenny Xiao, and Jeffrey Ding, "The Illusion of China's AI Prowess," *Foreign Affairs*, June 2, 2023; Cheyenne Dong, "Alibaba Rolls Out ChatGPT Alternative Tongyi Qianwen," *Technode*, April 10, 2023; Chang Che and John Liu, "China's Answer to ChatGPT Gets an Artificial Debut and Disappoints," *New York Times*, March 16, 2023; Alex Zhavoronkov, "Wu Dao 2.0 - Bigger, Stronger, Faster AI from China," *Forbes*, July 19, 2021.

The Open vs. Closed Debate and U.S.-China Competition—*Continued*

er innovation by allowing a wider range of users to customize it, build upon it, and integrate it with third-party software and hardware.[211] Open model advocates further argue that such models reduce market concentration; increase transparency to help evaluate bias, data quality, and security risks; and create more benefits for society by expanding access to the technology.[212] Advocates of the closed source approach argue that such models are better able to protect safety and prevent abuse, to ensure faster development cycles, and to help enterprises maintain an edge in commercializing their innovations.[213]

From the standpoint of U.S.-China technology competition, however, there is one key distinction: open models allow China and Chinese AI companies access to key U.S. AI technology and make it easier for Chinese companies to build on top of U.S. technology. In July 2024, OpenAI, a closed model, cut off China's access to its services.[214] This move would not have been possible with an open model; open models, by their nature, remain open to Chinese entities to use, explore, learn from, and build upon.[215] And, indeed, early gains in China's AI models have been built on the foundations of U.S. technology—as the *New York Times* reported in February 2024, "Even as [China] races to build generative A.I., Chinese companies are relying almost entirely on underlying [open model] systems from the United States."[216] In July 2024, at the World Artificial Intelligence Conference in Shanghai, Chinese entities unveiled AI models they claimed rivaled leading U.S. models.[217] At the event, "a dozen technologists and researchers at Chinese tech companies said open-source technologies were a key reason that China's A.I. development has advanced so quickly. They saw open-source A.I. as an opportunity for the country to take a lead."[218]

China Leverages Data for AI and Technological Supremacy

The U.S.-China competition in AI technology is dependent on who can procure and compile large-scale, high-quality datasets and create economic incentives and frameworks for sharing data. Access to proprietary data in different sectors can be an increasingly important source of competitive advantage because better results can be acquired by more relevant, real-world data that can be used to train the AI models, which has a net impact on the cycle and speed of innovation.[219] With the rising importance of data to governments, corporations, and next-generation technologies like generative AI and large models, data are quickly becoming the "new oil" that power AI and the global economy.[220]

The Importance of Data to China's Policymakers

Since Xi's 2012 appointment as China's President, Party leaders have swiftly identified data as a critical component for developing China's economic and technological capacity.[221] This was formalized as policy in the 2016 State Council National 13th Five-Year Plan

for the Development of Strategic Emerging Industries, which called for the construction of a "digital China" based upon the integration and leveraging of data, data technology, data standards, and data connectivity throughout China's economic and technological infrastructure.[222] The importance of data was further highlighted by Xi in subsequent Party speeches and study sessions, where he emphasized to policymakers that China must "build a digital economy with data as a key enabler" and "promote the deepened integration of Internet, big data, and artificial intelligence with the real economy."[223] Building off these policies and presidential directives, in 2020, China's State Council named data "factor[s] of production," codifying data—along with land, labor, capital, and technology—as crucial to China's economic development and requiring Party supervision to ensure economic development and avoid market distortions.*[224]

Efforts to Turn Data into a Factor of Production

Alongside Xi's directives and official policies mandating the importance of data, in March 2023, China established a new government administration: the National Data Administration (NDA).†[225] Since its formation, the NDA has been given economic portfolio responsibilities that were previously held by domestic and national security-minded government organs, chiefly the Cyberspace Administration of China.[226] So far, the economic mandate of the NDA has been to establish the economic value of data assets, increase data circulation throughout China, and develop data market ecosystems for key industrial fields such as smart manufacturing.[227] The NDA's newly appointed leader, Liu Liehong, has also made it a point of emphasis to meet with China's leading tech companies, such as iFlytek and Didi, to discuss how best to share, monetize, and ensure data property rights on the vast amounts of data they hold.[228]

China's data exchanges will be critical to the NDA's efforts to turn data into a factor of production. Broadly speaking, data exchanges are centralized markets for buying and selling data, data products, and data services.[229] China's first data exchange was set up in Guiyang in 2015; since that time, 48 data exchanges are now active in the country.[230] While in the United States these take the form of private third-party data brokers who aggregate public or private data for sale, China's data exchanges are state-managed by local governments, with the goal of building a cohesive national "data economy."‡ [231] Alongside data exchanges, China has also experimented with using its 21 free trade zones to facilitate companies that wish to export "cross-border data."[232] While still in the early stages, the development of China's data exchanges and free trade zones is part of a larger goal of constructing a "big data industry,"

*The term "factors of production" is generally seen as a key economic resource to be managed by the Party in order to avoid market distortions. Rebecca Arcesati, "China Activates Data in the National Interest," *Mercator Institute for China Studies*, July 4, 2022; Lillian Li, "Abridged: Data as a Factor of Production," *Chinese Characteristics: Substack*, November 4, 2021.

†The NDA sits under China's macroeconomic planner, the National Development and Reform Commission. Rebecca Arcesati and Jeroen Groenewegen-lau, "China's Data Management: Putting the Party-State in Charge," *Mercator Institute for China Studies*, 2023.

‡The United States and China have different models for data exchanges. Amba Kak and Samm Sacks, "Shifting Narratives and Emergent Trends in Data-Governance Policy," *Paul Tsai China Center, AI Now, New America*, August 2021; Julia Lu, "China's Data Exchanges, Explained," *Technode*, August 17, 2021.

promoting international digital trade, and developing China's digital economy.[233]

China's Authoritarian Practices May Provide an Edge in Certain Types of Data

China's efforts to create a national data economy has significant implications for both its leading technology firms and the development of AI itself. Experts have debated the general advantages that the United States and China have regarding data and how these advantages may affect their AI capabilities. According to Matt Sheehan, a fellow at the Carnegie Endowment for International Peace, in terms of quantity, China's advantage mainly lies in the fact that its leading tech companies have many more windows into a user's online and offline behaviors.[234] China also holds an advantage in terms of compiling data from public spaces, gathered from the country's vast public surveillance network, which has given China's facial recognition AI firms some advantages.[235] Prominent scholars have also raised concerns that China's "AI-Surveillance symbiosis" could lead to a "feedback loop" with data derived from surveillance leading to iterative improvements in AI innovation.[236] Furthermore, China's broad government collection of data could be used to enhance the datasets of Chinese firms across a variety of other important domains, including healthcare, education, and basic science.[237] The prevalence of Chinese companies in genomics, agricultural, and certain health-related biotechnology supply chains could provide a significant data advantage in generative AI models geared toward those technologies. (For more information on recent developments in China allowing local government entities to treat data as a financial asset, please see Chapter 1, "U.S.-China Economic and Trade Relations (Year in Review).")

U.S. companies and bureaucracies have a lead regarding the quality of data.[238] China has not invested as much in enterprise software or digitizing data, although this may change over time as Beijing is incentivizing localities to digitize records and adopt AI-powered analytical tools.[239] Regarding diversity of data, the United States holds a clear advantage because of its diverse domestic population and the global user base of many Silicon Valley companies.[240]

Other Aspects of AI Competition: Workforce and Research Output

China is attempting to advance its AI workforce in order to compete with the United States. China has developed AI talent partly because it invested heavily in AI education.*[241] China has created over 2,000 undergraduate-level AI programs at more than 300 of the country's most elite universities since 2018.[242] Data regarding global AI talent published by the think tank MacroPolo revealed that in 2022, 57 percent of "elite" AI researchers (i.e., the top 2 percent) worked in the United States as opposed to 12 percent in China, compared to 65 percent and less than 3

*CSET reported in February 2023 that collectively, at least $40.2 billion in announced investments into 251 Chinese AI companies involved U.S. investors, though it was not clear what exact portion of the $40.2 billion came from U.S. investors (e.g., an announcement may list multiple investors and a headline number, without breaking down the contribution of each). Emily S. Weinstein and Ngor Luong, "U.S. Outbound Investment into Chinese AI Companies," *Center for Security and Emerging Technology*, February 2023.

percent in 2019, respectively.[243] For "top-tier" talent (i.e., the top 20 percent), 42 percent worked in the United States in 2022 and 28 percent in China, compared to 59 percent and 11 percent in 2019.[244] According to a November 2023 report by CSET, 78 percent of China's AI-related job postings are geographically concentrated in three economically and technologically developed hubs with large population centers, including the Yangtze River Delta region, the Pearl River Delta, and the Beijing-Tianjin-Hebei area, while other provinces with relatively high demand for AI talent include Hubei, Shandong, and Hunan.[245]

Regarding AI research, the comparison between the United States and China depends on the metric chosen. China leads the United States based on sheer volume of research published—with 575,258 articles to the United States' 359,415 articles.[246] The Commission's *2023 Annual Report to Congress* examined at length, however, why publication volume is a flawed metric at best for measuring the progress of Chinese academia in advanced technologies like AI.[247] Plagiarism, error, and fraud have long plagued Chinese higher education, with China having the largest retraction rate globally of submitted research papers, exceeding 20 per 10,000 papers submitted.[248] The number of citations and number of international research collaborations may be better indicators of a country's progress in AI research. In these areas, the United States is still the global leader as of September 2024, with U.S. AI papers receiving 13,296,404 citations compared to China's 8,830,282 citations.[249] The United States also leads in global AI research collaboration with 132,672 articles published with international collaborators, though China is not far behind with 114,333 such articles.[250] A recent study also points to a large "diffusion deficit" between the United States and China in AI, with China struggling to adopt AI innovations at scale in academia and industry.[251]

China Engages on AI Safety Talks but Shuns Military AI Policy

Beijing has taken limited steps to engage with the United States on the issue of global AI risks and safety. In November 2023, Beijing attended the UK AI Safety Summit and agreed to share a common approach to identifying and mitigating AI risks with the EU, the United States, and 26 other countries.[252] The same month, President Joe Biden and General Secretary Xi met and agreed to hold talks regarding the risks of advanced AI systems and efforts to improve AI safety.[253] In March 2024, Beijing supported a U.S.-led, nonbinding UN resolution on the protection of data and monitoring of AI risks.[254] Chinese and U.S. officials also met behind closed doors in Geneva in May 2024 to discuss how each side views AI risks and safety.[255]

Despite its surface-level engagement in AI safety talks, China has shown little willingness to make firm commitments on limiting the military applications of AI. In December 2021, China submitted a position paper to the UN calling on all countries to refrain from using AI to "seek absolute military advantage" or "pursue hegemony," but it did not rule out its use for "legitimate

China Engages on AI Safety Talks but Shuns Military AI Policy—*Continued*

national defense capabilities."[256] This caveat regarding the use of AI for "legitimate national defense capabilities" could suggest Beijing envisions using AI-enabled weapons and processes in military operations to defend what it regards as its "core interests," including the forcible unification of Taiwan.[257] China did not support a U.S.-led declaration on the responsible military use of AI during November 2023.[258] Chinese officials did not publicly respond to a statement made by Principal Deputy Assistant Secretary of State Paul Dean in May 2024 that the United States welcomed a clear and strong commitment from both China and Russia to ensure that only humans, not AI, would control nuclear weapons.[259]

China Pursues AI for Military Applications

AI will serve as a core part of China's future military strategy, underpinning the PLA's efforts to exploit vulnerabilities in the technology systems the United States deploys on the battlefield and to make operational decisions more quickly than U.S. warfighters.[260] (For more on the PLA's approach to informationized warfare, see Chapter 8, "China's Evolving Counter-Intervention Capabilities and the Role of Indo-Pacific Allies.") Procurement records and writings by Chinese military experts in recent years suggest the People's Liberation Army (PLA) is already procuring AI systems for integration into its weapons platforms and capabilities.[261] One report by CSET comparing U.S. and Chinese military procurement of AI systems found that both militaries are focusing on similar applications, with most contracts being awarded for autonomous vehicles and intelligence, surveillance, and reconnaissance (ISR).[262] Of the almost 2,000 military contracts awarded by the PLA between April and November 2020, 119 contracts appeared to be directly related to AI, the majority of which were related to AI-enabled autonomous vehicles (38 percent), followed by ISR systems (17 percent), predictive maintenance and logistics systems (16 percent), information and electronic warfare (7 percent), simulation and training (4 percent), automatic target recognition (4 percent), and command and control (4 percent).*[263] This analysis reflects only a dated snapshot of unclassified procurement and precedes the significant increase in awareness around AI since the public release of ChatGPT—so it should be treated accordingly.[264] In any event, it is clear China is actively pursuing AI for military applications to enhance its capabilities, complement its current approach to informationized warfare, and facilitate the PLA's longstanding efforts to leapfrog the United States militarily and shift the global balance of power.[265]

*CSET categorized the remaining 10 percent of contracts as "other." Margarita Konaev et al., "U.S. and Chinese Military AI Purchases: An Assessment of Military Procurement Data between April and November 2020," *Center for Security and Emerging Technology*, August 2023, 8.

AI as the Eyes and Ears of the PLA

AI-enabled ISR systems appear to be a priority for the PLA.[266] The PLA sees value in leveraging AI capabilities for ISR to help speed up the processing of imagery, signals, and other kinds of intelligence across the land, air, sea, and space domains.[267] PLA experts have recognized that ISR improved by AI can be useful in detecting the movements of an adversary's conventional military assets as well as tracking its submarine and land-based nuclear forces.[268] China's incorporation of effective AI into its ISR capabilities could allow the PLA to rapidly locate U.S. military forces during a conflict over Taiwan or the South China Sea and help it combine joint forces across domains to launch precision strikes.[269]

According to the CSET report, most of the PLA's known contracts for AI-enabled ISR are awarded by the PLA Navy, and many focus on geospatial imagery tasks such as equipping satellites with image collection, polarized surface detection, and multi-source data fusion tools powered by machine learning.[270] A December 2023 article in Chinese state media provided one example of a platform that may integrate AI into ISR, noting that the Aviation Industry Corporation of China planned to incorporate AI into the Wing Loong unmanned aerial vehicle platform to improve the drone's ability to perform tasks like topographic mapping, among other things.[271] Other PLA contracts appear to focus on incorporating AI into air defense. For example, the Hebei Xintu Technology Company was awarded a contract by the PLA for a "drone aircraft detector" to be used in air defense.[272]

AI in Battlefield Decision-Making

Beijing is researching how AI can be utilized in decision-making to enhance wargaming and command and control. At least based on the relatively small percentage of procurements reflected in CSET's data snapshot, the PLA does not appear to be prioritizing these uses as much as other applications.*[273] Chinese experts note that AI can shorten the "observe-orient-decide-act"† loop, raise situational awareness, and assist PLA commanders in formulating judgments, planning missions, and controlling operations within increasingly complex warfare environments.[274] These include:

- *Reluctance to cede political control over military decision-making:* The Central Military Commission exercises the Party's political control over all military affairs and has historically maintained a tight grip on the use of the PLA's strategic as-

*As noted, this was a limited study, based on a 2020 subset of 119 PLA contracts for AI systems. The study found that only 4 percent of these contracts were related to battlefield decision-making systems and that China awarded just five contracts for command and control application systems between April and November 2020. It is not clear if the short "snapshot" reflects overall PLA priorities and spending patterns. Margarita Konaev et al., "U.S. and Chinese Military AI Purchases: An Assessment of Military Procurement Data between April and November 2020," *Center for Security and Emerging Technology*, August 2023, 14; Ryan Fedasiuk, Jennifer Melot, and Ben Murphy, "Harnessed Lightning: How the Chinese Military Is Adopting Artificial Intelligence," *Center for Security and Emerging Technology*, October 2021, 24–26.

†The observe-orient-decide-act (OODA) loop is a decision-making concept developed by U.S. Air Force Colonel John Boyd. The concept is designed to provide a disciplined means of thinking about events that are unfolding before military decision-makers. The concept is intended to help the military gain a decisive advantage in the decision-making process by dealing with situations in a more expedited fashion. Kimberly Wright, "OODA Loop Makes Its Mark on Maxwell," *Air University Public Affairs*, August 25, 2010.

sets, such as nuclear weapons and cyber capabilities.[275] While advances in AI will give Chinese leaders new technologies to assist decision-making, Chinese officials may be reticent to defer to AI-generated recommendations for military decision-making. Yang Zi, a PhD candidate at the S. Rajaratnam School of International Studies, argues that Xi's personal preferences are still likely to overshadow AI-generated recommendations and that such a dynamic could handicap the PLA's AI-enabled decision-making in a crisis scenario.[276] Tong Zhao, a senior fellow in the nuclear policy program at Carnegie China, has observed that China's policy community also supports keeping humans "in the loop" and limiting the use of AI in nuclear weapon systems for safety reasons.[277]

- *Concerns that limited data training and visibility into AI algorithms could distort military decision-making:* One challenge for the PLA going forward will be training AI algorithms to account for complex battlefield scenarios, in part because the PLA lacks data from real wars.[278] Without adequate data based on actual combat scenarios gained while fighting an adversary, AI models could potentially provide false assessments or erroneous recommendations to military officials.[279] In order to maximize performance, the PLA will also need to train its AI algorithms to analyze variables in realistic natural environments, such as the weather or atmospheric conditions, and in artificial environments, like defensive networks or battle lines.[280] The PLA likely recognizes the problems associated with this data deficit, but it is unclear what steps it is taking to rectify it. For example, it is not clear if China and Russia are using Russia's war of aggression in Ukraine as a data source.
- *Concerns that AI-enabled decision-making could exacerbate risks in conflict with the United States:* Experts from both the United States and China have recognized that the integration of AI into military decision-making systems could accelerate a crisis by facilitating hasty decision-making.[281] Furthermore, experts from both countries have assessed that the adversary may deliberately "poison" the data used by the other side, which may degrade the performance and judgments of their AI systems.[282] These concerns may make Chinese leaders more reticent to rely on AI to make high-stakes military judgments.

AI to Enhance Combat Performance and Lethality

The PLA is exploring the use of AI to enable autonomous systems for battlefield support and to increase the lethality of military units by carrying out warfighting tasks traditionally conducted by humans.[283] China is researching and developing AI technologies that seek to enhance the target recognition and coordination of lethal autonomous weapons, which are weapons systems that use sensor suites and computer algorithms to identify targets and subsequently engage and destroy the target without manual human control.[284] Lethal autonomous weapons systems are not yet in widespread development, but they could someday enable military operations in communications-degraded or -denied environments where traditional systems may not be able to operate.[285] Platforms that

are classified as lethal autonomous weapons systems include missile defense systems, sentry systems, and loitering munitions.[286] AI systems performing automatic target recognition made up only 4 percent of PLA contracts in the limited CSET snapshot of public contracts examined, but there are early signs that Chinese defense manufacturers are designing systems that could someday actualize the lethal autonomous weapons concept.*[287] For example, one Chinese manufacturer of intelligent unmanned aerial systems known as Zhuhai Ziyan UAS has produced the Blowfish A2, an unmanned helicopter equipped with guns, bombs, radar technology, and jamming devices.[288] The Blowfish A2 reportedly uses an AI module to automatically identify multiple targets such as ships, vehicles, and personnel to assist PLA combat units in carrying out attacks and reconnaissance missions.[289]

AI in Disinformation and Cognitive Warfare Operations

A major area of U.S.-China competition within AI is large language models, or LLMs,† which China could deploy against the United States in cognitive warfare operations.‡[290] China has engaged in online influence operations against the United States for years and appeared to escalate large-scale online influence operations on U.S.-based social media platforms since 2019, when Meta and X (formerly known as Twitter) first attributed inauthentic accounts originating from China.§[291] Nathan Beauchamp-Mustafaga, a senior policy researcher at the RAND Corporation, testified before the Commission that AI could significantly enhance China's existing cyber-enabled influence operations.[292] Mr. Beauchamp-Mustafaga argued that generative AI could dramatically improve the authenticity, cost effectiveness, and scale of state-sponsored influence oper-

*An automatic target recognition system is not necessarily a lethal autonomous weapon system, as human intervention could still be a necessary step in the decision to use lethal force against the recognized target.

†LLMs are mathematical representations of patterns found in natural language that can create text, answer questions, and hold conversations by making inferences about subsequent words in sentences. LLMs power generative AI tools such as OpenAI's ChatGPT and Google's Bard. Generative AI refers to algorithms that can be used to create new content, including audio, images, text, simulations, and videos. McKinsey and Company, "What Is Generative AI?" *McKinsey and Company*, April 2, 2024; Katrina Manson, "The US Military Is Taking Generative AI Out for a Spin," *Bloomberg*, July 5, 2023; William Marcellino et al., "The Rise of Generative AI and the Coming Era of Social Media Manipulation 3.0: Next-Generation Chinese Astroturfing and Coping with Ubiquitous AI," *RAND Corporation*, 2023, 5–6.

‡Cognitive warfare consists of influencing international public opinion, shocking and demoralizing enemy soldiers and citizens through psychological operations, and conducting influence campaigns to shape international law in Beijing's favor. LLMs and text-to-image models are also well suited to social media manipulation due to their ability to produce convincing text and images—with little effort by the user—that can then be disseminated online. William Marcellino et al., "The Rise of Generative AI and the Coming Era of Social Media Manipulation 3.0: Next-Generation Chinese Astroturfing and Coping with Ubiquitous AI," *RAND Corporation*, 2023, 7; Koichiro Takagi, "The Future of China's Cognitive Warfare: Lessons from the War in Ukraine," *War on the Rocks*, July 22, 2022.

§For example, in March 2020, China-linked accounts disseminated false warnings about a nationwide COVID-19 lockdown to allegedly incite public panic within the United States and decrease trust with the U.S. government. A September 2023 report by the U.S. Department of State's Global Engagement Center noted that aside from narratives on COVID-19, China has also carried out disinformation campaigns about the AUKUS partnership as well as echoing Russia's false accusations that the United States is escalating the war in Ukraine. U.S. Department of State, *How the People's Republic of China Seeks to Reshape the Global Information Environment*, September 28, 2023, 26, 38; Edward Wong, Matthew Rosenberg, and Julian E. Barnes, "Chinese Agents Helped Spread Messages That Sowed Virus Panic in U.S., Officials Say," *New York Times*, January 5, 2021; Sarah Cook, "Welcome to the New Era of Chinese Government Disinformation," *Diplomat*, May 11, 2020.

ations by malign actors while reducing human labor requirements and the probability of detection.[293]

Similarly, reporting by Microsoft has established that an actor affiliated with China's domestic security services has used AI to spread disinformation in democracies such as the United States and Taiwan.[294] In April 2024, Microsoft reported that the CCP-linked actor Storm-1376 (also known as "Dragonbridge" or "Spamouflage") has used AI-generated content to conduct influence operations spanning 175 websites and 58 languages.[295] Storm-1376 was reportedly responsible for spreading conspiratorial narratives on multiple social media platforms, alleging that the U.S. government had deliberately initiated the wildfires on the northwest coast of Maui, Hawaii.[296] Storm-1376 also targeted Taiwan's 2024 presidential and legislative elections, attempting to undermine the legitimacy of multiple candidates, including now president William Lai, in what Microsoft claimed was the first time AI had been used to influence a foreign election.*[297] (For more information on China's attempts to influence Taiwan's elections, see Chapter 9, "Taiwan.")

In their writings, PLA researchers have shown interest in using generative AI for future cognitive warfare operations.[298] In 2020, for example, two PLA researchers argued in the *China Military Science* journal that deepfakes using AI are cheap and easy to create and require less time than other methods, asserting that improvements in machine learning will lead to their prevalence.[299] There is also evidence that PLA-affiliated researchers at Base 311, a Chinese military unit headquartered in Fuzhou Province that conducts cognitive warfare, have explored how the Chinese military can use AI to automatically generate authentic-looking content.[300]

China Developing Humanoid and Quadruped Robots

One of the areas AI is helping revolutionize is robotics. AI is helping accelerate the development of humanoid and quadruped robots, both in their ability to respond to human commands and in their capacity for fine and gross movement for expanded versatility.[301] For instance, China's state media has said that the application of LLMs can make humanoid robots more capable of possessing decision-making capabilities, although the connection between the robot's "brain" and its "limbs" is still awaiting new technological breakthroughs.[302] China's MIIT announced in October 2023 that the country would establish a world-class humanoid robot innovation system by 2025 and deploy humanoid robots in "real economy" industries such as manufacturing, build an in-

*In December 2023, Storm-1376 also promoted a series of AI-generated memes of Taiwan's then Democratic Progressive Party candidate William Lai with a countdown theme noting "X days" to take the Democratic Progressive Party out of power, as well as an AI-generated video of a woman claiming to "reveal" Mr. Lai's mistresses and illegitimate children and an AI-generated audio file claiming Mr. Lai was an informant in the 1980s. On election day in January, Storm-1376 posted suspected AI-generated audio clips of Foxconn owner Terry Gou, an independent candidate in the presidential race. The audio manipulated Mr. Gou's voice to make it sound as though he was endorsing another candidate in the presidential race, even though he never formally endorsed any presidential candidate in the race. During the same month, Storm-1376 also created and amplified a defamatory video series about then President Tsai Ing-wen using AI-generated news anchors and ByteDance's CapCut video editing app. Microsoft Threat Intelligence, "Same Targets, New Playbooks: East Asia Threat Actors Employ Unique Methods," April 2024, 6–8.

China Developing Humanoid and Quadruped Robots—*Continued*

ternationally competitive industrial industry, and expand the use of humanoid robots throughout society by 2027.[303]

The realistic timing for the wide-scale availability of fully functional humanoid and quadruped robots within China is not clear. Humanoid robot firms globally face technical obstacles, including the limited storage capacity of batteries that power the robots and the current technical limitations of components like actuators that allow the robot to move itself and manipulate other objects.[304] Far more progress is needed before humanoid robots will be able to reason through an unexpected situation and then act on it.[305] While China's capacity to achieve its goals in the stated time frames may be doubtful, if their overall efforts are successful, humanoid robots could have transformative implications across commercial industries, including manufacturing, agriculture, and healthcare and potentially for military and law enforcement as well.[306]

When sufficiently advanced, these rapidly developing humanoid robot technologies have serious implications for China's military capabilities. China's policy of military-civil fusion, which leverages commercial technologies for the advancement of China's military, blurs the boundaries of what would constitute a commercial or military product.[307] Chinese military analysts have put forth new theories of human-robot cooperation if the technology advances, such as replacing front-line soldiers with humanoid robots while humans maintain control of command and decision-making.[308] Chinese state media outlets claim that humanoid robots will change the organization and use of combat forces, since they can theoretically be mixed with humans and grouped separately according to combat missions and objectives; they can also be used for logistical support such as carrying equipment, for heavy construction tasks, or for planting and removing mines.*[309]

One example of military applications emerged in May 2024 during China's Golden Dragon-2024 joint military exercise with Cambodia, when the PLA unveiled a modified version of a quadruped robot "dog," the B1, made by Chinese robot maker Unitree.†[310] Equipped with a mounted assault rifle on its back, the quadruped can jump as well as follow and lead an infantry team.[311] One PLA soldier told Chinese state media that the quadruped robot could engage a target upon discovery, asserting that the technology will serve as a "new team member for our urban

*Former PLA officer and military commentator Fu Qianshao wrote in an online commentary in April 2024 that humanoid robots could aid the PLA in an invasion of Taiwan by replacing actual troops on the battlefield, which would reduce the risk of human casualties. Fu Qianshao, "The Rise of China's Humanoid Robot Industry Will Replace the People's Liberation Army in Performing Tasks, Making the Reunification Easier," (中国人形机器人产业崛起，代替解放军执行任务，让统一大业更), *Gaze into the Sky [NetEase Blog]*, April 15, 2024. Translation. *https://web.archive.org/web/20240430181509/https:/www.163.com/dy/article/IVQR04OO0535T18G.html*.

†According to Unitree's company website, a commercial version of the B1, which can be used for inspecting power plants, is equipped with AI capabilities that enable it to avoid collisions in real time, control switches, press buttons, and carry out other tasks. Unitree, "Recognition Devices + AI Algorithm Bring Unitree Power Robotic Inspectors to the Posts." *https://web.archive.org/web/20240601021926/https://shop.unitree.com/blogs/news/recognition-devices-ai-algorithm-bring-unitree-power-robotic-inspectors-to-the-posts.*

China Developing Humanoid and Quadruped Robots—*Continued*

attack and defense operations."[312] Unitree has claimed that it does not sell its products to the PLA, but the use of its product in a formal military exercise underscores the ease with which the PLA can potentially acquire products from civilian companies.[313]

In the future, China's demographic decline could lead to humanoid robots as replacements for an aging, shrinking workforce.[314] In the present, Chinese researchers are also exploring the use of humanoid robots for economic and commercial purposes. Humanoid robots in China are undergoing limited deployment in various sectors but are primarily being used for research, and reports indicate humanoid robot firms are not generating commercial sales yet.[315] However, rapidly declining costs of producing humanoid robots could allow for more widespread adoption.[316] A Goldman Sachs report from February 2024 estimates that the humanoid robot market could reach $38 billion by 2035, with 1.4 million units shipped, primarily for industrial settings.[317] The Goldman Sachs report also notes that the viability of "mass-produced, general-purpose humanoid robots… hasn't been proven yet."[318]

Quantum Information Science: The Next Frontier of U.S.-China Technology Competition

Quantum information science (QIS)* may eventually become a paradigm-shifting technology enabling computation and sensing at a speed and scale heretofore impossible. Quantum technology will enable a significant performance boost in processing that will potentially help solve complex problems more efficiently. Advancements in quantum technology could potentially revolutionize global supply chains by refining production processes, streamlining logistics, and optimizing resource allocation.[319] QIS also has significant military and national security implications. QIS can enable a state to decrypt an adversary's communications, improve the ability to locate and track an adversary's military assets, and process battlefield data faster than an opponent.[320] Arthur Herman, a senior fellow and director of the Quantum Alliance Initiative at the Hudson Institute, asserts that "the nation that enjoys quantum supremacy, will dominate the future of the global system," as the technology will offer significant advantages for business and national security.[321]

QIS can be grouped into three primary categories, each of which can be used for military and civilian-commercial applications: communications, sensing, and computing.[322] Quantum communications uses qubits, or photons of light that transmit data along optical cables, making communications extremely secure against eavesdropping and interception.[323]

*According to the Pacific Northwest National Laboratory, QIS seeks to understand how information is processed and transmitted using quantum principles, merging quantum mechanics, and information/computation theory. Quantum computers process information in the form of qubits, which may occupy intermediate values rather than using bits with a 1 or 0 value (like classical computers). Qubits operate cooperatively through quantum entanglement, which multiply interactions over billions of switches to create a powerful computer that can tackle computational challenges that classical computers cannot. Pacific Northwest National Laboratory, "What Is Quantum Information Science?"

Quantum sensing technologies analyze data at the atomic level, making them significantly more sensitive and accurate compared to conventional sensors.[324] In military applications, quantum sensing is used to help enhance imaging, radar, sub-surface sensing, and navigation capabilities (including in GPS-denied environments).[325]

Lastly, where a classical computer can solve a problem with multiple variables along a single path, quantum computers can explore multiple paths in parallel to scale their operations exponentially.[326] Quantum computing could enable countries to break through encryption methods used by adversarial governments and militaries, improve military logistics, enhance modeling and simulation, and rapidly increase the pace of scientific research.[327]

Experts differ on the likely timeframe over which the potential of QIS can be realized, and it varies across the three categories. While the field of quantum mechanics has been studied for over a century, applications in advanced technologies have entered or approached practical development only in recent years.*[328] Some experts assert that we are on the cusp of a new revolution in quantum technology, as experimental concepts are being actualized into technological breakthroughs.[329] The U.S. Defense Science Board has estimated that quantum sensing technology, which is generally considered by experts to be the closest to useful deployment, will have "operational utility" in the 2024 to 2029 timeframe.[330] In a response to a question for the record before the Commission, Edward Parker, physical scientist with the RAND Corporation, agreed with this assessment, stating that broadly speaking, quantum sensing is the most technically mature of the three subfields of QIS.[331] Dr. Parker noted that within quantum computing, technical approaches based on superconducting, trapped-ion, or neutral-atom qubits are more advanced than quantum computers based on photonic, silicon-spin, or topological qubits.[332] Furthermore, Dr. Parker stated that the highest-impact applications of quantum computing, such as decryption, are unlikely to arrive prior to 2030.[333] Boston Consulting Group reports that between 2025 and 2030, new quantum communications technologies will be adopted by private companies, and a growing number of quantum random number generator chips will become more prevalent in Internet of Things (IoT) infrastructure, while new quantum communications repeaters, memories, and error-correction algorithms will be adopted from 2030 onward.[334]

Because of its potential importance, both the United States and China are investing heavily into QIS and are the two leading countries by most relevant metrics.[335] In October 2020, Xi himself emphasized the importance of quantum technology, telling the CCP's Central Committee that the development of quantum science and technology "is of great scientific significance and strategic value" and that it is a "major disruptive technological innovation."[336] More recently, in August 2024, the United States said that QIS "holds the potential to drive innovations across the American economy, from

*Dr. Parker asserts that broadly speaking, the field of quantum technology "is still very nascent," with atomic clocks being the only quantum technology publicly known to be deployed by any nation's military. Edward Parker, written testimony for U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024, 4.

fields as diverse as materials science and pharmaceuticals to finance and energy."[337]

The United States and China are competing heavily to outpace each other in QIS research.[338] China's quantum R&D is largely carried out in Hefei, Anhui Province, at state-funded laboratories, with additional support from several startups.[339] The Hefei National Laboratory for Physical Sciences at the Microscale (HFNL), affiliated with the University of Science and Technology of China, received $1.06 billion in laboratory funding in 2017, according to Chinese media reporting, with an additional (although not confirmed) funding package of $2.95 billion per year planned between 2017 and 2022.[340] Assuming this funding was provided as described, the figure for this single laboratory far exceeds the estimated annual R&D spending on quantum research for the entire country, listed in the 13th Five-Year Plan (2016–2020) at approximately $84 million, illustrating its importance as the center for China's development of quantum technologies.[341] In addition to this state laboratory, Hefei is also home to three of the eight major quantum startups in China, including Ciqtek, Origin Quantum, and QuantumCtek.*[342] Outside of Hefei, other major quantum startups include Kunfeng, Qasky, QuDoor, Shenzhou Quantum Communication Technology, and SpinQ.[343] Although other large Chinese technology companies—including Alibaba, Baidu, Huawei, Tencent, and ZTE—had invested in quantum technology R&D, Dr. Parker notes they appear to have reduced their investment in the field, with both Baidu and Alibaba closing their quantum research labs since November 2023.†[344]

The U.S. government is a primary funder of open QIS research domestically, growing significantly every year since the 2018 National Quantum Initiative.‡[345] The National Quantum Initiative Act authorized eight initiatives in QIS for sustained multiyear

*Dr. Parker et al. assert that the largest difference between Chinese startups and their U.S. counterparts is that the Chinese companies have announced far less capital funding, with only $44 million in publicly identified capital for Chinese quantum startups compared to $1.28 billion for U.S. startups. Edward Parker et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," *RAND Corporation*, February 2, 2022, 84.

†According to Dr. Parker, several of the large Chinese companies, such as Baidu and Tencent, had shut down their quantum computing efforts. He noted that Baidu announced it was selling all of its quantum computing hardware to a national lab, assessing that the concentration to national labs appeared to be consolidating even more in the six months prior to February 2024. Although Dr. Parker said he did not have great visibility into why Baidu made this decision, he speculated that the company assessed it would not be technically competitive in this field, as they were "far behind U.S. companies, did not seem to be catching up, and did not see it as a revenue generator." Dr. Parker argues that when discussing China as a whole, the country appeared to be doubling down on national laboratories, as none of the Chinese quantum technology companies seemed to be globally competitive. In Baidu's 2023 annual report to the U.S. Securities and Exchange Commission, the company acknowledges the impact of the Biden Administration's August 2023 executive order directing the Treasury Department to create an outbound foreign direct investment review program that will require reporting on (or in more narrow circumstances prohibit) investments by U.S. persons involving "covered national security technologies and products," including quantum information technologies, as well as the Treasury Department's Advanced Notice of Proposed Rulemaking. Baidu claims that "uncertainties on whether the outbound foreign direct investment review program will have a material impact on our business, results of operations, financial condition, and prospects." U.S. Securities and Exchange Commission, *Form 20-F*, March 15, 2024. 45–46; Edward Parker, oral testimony for U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024, 167.

‡The National Quantum Initiative is authorized through 2029, but certain programs within it had specific authorized appropriations levels only through FY 2023. National Quantum Initiative Advisory Committee, "Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science," June 1, 2023.

funding, such as the National Science Foundation-led Institute for Hybrid Quantum Architectures and Networks and the Department of Energy's Co-design Center for Quantum Advantage.[346] The U.S. government provided actual budget expenditures for QIS R&D of $449 million in fiscal year (FY) 2019, $672 million in FY 2020, $855 million in FY 2021, and $1.03 billion in FY 2022, followed by $932 million of enacted budget authority for FY 2023 and a requested budget authority of $968 million for FY 2024.[347] Some of these expenditures have resulted in additional government support at the state level. For example, the U.S. Department of Commerce's Economic Development Administration announced $41 million in funding on July 2, 2024, for Elevate Quantum ("Elevate"), a private-public consortium seeking to advance quantum research in the Mountain West, which unlocked $77 million in funding for Elevate from Colorado and $10 million from New Mexico.[348] The United States also has a strong private industry in QIS with at least 182 firms, a majority of which (139 companies) are part of Quantum Economic Development Consortium (QED-C), established by the National Quantum Initiative.[349] As of 2021, 55 of these QED-C companies focus on computing, 20 focus on sensing, 12 focus on communications, and 40 deal with cross-cutting sectors of QIS.[350] The venture capital (VC) industry has been a significant source of funding for quantum in the United States, with sources indicating over $2.5 billion invested through 2022, though perhaps echoing the private sector investment decline in China, 2023 saw a significant decline of 80 percent in VC funding for quantum computing in the United States.[351]

Overall, Dr. Parker assesses that China's progress across the three main subdomains of QIS has made the country "impressively fast followers across many quantum technology areas" and that some experts regard China as the world leader in quantum communications.[352] A 2022 research report by Dr. Parker et al. comparing the quantum industrial bases of China and the United States found that the United States is the overall top producer of high-impact* scientific publications in QIS, most notably in the fields of quantum computing and sensing.[353] By contrast, China leads in high-impact quantum communications research.[354] In terms of institutional research capacity, as of 2020, China actually had a greater number of institutions working on quantum research across the three primary subdomains of QIS than did the United States, though the qualitative edge this may provide remains unclear (see Table 1).[355]

*RAND Corporation defines "high-impact" by the number of academic citations a publication receives. The authors of the report argue that "if a nation is a global leader in developing new quantum technologies, then its research activity will strongly impact the rest of the world's R&D as well." The report notes that a "widely accepted metric of research impact" is the number of citations a publication receives. Edward Parker et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," *RAND Corporation*, February 2, 2022, 19.

Table 1: Number of U.S. and Chinese QIS Publishing Research Institutions

	United States			China		
Metric	***# of Labs****	***% of Pubs**†*	***H-index**‡*	***# of Labs***	***% of Pubs***	***H-Index***
Computing	1,236	21.5	104	1,592	22.4	61
Communications	581	12.2	39	1,288	38.6	51
Sensing	376	15.3	67	535	26.1	59

Note: The covered time period for the number of labs working on quantum technology is 2011–2020, while the percentage of publications and H-index scores cover 2019–2023.

Source: Edward Parker et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," *RAND Corporation*, February 2, 2022, 34, 74; Jamie Gaida, Jenny Wong-Leung, and Stephan Robin, "Critical Technology Tracker," *Australian Strategic Policy Institute*, 2023.

However, these U.S. and Chinese leads in particular quantum areas may change, given the long timelines for implementation.

Below is a brief discussion of some areas of apparent progress in China on QIS. There may be a basis for skepticism regarding some of the claimed breakthroughs announced by Chinese researchers; when these have been questioned by U.S. scientists and experts, it is noted.[356]

- ***Potential progress in computing:*** Recent developments illustrate China's potential progress in quantum computing capabilities.
  - In September 2024, the *South China Morning Post (SCMP)* reported that Chinese scientists at Shanghai University had demonstrated the first effective attack using a quantum computer on the class of algorithms used in password-protection and encryption mechanisms common in military and financial networks.[357] The researchers used a quantum computer produced by Canadian company D-Wave Systems.[358] According to the authors, this study did not produce a passcode for the best available military-grade encryption like Advanced Encryption Standard (AES-256), but such a breakthrough may be closer than ever before.[359] The authors of the study did note that underdeveloped hardware and the incapability of a single attack algorithm to target multiple cryptographic systems presented practical constraints.[360]
  - Quantum experts agree that the study indicates "incremental advances in quantum computing" but also note that the SCMP article was misleading, as the study itself applied only to RSA encryption,§ not military-grade AES (Advanced En-

*Number of research institutions with at least one publication in each subfield from 2011 to 2020.

†Percentage of total global published research by Chinese researchers and institutions.

‡H-index (Hirsch Index) is commonly used to assess both the breadth and impact of research and is considered the best single metric for measuring research quality of a corpus of publications.

§The Rivest-Shamir Adleman (RSA) algorithm is a basic key encryption that is widely used to secure sensitive data. Michael Cobb, "RSA Algorithm (Rivest-Shamir Adleman)," *Tech Target*.

cryption Standard) encryption, and did not render current cryptographic systems obsolete.[361]

- In January 2023, a group of Chinese scientists claimed they used a combination of classical and quantum computing techniques to breach the RSA encryption algorithm used in military, banking, and communications systems.[362] Notably, the paper summarizing their findings asserts that the RSA algorithm could be broken with a quantum machine using only 372 qubits (which is less than IBM's world-class Osprey, operating with 433 qubits), potentially illustrating the efficiency of the Chinese quantum computer if the findings are true.[363] However, quantum researchers and scientists have offered mixed reviews of the paper, with Massachusetts Institute of Technology (MIT) scientist Peter Shor stating, "As far as I can tell, the paper isn't wrong" but that the Chinese researchers failed to demonstrate the speed with which the quantum algorithm would run, leaving questions regarding the degree of improvement.[364] At the time of the announcement, the *SCMP* noted that the paper had not been officially peer reviewed, and Scott Aaronson, director of the Quantum Information Center at the University of Texas at Austin, said the article was "one of the most actively misleading quantum computing papers I've seen in 25 years."[365]
- In June 2024, the Anhui Quantum Computing Engineering Research Center and QuantumCTek (the latter of which is a quantum company currently on the Commerce Department's Entity List)* jointly announced that their quantum computer dilution refrigerator is the first equipment of its kind commercially available for mass production in China.†[366] According to an article published by the *Anhui Daily*, the dilution refrigeration products were delivered to two scientific research units, and "after many months of testing by customers, the equipment has been operating continuously and stably for a long time."[367] (For more on the importance of certain refrigeration technology to QIS, see "The Global Quantum Supply Chain and Relevant U.S. Export Controls" below.)
- Origin Quantum‡ announced in May 2024 that it had successfully developed a high-density microwave interconnect module that domestic media has described as a "neural net-

*QuantumCTek also appears under the aliases of HKUST National Shield Quantum Technology Co., Ltd.; HKUST Guodun Quantum Technology Co., Ltd.; National Shield Quantum; and Anhui Quantum Communication Technology Co., Ltd. in the Commerce Department's Entity List. U.S. Department of Commerce, *Addition of Entities and Revision of Entries on the Entity List; and Addition of Entity to the Military End-User (MEU) List*, November 26, 2021.

†Heat causes errors in qubits that serve as the building blocks of quantum computers, necessitating the use of refrigerators that keep the temperature just above absolute zero. In Dr. Parker's oral testimony before the Commission, he asserted that "a surprising amount of quantum supply chain revolves around extremely powerful refrigerators." Edward Parker, oral testimony for U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024, 165; Adam Zewe, "A New Way for Quantum Computing Systems to Keep Their Cool," *MIT News Office*, February 21, 2023.

‡Origin Quantum was established in 2017 in Hefei, Anhui Province, by Guo Guancan, an academician of the Chinese Academy of Sciences, and Guo Guoping, who serves as deputy director of the Chinese Academy of Sciences Key Laboratory of Quantum Information and associate dean of the School of Microelectronics and the Institute of Advanced Technology at the University of Science and Technology of China.

work" for quantum computers.*[368] A major obstacle to the module's domestic production in China has been sourcing an ultra-low-temperature specialized high-frequency coaxial cable, which was previously imported from Japan.[369] This new device can allegedly provide microwave signal transmission channels for quantum chips with more than 100 bits and can achieve stable signal transmission across temperature zones in cool environments.[370] According to Kong Weicheng, a researcher at Origin Quantum, the module will allow quantum chips to exert "more powerful computational capabilities," which enable quantum computers to operate efficiently.[371]

- ***Potential progress in sensing:*** There are signs of progress in China's prototype quantum radars, which could advance the PLA's capability to detect foreign military assets.[372] In 2018, for example, the 14th Institute of the defense SOE China Electronics Technology Group Corporation announced that its quantum radar technology had successfully tested detecting targets up to 62 miles away, asserting that the technology is expected to solve bottleneck issues associated with traditional radars, such as low-visibility target detection, survival under electronic warfare conditions, and other challenges.[373] In 2021, a laboratory at Tsinghua University also tested a quantum radar that its researchers claimed was capable of increasing the probability of detecting stealth aircraft by generating a small electromagnetic storm.[374]
  - However, MIT professor Jeffrey Shapiro, one of the technology's inventors, has previously argued that there are problems with this approach that make it unfeasible.[375]
- ***Potential progress in communications:*** China has sought to create secure communications links through both ground-based stations and satellites.[376] Dr. Parker notes that Beijing may be seeking to build an internal communications system without any Western technologies, which reflects the Chinese leadership's anxiety about vulnerability to foreign espionage.[377] Chinese scientists have primarily focused their quantum communications R&D on a method known as quantum key distribution (QKD), which may improve communications security against enemy interception.[378] In 2021, China successfully tested the world's first integrated QKD network, combining a satellite link through the Mozi (Micius) satellite that connects two ground stations approximately 1,616 miles apart (which achieved QKD in 2016) as well as an optical fiber network stretching around 1,243 miles from Beijing to Shanghai (completed in 2017), providing a total distance of roughly 2,858 miles of coverage across China.[379] China launched its second QKD satellite in July 2022—known as Jinan 1—for additional experimentation

*This breakthrough was announced shortly after BIS added Origin Quantum and 21 other Chinese quantum organizations to its Entity List for "acquiring [and/or] attempting to acquire U.S.-origin items in support of advancing China's quantum technology capabilities." It is too early to assess the impact of BIS action on China's continuing ability to make quantum advancements. U.S. Department of Commerce Bureau of Industry and Security, "Additions of Entities to the Entity List," *Federal Register* 89 FR 41886 (May 14, 2024); Origin Quantum, "About Origin Quantum."

in low Earth orbit.[380] The Mozi satellite was used to establish a secure communications link with Russia in March 2022.*[381]

U.S. Response to Quantum National Security Risks

Unlike the broad, country-based controls imposed by the United States in the advanced semiconductor space, until September 2024, the U.S. policy response to QIS national security risks had been more limited perhaps due to the earlier stage of the technology and the possibility that many QIS uses are not military. Until that time, the United States had primarily taken an entity-based approach with respect to QIS-related export controls against China.†[382] In November 2021, the Commerce Department's Bureau of Industry and Security (BIS) added eight Chinese entities to the Entity List, including QuantumCTek, "to prevent U.S. emerging technologies from being used for the PRC's quantum computing efforts that support military applications" and citing potential uses in counter-stealth and anti-submarine applications as well for breaking encryption and developing unbreakable encryption.[383] In May 2024, BIS added another 22 Chinese institutes and firms to the Entity List, including Origin Quantum, for aiding China's quantum development.[384]

In September 2024, BIS issued a new interim final rule imposing worldwide export controls on "quantum computers, related equipment, components, materials, software, and technology that can be used in the development and maintenance of quantum computers."[385] BIS notes that the controls had been aligned with international partners; they are similar to those put in place this year by the UK, France, Spain, the Netherlands, and Canada, which some reporting suggests resulted from "Wassenaar minus 1" discussions.[386] The new BIS quantum controls also include provisions creating a licensing exception for countries that implement "equivalent national controls," thus incentivizing countries to adopt similar controls to ease their access to U.S. technology and ability to engage in cooperative research.[387] Finally, the new controls include limited exceptions, so as not to disrupt ongoing R&D efforts across borders or with foreign persons engaged in QIS research in the United States, and annual reporting requirements to provide greater visibility into the types of such activities.[388]

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*According to the South China Morning Post, China launched Mozi, or Micius, the world's first quantum communications satellite, in 2016. A team of Russian scientists began working with the Mozi team in 2020 to help them set up systems to begin conducting experiments with the satellite, according to Alexey Fedorov, one of the paper's coauthors. Speaking on the results of the experiment, the Russian scientists said the results help account for the imperfections of QKD protocols, such as the problem of detector efficient mismatch, which they say are "important in the context of their practical security." The Russian scientists who wrote the paper are affiliated with six different Moscow-based institutions, including the Russian Quantum Center, Moscow Institute of Physics and Technology, QSpace Technologies, HSE University, National University of Science and Technology MISIS, and the Steklov Mathematical Institute of the Russian Academy of Sciences. In the acknowledgements section of the paper, the Russian authors thanked "our colleagues from the University of Science and Technology of China" for their assistance and recommendations during the joint experiment. Victoria Bela, "China and Russia Test 'Hack-Proof' Quantum Communication Link for Brics Countries," *South China Morning Post*, December 30, 2023; Aleksandr V. Khmelev et al., "Eurasian-Scale Experimental Satellite-Based Quantum Key Distribution with Detector Efficiency Mismatch Analysis," *Optics Express* 32:7 (March 2023): 1, 8.

†The United States did impose a broader technology-based ban relating to quantum computing against Russia and Belarus in September 2022. U.S. Department of Commerce Bureau of Industry and Security, "Implementation of Additional Sanctions against Russia and Belarus under the Export Administration Regulations (EAR) and Refinements to Existing Controls," *Federal Register* 87:179 (September 16, 2022).

*The Global Quantum Supply Chain and Relevant U.S. Export Controls**

The nature of the QIS supply chains have made a U.S. policy response more challenging than the more concentrated semiconductor supply chain.[389] Additionally, some argue that the early stage of the technology and the uncertainty surrounding which QIS applications will be national security-sensitive necessitate a nuanced approach to export controls to ensure they do not interfere with the research and collaboration needed to develop the technology.[390] Dr. Parker argues that export controls should primarily be applied to systems with operational military capabilities instead of more broadly.[391] Under a capability-focused approach, U.S. export controls would only target specific quantum technology when it becomes capable of delivering qualitatively new capabilities like decryption.[392] To illustrate this approach, in his February 2024 testimony to the Commission, Dr. Parker provided the example of "quantum sensors" as a category, where at that point there were no general export controls on the technology as a whole, but instead there were export controls applicable to certain highly sensitive sensors (e.g., high-sensitivity magnetometers, gravimeters, and superconducting electromagnetic sensors) that would cover certain quantum sensors if they are successfully developed.[393] Such an approach is different than the broad-based approach currently taken for advanced semiconductors, which seek to deny China's access to a key foundational technology for AI given the inherent risks, rather than just limiting access to specific military applications.

A more broad-based approach to export controls for QIS could be more complicated than the similar approach used for advanced semiconductors and semiconductor manufacturing equipment given that the QIS supply chain is more varied. As Dr. Parker notes, "there are currently a wide variety of technical approaches [to QIS] being researched in parallel, which require very different critical components."[394] A May 2024 report by Sam Howell, an associate fellow at CNAS, noted that the quantum computing sector has several different modalities under development that each require a different and evolving set of inputs with very little overlap.[395] Further, the inputs could change as the technology matures, so the quantum technology supply chain could remain in flux for the next several years or even decades.[396]

BIS has identified a number of quantum computing-related technologies for export controls. In September, 2022, BIS prohibited export of quantum computing-related technology to Russia and Belarus, including quantum computers and certain components, cryogenic refrigeration systems and components, ultra-high vacuum (UHV) equipment, high quantum efficiency photodetectors and sources, and software and technology related to each the development, production,

*Please note that the new BIS quantum controls announced in September 2024 likely overtake some of the analysis in this subsection. Due to the timing of the release of these new controls relative to finalization of this report, their length (31 *Federal Register* pages), and the complexity of both the Export Control Classification Number system and QIS-related technology supply chains, a full analysis of the policy implications of those controls is beyond the scope of this report. U.S. Department of Commerce, *Department of Commerce Implements Controls on Quantum Computing and Other Advanced Technologies alongside International Partners*, September 5, 2024, 3.

or use of the foregoing.*[397] In its September 2024 QIS-focused controls, BIS took a broader approach, imposing controls on a variety of new Export Control Classification Number (ECCN) product categories and amending the scope of other existing ECCNs.†[398] The BIS quantum controls cover extremely powerful cooling systems, which are needed to reduce heat that causes errors in qubits that serve as the building blocks of quantum computers.[399] Although the United States produces some of its own quantum cryogenic products, it is allied or partner countries—not China—that largely make up the remainder of the supply chain for the refrigeration technologies needed in quantum devices.[400] A September 2022 report by Sandia National Laboratories notes that aside from two U.S.-based manufacturers of the technology, there are manufacturers in Canada, France, Finland, the Netherlands, and the UK.[401]

Other potential key "chokepoint" components have been more difficult to identify.‡ A 2022 Hyperion Research survey of 47 respondents across the U.S. quantum computing supply base listed various materials and products that respondents identified as the most likely potential causes of quantum computing supply chain disruption in the coming years: helium-3 gas, silicon-28, copper, aluminum, gold, high-performance cryocoolers, pumps, valves, compressors, power supplies, RF generators, superconducting wiring assemblies, dilution fridge components, fiber and coaxial cables, low-noise lasers at relevant atomic wavelengths, and key manufacturing equipment useful for quantum and classical chip manufacturing and testing.[402] Some of those materials and components are likely to have multiple sources of availability outside of the United States and allied countries. The September 2024 BIS quantum controls do apply to certain QIS-related components.[403] It is beyond the scope of this chapter to further analyze these supply chains.

Biotechnology: State-Backed Firms Build Global Imprint

Biotechnology is an emerging field with wide-ranging commercial and military applications and the potential to revolutionize various key sectors of the economy.[404] A deeper understanding of natural systems, biochemistry, and genetics paired with increasingly powerful tools for manipulating cell structures has resulted in improved medicines and therapeutics, increased crop yields, new biofuels and bioenergetics, inorganic substances, and advancements in material science and manufacturing processes.[405] The application of AI

*At the same time as the noted BIS action relating to QIS and Russia, U.S. Department of the Treasury, Office of Foreign Assets Control imposed sanctions that prohibited "U.S. persons" located anywhere in the world from exportation, reexportation, sale, or supply, directly or indirectly, of quantum computing services to any person located in Russia. U.S. Department of the Treasury, Office of Foreign Assets Control, Determination Pursuant to Section 1(a)(ii) of Executive Order 14071: Prohibitions Related to Certain Quantum Computing Services, September 15, 2022.

†The various ECCNs applicable to quantum include certain cryogenic CMOS integrated circuits, certain cryogenic cooling systems and components, certain cryogenic wafer probing equipment, certain silicon, silicon oxides, germanium or germanium oxides, certain quantum computers, quantum computing-related electronic assemblies and components, and related software. U.S. Department of Commerce Bureau of Industry and Security, "Commerce Control List Additions and Revisions; Implementation of Controls on Advanced Technologies Consistent with Controls Implemented," *Federal Register* 89:173 (September 6, 2024).

‡Dr. Parker et al. note in a 2022 publication that pieces of the quantum supply chain sourced from China are generally low-cost, off-the-shelf products like electronics and optics as well as some raw materials such as nonlinear crystals. Edward Parker et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," *RAND Corporation*, February 2, 2022, 53, 150.

in biotechnology holds potential to be an accelerant on the pace of discovery, for example by rapidly filling in gaps in researchers' understanding of gene sequences.[406] Though the full extent to which fast-advancing subfields like synthetic biology and gene editing will reshape the realm of possibilities using living organisms is not yet clear, former Google CEO and Chairman and current Commissioner on the National Security Commission on Emerging Biotechnology Eric Schmidt said in April 2024 that we may be approaching a "ChatGPT" moment for biotechnology, one as ground-shifting as the breakthrough in generative AI in November 2022.[407] The importance of the technology has not been lost on China. A Chinese Academy of Science official typified the strategic emphasis China placed on biotechnology by stating, "As Europe won in the 19th century using industry, and the United States won in the 20th century using information technology, so China will win in the 21st using biology."[408] This section will examine the state of U.S.-China biotechnology competition, China's biotechnology ambitions, cases of concern, and the potential risks for the United States.

China Rises up the Value Chain in Biopharma despite Lagging in Fundamental Research

The CCP's leadership has long viewed biotechnology—and in particular biopharmaceuticals—as a critical technology, and it has sought to become a leader in this field with massive state support for the sector.[409] Starting with the 12th Five-Year Plan (2011–2015), the Chinese government shifted its strategy in the sector from one focused on growing copycat manufacturing capabilities toward one incentivizing innovation not just on pharmaceuticals but also across agriculture and biomanufacturing.[410] The "Made in China 2025" plan, a high-level Chinese policy document released in 2015, identified "biomedicine and high-end medical equipment" and "new materials, such as polymers" as two of the ten key sectors set for state backing.[411] The 14th Five-Year Plan for the Bioeconomy called for investments in biotechnology across a range of industries to put China "at the forefront globally" by 2035.[412] Biotechnology has been designated a strategic emerging industry by Beijing, and therefore companies enjoy a host of preferential treatments, including tax benefits, subsidies, and government procurement benefits.[413] The government has also supported development of high-tech science parks where companies can cluster and have access to state-of-the-art R&D facilities and equipment such as DNA sequencers.[414]

Though traditionally a copycat and maker of generic drugs, China has prioritized success in biopharma, investing in R&D infrastructure and supporting biotech companies that have captured key segments of the value chain for genomic sequencing and biopharma.[415] Additionally, there are signs that the Chinese biopharma sector is becoming more innovative, with metrics such as high-quality publications, patent filings, and approval of novel drugs on the rise.

China's efforts have resulted in some significant successes. With regard to biopharma, China increased its share of global value added in pharmaceuticals from 5.6 percent in 2002 to 24.2 percent in 2019, surpassing the EU.[416] China's biotechnology sector has been the recipient of sizable investment increases, with venture capital,

equity funds, and IPOs providing funding to the tune of $216 billion from 2015 to 2023.[417] Seven of the world's ten largest biopharmaceutical IPOs were by Chinese companies from 2018 to 2020, according to McKinsey & Company, while the total combined market value of China's biopharmaceutical industry grew exponentially from $3 billion in 2016 to more than $380 billion in 2021.[418]

Nevertheless, until very recently, China's biotechnology industry has struggled to deliver innovative new products, particularly in biopharmaceuticals.[419] Chinese funding has been geared more toward experimental and translational research; China is not primarily focusing on basic research, which remains an area in which the United States leads.*[420] More than a dozen biotechnology experts interviewed by *Bloomberg News* argue that the persistent lack of basic research in China has stymied domestic innovation by failing to build the knowledge foundation on which to explore novel applications.[421] Academic researchers in China struggle to collaborate with biotech firms to create high-end commercial products, and as a result, Chinese biopharmaceutical firms have produced very few truly innovative medicines.[422] Many Chinese biopharmaceutical firms continue to seek to "copycat" products developed abroad.[423] As a result, Chinese biopharma firms have lagged behind in bringing novel therapeutics to market quickly, as was the case with China's mRNA COVID-19 vaccines, which only gained approval in March 2023, two years after vaccines developed in the United States.[424]

With a robust life sciences innovation ecosystem comprising top universities, venture capital funding, and industry leading firms, the United States has long been the global leader in biopharmaceuticals and non-pharmaceutical biotechnology. U.S.-headquartered biotech firms lead in new drug development, producing twice as many new chemical or biological entities as those in Europe between 2014 and 2018.[425] U.S. firms received 62 percent of global venture capital funding in biotechnology in 2020, a figure that declined from 69 percent a decade earlier but still far exceeded China (19 percent) and Europe (15 percent).†[426] Accounting for 40 percent of the world's total, the United States still publishes nearly double the Patent

*From 2000 to 2019, 80 percent of China's R&D expenditures were focused on experimental development, using existing knowledge to improve products and processes, compared to 62 percent in the same time period for the United States. This emphasis on translational research may advantage China in developing products for defense and other critical sectors, altering human genetic structures, and some other applications. As Michelle Rozo, vice chair of the National Security Commission on Emerging Biotechnology, testified before the Commission, "A system that funds translational research is better poised to realize applications in certain biotechnology sectors, including agriculture, [industry], and defense. In a way, China is taking advantage of American basic R&D by heavily funding translational research." Michelle Rozo, written testimony for the U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024, 2–3.

†Funding activity for biotechnology in the United States boomed during the COVID-19 pandemic, with venture capital and IPO follow-on funding both peaking at over twice their pre-pandemic level in 2021 before falling off in 2022 and 2023. The collapse of Silicon Valley Bank in March 2023 further constrained funding, with an estimated 50 percent of U.S. biotech companies banking with the institution. There are signs in 2024 that the industry is recovering, driven by factors like investment in weight loss drugs and a shifting focus from IPOs to mergers and acquisitions (M&A) activity. Gwendolyn Wu, "Private Biotech M&A Surges amid Difficult IPO Market," *Biopharma Dive*, July 22, 2024; Chad Wessel, "The State of Emerging Biotech Companies: Investment, Deal, and Pipeline Trends," *Biotechnology Innovation Organization*, June 4, 2024; Irena Maragkou, "Biotechs Ride Obesity Drug Wave with Novel Approaches That Go beyond GLP-1Ras," *Pharmaceutical Technology*, February 15, 2024; Nicholas Megaw, "US Biotech Fundraising Boom Ends 2-Year Deal Drought," *Financial Times*, February 12, 2024; Patrick Wingrove, "SVB Fall Casts Shadow on Early-Stage U.S. Biotech," *Reuters*, March 13, 2023.

Cooperation Treaty (PCT) biotech-related patents as China.[427] U.S. biotechnology companies attracted $56.8 billion in total funding in 2023, 35 percent of the world's total in comparison to $20.6 billion to Chinese firms.[428] There are positive trends for China, however. Despite the U.S. lead in basic research, there are recent indications that Chinese biotech is becoming more innovative in cutting-edge research. In 2023, five first-in-class drugs were approved in China and three by the U.S. Food and Drug Administration, including the first FDA-approved drug to treat nasopharyngeal cancer.[429] There were 33 licensing deals in 2024 between Chinese drug makers and multinational enterprises.[430] These are deals in which multinational companies license the IP created by a smaller company and typically signal some level of innovation in the product. The number of licensing deals has more than doubled since 2019 and indicates the increasing confidence of international companies in the quality of Chinese innovations.[431] The amount of high-quality scientific publications from Chinese academics has overtaken that of the United States in certain subfields, including novel antibiotics and antivirals and biomanufacturing.[432] Chinese researchers have also made significant strides in synthetic biology, the replication of living organisms or creation of novel materials, therapeutics, or organisms.[433] The Australian Strategic Policy Institute (ASPI) ranks Chinese research in synthetic biology ahead of the United States in terms of both the volume and quality of research published.[434]

Additionally, Chinese biotech companies have become industry leaders in genomic sequencing, mass production of precursors, and intermediary services needed by innovative pharma and biotech companies, capturing larger segments of the value chain as contract research organizations (CROs), contract manufacturing organizations (CMOs), and contract development and manufacturing organizations (CDMOs).[435] A survey from Biotechnology Innovation Organization, a trade association, found that of 124 U.S. biotech companies that responded, 79 percent had at least one contract or product agreement with firms based in China or owned by China for services such as gene sequencing, data management, and conducting clinical trials.[436]

Chinese Firms Become Major Players in Genomics

China has significant capabilities in genomics. Genomics is the study of an entire organism's genetic sequence, including that of humans.[437] The Chinese government has a longstanding interest in the development of genomics, funding its development since the early 2000s.[438] In 2023, the National Natural Science Foundation under the State Council named Chinese research in genomics as one of the "ten major advancements in Chinese science."[439]

The ability to analyze vast quantities of genomic data has been likened to the holy grail of drug discovery, while giving distinct advantages in healthcare for diagnosing medical conditions and in determining predispositions for disease.[440] Yet, genomics and synthetic biology can also be used for malevolent purposes, such as surveillance using bioindicators and to make more virulent pathogens that may one day be capable of targeting subsections of populations based on shared genetic signatures.[441]

China has significant advantages in genomic data. China has pursued a comprehensive state-led effort to amass genetic data on humans and living organisms around the world stored in a central repository known as the China National GeneBank.[442] Given the nature of innovation in biotechnology, access to a massive amount of genetic data could accelerate the pace of discovery and development in emerging subfields like synthetic biology, providing the Chinese R&D community an advantage in the next evolution of biotechnology. The Chinese government designated genetic data as a national strategic resource in 2022, and it restricts the transfer of genetic information to parties outside of China.[443]

Chinese firms are becoming main drivers in genomics research and global leaders in providing genetic sequencing and related genomics services.[444] Principal among these is BGI Group, which was initially founded as the Beijing Genomics Institute in 1999 to serve as China's representative to the U.S.-led Human Genome Project, an international research collaboration in sequencing human DNA.[445] Over the subsequent two decades, BGI's research has expanded from mapping the human genome to groundbreaking research on mapping primate brains and sequencing blood samples to identify viruses.[446] The firm has also made strides in developing low-cost genome testing services and marketing them abroad, building a global brand as a commercial genetic sequencing firm.[447] As a global competitor in genomics, BGI has grown to become one of the world's largest genetic sequencing firms by capacity, with $973 million (RMB 7.05 billion) in revenue in 2022.[448] The company maintains offices and research laboratories across the world, including in Europe, Japan, and the United States, and has distributed testing products in at least 80 countries.[449] During the COVID-19 pandemic, BGI deployed genetic testing labs in more than 20 countries around the world capable of collecting genetic data, which has raised concerns that China is engaged in a concerted effort to amass genetic data abroad while walling off domestic data.[450] As of October 2024, BGI's market capitalization was $2.6 billion, well behind industry leader Illumina ($23.7 billion) and other peer genomics companies, yet the company has shown prowess in scaling globally and expanding market share.[451] BGI also runs China's National GeneBank, overseeing millions of genetic samples in cooperation with the National Development and Reform Commission and Ministry of Health, among other Chinese government agencies.[452] Amid this close government collaboration, BGI has benefited from favorable state-led subsidies, including a $1.5 billion ten-year loan from the state-controlled China Development Bank.[453]

Other Chinese firms are becoming leading firms in genomics, too. Beijing-based Novogene has created a dominant presence in next-generation genetic sequencing—DNA sequencing that provides higher-volume, faster, and cheaper genetic sequencing capabilities—completing 1.2 million samples as of 2021.[454] To develop its genetic sequencing capabilities, the firm has sought out research partnerships with U.S. partners, a pattern in Chinese-based biotech firms.[455] This includes the establishment of a "genome sequencing center" on the campus of University of California, Davis meant to research and refine genetic sequencing capabilities.[456] In 2022, Novogene also set

up a genome sequencing facility in San Jose, California, positioning it to offer genetic sequencing services to U.S. biotechnology firms in Silicon Valley.[457]

China's Biotech Industry Is Deeply Interconnected with U.S. Firms

Chinese companies have become integral in U.S. pharmaceutical supply chains, leading to dependencies and heightened risk of the transfer of sensitive health data of U.S. citizens.* A few Chinese companies do have significant globally competitive capabilities in genomic sequencing and biotech services for innovative companies. The virtues of an open and collaborative research environment between the United States and China have been extolled by many in the scientific community, yet national security experts have raised concerns particularly around the possible transfer of sensitive health data of U.S. citizens, which could enable China's technology advancement and create vulnerabilities for Americans.[458]

Chinese companies have been able to capture market share as providers of services such as genetic sequencing, offering intermediate services and conducting clinical trials, lowering the cost and occupying a significant space in the biopharma supply chain in the United States and globally. Despite growing evidence of collaboration with the PLA, Chinese genomics firm BGI and other major international biotech player WuXi have longstanding operations in the United States, enabling them to conduct U.S.-based R&D.[459] Since 2010, BGI has operated its BGI Americas laboratory in Cambridge, Massachusetts, and in 2013 BGI acquired U.S.-based DNA sequencing firm Complete Genomics.[460] BGI was a main supplier of COVID-19 test kits in the United States, providing 35 million COVID-19 tests to U.S. users by August 2020.†[461] Reporting from the *Washington Post* in September 2023 details how BGI collected vast amounts of genetic data from populations around the world during the pandemic by deploying its Fire-Eye labs—portable labs that analyzed genetic samples for traces of COVID-19—in over 20 countries.[462] BGI has also conducted extensive research collaborations with U.S. firms and institutions, including partnerships with the University of California and the Children's Hospital of Philadelphia on human genome sequencing.[463]

WuXi Group Raises Dependency and Security Concerns

WuXi Group encompasses a constellation of integrated CROs and CDMOs known as contract research, development, and manufacturing organizations (CRDMOs) that specialize in services related to drug development and production.[464] WuXi has expanded market presence in the United States and Europe, with WuXi Biologics and WuXi AppTech among the two largest subsidiaries.[465]

*Chinese state-sponsored hackers were believed to have played a role in a hack of healthcare records on 80 million Americans in 2015. There is no known evidence indicating that data from this attack have been used or made available within China for biomedical-related research. Michael Riley and Jordan Robertson, "Chinese State-Sponsored Hackers Suspected in Anthem Attack," *Bloomberg*, February 5, 2015.

†For more on BGI's role in supplying COVID-19 testing kits, see U.S.-China Economic and Security Review Commission, Chapter 2, Section 2, "The Chinese Communist Party's Economic and Technological Ambitions," in *2021 Annual Report to Congress*, November 2021, 178–179.

WuXi Group Raises Dependency and Security Concerns—*Continued*

These firms have become integral to the U.S. pharmaceutical industry: it is estimated that WuXi has been involved in developing one-fourth of the drugs currently used in the United States.[466] For example, it has developed key ingredients for drugs used in treatments for HIV, cystic fibrosis, obesity, and cancers like some types of leukemia and lymphoma.[467] About two-thirds of WuXi AppTech's revenue ($3.6 billion) came from the U.S. market in 2023.*[468] As the firm has expanded its footprint in the United States, it has benefited from state and local subsidies, including an $11.5 million tax break to build a manufacturing plant in Massachusetts and a $19 million subsidy to build a manufacturing site in Delaware.[469]

WuXi's role in the U.S. drug development and manufacturing market raises significant concerns that a key U.S. industry has become reliant on a Chinese company with links to the PLA.†[470] Many companies that contract with Chinese-based CRDMOs like WuXi Group have expressed concerns that a disruption in these contracts would present major setbacks for drug development timelines. One survey of 105 U.S. biotechnology companies found over 90 percent would expect delays in their development pipeline if they were forced to switch from a China-based CRDMO and 64 percent saying this would constitute a "substantial slowdown."[471] Another survey—as previously mentioned—from the trade group Biotechnology Innovation Organization (BIO) yielded similar results, with 79 percent of 124 biopharma companies surveyed saying they had at least one contract with a China-based or -owned CRDMO; the survey indicated that fully unwinding these partnerships would take up to eight years.[472] This comes at a moment when the U.S. pharmaceutical industry is dealing with active drug shortages near all-time highs.[473]

WuXi's position in the drug development pipeline grants it potential access to U.S. clients' proprietary IP and know-how.[474] Furthermore, the company's recent expansion into genomics makes the collection of genetic data a core component of its services, raising concern over the potential transfer of genetic data of U.S. persons.[475]

In light of both firms' alleged ties to the Chinese military, U.S. policymakers are seeking to limit their reach into the United States

*In 2015, WuXi purchased an ownership stake in U.S. genetic sequencing firm 23andMe, which company representatives claimed in 2021 amounted to less than 1 percent. For more on Chinese firms investing in U.S. genetic sequencing firms, see U.S.-China Economic and Security Review Commission, Chapter 2, Section 2, "The Chinese Communist Party's Economic and Technological Ambitions," in *2021 Annual Report to Congress*, November 2021, 178; Julian E. Barnes, "U.S. Warns of Efforts by China to Collect Genetic Data," *New York Times*, October 22, 2021.

†In June 2024, it was reported that WuXi AppTec employees were listed as co-inventors alongside scientists from the PLA General Hospital in Beijing on at least ten patents for altitude sickness drugs in recent years. This follows documented links between the company and the CCP going back years, with one in seven of WuXi AppTec's employees believed to be CCP members in 2013. Kirsty Needham and Andrew Silver, "Staff at Drugmaker under U.S. Scrutiny Worked with Chinese Military Scientists," *Reuters*, June 6, 2024; Sunny Cheung, Arran Hope, and Peter Mattis, "Red Genes: Assessing WuXi AppTec's Ties to the Party-Army-State in China," *Jamestown Foundation*, February 9, 2024

and access to U.S. genetic data.[476] In the last three years, the Commerce Department placed BGI subsidiaries on the BIS Entity List and the Pentagon has labeled BGI a Chinese military company, both moves that significantly limit BGI's ability to work with U.S. firms and to access U.S. technologies.[477] Yet limiting these firms' access to the U.S. market poses challenges given their extensive network of U.S. subsidiaries and partnerships and deep involvement in numerous pharmaceutical R&D supply chains.[478] For example, MGI Group, which sells gene sequencing equipment in the United States, avoided the first round of government sanctions on BGI despite being a subsidiary of BGI until being spun out in 2022.[479] Although the firm claims to be a "completely different company," BGI's founder and chairman Wang Jian holds 47 percent of MGI shares following MGI's public listing.[480] Members of Congress have called for MGI to be named a "Chinese military company" along with other alleged BGI subsidiaries that have avoided sanctions as of April 2024, including genetic sequencing firms Innomics and STOmics.[481]

Other Chinese biotech firms have also sought collaborations with U.S. firms and research institutions. VCanBio Cell and Engineering Corporation, which markets itself as China's largest biotechnology firm, boasts a 15,000-square-foot research center and a facility with an explicit focus on translating advancements in biological research, both near Boston.[482] Another Chinese firm, QLB Biotherapeutics, similarly oversees a biotech incubator in Boston, with QLB aiming to invest in U.S. biotech startups housed in the incubator and to acquire the rights to any therapeutics the Chinese-owned, U.S.-based incubator produces.[483]

Chinese State Support Helped Create One of the World's Largest Bio-Agriculture Companies

China has pursued its biotechnology ambitions in bio-agriculture, seeking to enhance agricultural processes to create higher yields and stronger crop resiliency, benefits that are sought after in China due to the country's longstanding concerns surrounding food insecurity.[484] As Chinese companies have become major players in an already highly concentrated global agribusiness industry, there are growing concerns about overdependency. Chinese firms have aggressively registered bio-agricultural patents and are now the global leaders in government funding of agricultural R&D, according to 2022 estimates by the U.S. Department of Agriculture's Economic Research Service.[485] China's progress in genome sequencing and analysis, which can be leveraged in the agricultural industry for genetically engineering agricultural products, is also gaining ground.[486] A 2022 study found Chinese scientists had published more papers concerning crop genomics and plant gene editing technologies in recent years than any other country.[487]

To achieve its bio-agricultural ambitions, the Party-state has staunchly backed the growth of its largest state-owned firms.[488] One such state-owned company is ChemChina, China's largest chemical company, which in 2017 purchased Swiss-based seed-producing giant Syngenta, a leading firm in bio-agriculture.[489] A major state support component was included as part of the $44 billion acquisition, with the Bank of China providing a $10 billion bond and

another worth $7 billion coming from China Reform Holdings Corp, a state-owned asset manager.[490] Recent consolidation of global agricultural companies has increased Syngenta's market share, enabling China to position itself strategically in the bio-agricultural sector.[491] According to Michelle Rozo, vice chair of the National Security Commission on Emerging Biotechnology, following ChemChina's acquisition of Syngenta, four companies now control large segments of agricultural biotechnology and other agricultural inputs: U.S.-based Corteva, German-based Bayer and BASF, and Syngenta.[492] These four firms are now responsible for the vast majority of pesticide and seed treatment research and manufacturing.[493] They also conduct most global seed research, developing genetically engineered (GE)* seeds that they themselves sell or license to other firms.†[494]

Chinese state ownership of Syngenta affords Beijing influence over global agricultural markets, disadvantaging U.S. companies. The Chinese government is both the key biotechnology regulator in China and the owner of a major bio-agriculture firm that competes with other firms it regulates, including U.S. firms.[495] Therefore, Syngenta is in a privileged position of being owned by the same entity that regulates matters vital to the firm's success.[496] This beneficial regulatory relationship with the country's largest domestic agricultural firm occurs as Chinese regulators continue to stymie foreign competitors.[497] According to Dr. Rozo, the Chinese government routinely slows licensing for U.S. firms to market GE crops in China and exploits samples of U.S.-produced GE seeds to develop domestic competitors on a reduced timeline.[498] This is a direct violation of China's WTO commitments and agreements made as part of the Phase One trade deal, where Chinese authorities agreed to efficiently review and approve U.S.-made biotechnology products.[499] According to a report from the Office of the U.S. Trade Representative (USTR), China's lagging approval process of U.S.-made biotechnology goods "remains among the most significant commitments under the Phase One agreement for which China has not demonstrated full implementation."[500] In one instance of delayed licensing, after a

*A genetically engineered organism refers to any organism that is modified using techniques to directly transfer or remove genes in that organism, as opposed to the more common yet broader category of genetically modified organism (GMO), encompassing organisms altered by GE or conventional breeding. Canadian Biotechnology Action Network, "GM/GE Definition," 2024.

†The Chinese acquisition of Syngenta, which had to be cleared by the Committee on Foreign Investment in the United States, also faced opposition by U.S. agricultural stakeholders on security grounds. Previously, Syngenta had led major research programs relevant to U.S. military interests, particularly in biofuels. As highlighted in testimony by Dr. Rozo, now that Syngenta is a Chinese SOE, it could withhold biofuel advancements from the U.S. military, a concern expressed by domestic farming unions at the time of the ChemChina acquisition deal. Furthermore, several of Syngenta's U.S. agricultural facilities are near U.S. military facilities, raising concerns by some that Syngenta's ostensibly commercial research sites could serve as covert research sites near U.S. national security activities. Following Syngenta's acquisition by ChemChina, the state of Arkansas announced investigations into Syngenta's ownership of land in the state. After finding that the company did not properly disclose its Chinese ownership, the company was ordered to sell 160 acres of land. Nova J. Daly, written testimony before the Committee on Agriculture U.S. House of Representatives, *Chinese Acquisitions of U.S. Agriculture and Land Holdings and Control of Relevant U.S. Supply Chains: Addressing National Security Risks*, March 20, 2024, 4, 7–9; Michelle Rozo, written testimony for the U.S.-China Economic and Security Review Commission, *Hearing on Current and Emerging Technologies in U.S.-China Economic and National Security Competition*, February 1, 2024, 9; Neal Earley, "State Orders a Chinese-State Owned Syngenta Seeds to Divest Ownership of Arkansas Farmland," *Arkansas Democrat Gazette*, October 18, 2023; Attorney General of Arkansas, *Attorney General Griffin Orders Divestment of Chinese-Owned Land and Imposes $280,000 Civil Penalty*, October 17, 2023; Food & Water Watch, National Farmers Union, "China National Chemical Corporation Proposed Purchase of Syngenta AG," July 21, 2016, 12–14.

decade-long wait, the Chinese government in 2023 finally approved licenses for U.S. firm Corteva to market product grown in the United States using a GE canola seed.[501] However, due to the delayed timeline, that canola variety had become outdated.[502]

Since acquiring Syngenta, the Chinese government continues to assert its position in the global bio-agriculture sector. In 2020, the State Council's State-Owned Assets Supervision and Administration Commission began combining agricultural assets of ChemChina and other firms under the Syngenta name.[503] The resulting Chinese state-owned Syngenta is now the world's largest seed and agrochemicals conglomerate, with $27 billion of annual sales and major markets across Europe, North America, Latin America, and Africa.[504] Since 2021, Syngenta has also reportedly been planning a Shanghai IPO worth as much as $10 billion, which could provide the firm with RMB liquidity to facilitate Chinese government-directed acquisitions of emergent bio-agricultural companies.*[505] If the Syngenta case is illustrative, there may be further consolidation of international bio-agricultural firms under direct Chinese state ownership.[506]

AI May Enhance China's Biotech Ambitions

Chinese breakthroughs in biotech for both commercial and military sectors can be propelled by AI and advances in machine learning, according to Dr. Rozo's testimony before the Commission.[507] AI and machine learning can be applied to assist in analyzing genetic codes, conducting image analysis for agriculture and medical diagnostics, and running autonomous experimentation to accelerate the speed of cutting-edge technological development.[508] Dr. Rozo testified that nearly every area of biology has advanced through the use of AI/machine learning tools and will continue to do so as the data and models improve.[509] Chinese firms already claim to be benefiting from this AI-biotech nexus.[510] Insilico Medicine, with headquarters in Hong Kong, claims to have used AI in pharmaceutical development to reduce a multiyear discovery process down to 18 months and at a fraction of the cost.[511] BioMap, a biotech firm with headquarters in Beijing, claims to have developed an AI Foundation Model with over 100 billion parameters to speed drug discovery.[512]

A key aspect of the AI-biotech nexus is quality data. According to the U.S. National Counterintelligence and Security Center, China "has enacted national policies prioritizing the collection of healthcare data both at home and abroad to achieve its goal of becoming a global biotech leader" and has collected large datasets from the United States and other countries.[513] Dr. Rozo argues that thanks to government support, China's biotech ecosystem may be better suited than the United States to utilize AI and other emerging technologies to advance biotech research, particularly given its National Genome Sequencing Data Center and BGI's significant role in providing genomic sequencing ser-

*As of March 2024, that IPO is currently withdrawn at the direction of Chinese authorities due to weakness in Chinese equity markets. *Reuters*, "Exclusive: Beijing Nudged Syngenta to Withdraw $9 billion Shanghai IPO on Market Weakness," April 3, 2023.

AI May Enhance China's Biotech Ambitions—*Continued*

vices.[514] Similarly, WuXi Apptec's role in numerous biotech supply chains provides WuXi access to a wide variety of otherwise proprietary data. "It appears that the Chinese system is better oriented towards convergent [AI-enhanced biotech] research," Dr. Rozo testified, and "the Chinese government has been prioritizing this intersection at a national level for years, while the U.S. Government has yet to do so at the same scale."[515]

Batteries: China's State Support Powers Growing Market Dominance

From powering EVs to supporting the U.S. power grid, battery technology plays an increasingly crucial role in the U.S. economy and military readiness.[516] The U.S. battery market, already estimated at $16.9 billion in 2023, is expected to more than double by 2030 with the transition to battery-powered vehicles and the installation of more batteries in energy systems.[517] In contrast to the other technologies examined in this chapter where the United States and China are competing to gain a clear advantage, China currently dominates nearly all stages of battery production.[518] Six out of the world's top ten battery producers are based in China, accounting for 77 percent of global production capacity* as of 2022, compared to just 6 percent for the United States.[519] This advantage is set to continue, with energy data firm BloombergNEF projecting that by 2025 and beyond, China will maintain at least three times as much battery production capacity as the rest of the world combined.[520] With China's leading role in battery production, the United States has become increasingly dependent on China for finished batteries as well as battery technology, components, and materials.[521] Despite recent attempts to reduce U.S. reliance on Chinese batteries, China remains the leading battery exporter to the United States, accounting for over 70 percent of lithium-ion batteries imported in 2023 by price and over 50 percent of all electric storage batteries, including separators and parts.[522]

China's Dominance in the Battery Supply Chain

China has attained a sizable advantage at each stage of the battery supply chain, from upstream mining of raw materials, to midstream processing and fabrication of components, and finally to downstream assembly and production of finished batteries.[523] In its 14th Five-Year Plan for Raw Material Industry Development, China describes raw materials as the "foundation of the real economy" and a "main battlefield for industrial green development."[524] China's success in battery manufacturing stems in large part from its leading position in producing and processing critical minerals.†[525] As

*Production capacity refers to the maximum potential manufacturing capacity a country can produce of a given good; for batteries, it is measured in gigawatt hours (GWh).

†Critical minerals currently include 50 minerals and elements considered essential to the economic or national security of the United States. They are vulnerable to supply chain disruptions and are used in manufacturing of a product that, if curtailed, would have significant consequences for U.S. interests (e.g., lithium, cobalt, graphite, gallium, germanium, nickel, tin, etc.). U.S. Department of the Interior, U.S. Geological Survey, *What Is A Critical Mineral?*

of January 2024, China is responsible for 60 percent of the world's rare earths mining production, a subset of critical minerals crucial not only for battery production but also for defense technologies, including missiles, lasers, and tanks.[526]

Chinese firms have augmented their significant domestic processing and refining of rare earths by securing mining agreements with resource-rich countries to secure supply of the critical minerals used in batteries.[527] Nickel, lithium, and cobalt are vital inputs for battery manufacturing for which China lacks substantial domestic resources.[528] In 2022, China signed a $14 billion deal to mine nickel in Indonesia and a $422 million deal for lithium mining in Zimbabwe, complementing existing agreements in the Democratic Republic of the Congo, where Chinese firms own 80 percent of cobalt mining.[529] Chinese firms continue to expand control of the global critical mineral mining industry. According to GlobalData, the number of planned critical mineral mines either under development or set for exploration by Chinese companies outside of China is set to more than double to 89, up from the 40 currently in operation.[530] Many of these planned mines are set to operate in developing Belt and Road Initiative member countries in Africa and Southeast Asia, where Chinese investment in metals and mining is reaching record highs.[531]

In line with government directives for rare earth and raw material enterprises to consolidate and extend their industrial chains further downstream, China has also invested heavily in refining capabilities, constructing factories domestically and abroad to bolster and enhance its ability to process the materials needed to produce batteries.[532] China now processes and refines 90 percent of the world's rare earths and a significant portion of other critical minerals needed for lithium-ion batteries, including 95 percent of manganese, 70 percent of cobalt and graphite, 66 percent of lithium, and over 60 percent of nickel.[533] This includes a Chinese-owned $300 million lithium processing plant in Zimbabwe that reportedly has the capacity to process 4.5 million metric tons of hard rock lithium annually for export; Zimbabwe has one of the largest concentrations of lithium reserves in Africa.[534] According to Rodrigo Castillo and Caitlin Purdy at the Brookings Institution, China's state-owned investment bank CITIC also boosts China's refining capabilities by channeling government funds to support Chinese firms, including Chengdu-based Tianqi's overseas lithium refining operations.[535] At the same time China is investing in refining capabilities, efforts to upgrade resource-refining capabilities in the United States and Europe are facing pushback due to health and environmental concerns.[536]

Downstream, China is further solidifying its lead in battery manufacturing. China has invested heavily in manufacturing battery components and with subsidies for battery manufacturing companies for years.[537] The Chinese government has designated the battery and EV industry as an industry of strategic importance since at least 2010, when it was specifically identified as a matter of priority by the State Council.[538] Support for the development of the "new energy vehicle" industry was included in the 12th Five-Year Plan (2011–2015), in the Energy-Saving and New Energy Vehicle Indus-

try Development Plan (2012–2020), and as one of the ten industrial priorities in Made in China 2025.[539] The most recent 14th Five-Year Plan (2021–2025) names new energy vehicles as a strategic emerging industry, and a New Energy Vehicle Industry Development Plan (2021–2035) outlines advancement objectives in efficiency, global market share, and integration of autonomous driving systems.[540] A 2024 report from the Center for Strategic and International Studies estimates that between 2009 and 2023, Chinese government support for the EV and battery industry totaled at least $230.9 billion, equivalent to 18.8 percent of total EV sales of Chinese car companies.[541] The subsidization has continued, even as China dominates global battery production. Notably, Fujian-based Contemporary Amperex Technology Co., Ltd. (CATL) received $391 million (RMB 2.85 billion) in government support over the first six months of 2023.[542] This constituted a nearly threefold increase in government subsidies year-over-year for a company that comprises 36.8 percent of global market share of batteries for EVs.[543]

Buoyed by strong government backing, as of 2023, Chinese firms produced 77 percent of all battery cathodes produced globally, 74 percent of separators, 82 percent of electrolytes, and 92 percent of anodes at a fraction of the cost compared to U.S. competitors.*[544] This environment has also allowed Chinese battery makers to develop batteries key to powering future cutting-edge products.[545] For example, a new condensed battery produced by CATL claims to maintain an energy density of up to 500 watt-hours per kilogram (Wh/kg).[546] This is an energy density above the projected requirements needed to power a future fully electrified airplane.[547] Meanwhile, Chinese breakthroughs in solid-state batteries are set to broaden the efficiency and duration with which Chinese automotive manufacturers can power the newest generation of EVs.[548] With such an extensive array of subsidies and existing market dominance of nearly all battery components, Chinese firms are poised to continue dominating global battery markets, including in the United States.[549]

China's Dominance in EVs

As automotive firms increasingly focus on the production of EVs, China's car manufacturers are well positioned. The global EV market, which already grew from $384.65 billion in 2022 to $500.48 billion in 2023, is projected by Fortune Business Insights to more than triple by 2030, with significant growth in the Asia Pacific.[550] About 60 percent of total EV batteries sold globally in 2022 were made in China.[551] This creates dependencies on Chinese-produced EV batteries for U.S. automakers, while Chinese EV manufacturers work to vertically integrate domestic battery production into their supply chains in order to solidify first mover advantages and ascend the ranks of global auto manufacturers.[552]

According to the Center for Strategic and International Studies, China's investment in EV batteries has been backed by about

*Most batteries comprise the same basic components, including positively charged cathodes, negatively charged anodes, electrolytes made up of lithium salts needed for conductivity, and a porous separator to prevent the positive and negative sides from touching. Agnes Chang and Keith Bradsher, "Can the World Make an Electric Car Battery without China?" *New York Times*, May 16, 2023; Shawn Hymel, "What Is a Battery?" *Sparkfun*.

China's Dominance in EVs—*Continued*

$130 billion in government-led research incentives, government contracts, and consumer subsidies.[553] While Chinese battery subsidies consistently cost the Chinese government billions of dollars a year, they combine with relatively low labor costs and significant manufacturing expertise to allow Chinese firms to produce battery packs for EVs at a cost of $127 per kilowatt hour compared to their North American and European competitors, whose costs are 24 percent and 33 percent higher, respectively.[554] Chinese EV battery factories can also be constructed at a price more than $200 million less than a potential counterpart in Europe.[555]

While some countries are seeking to diversify away from Chinese batteries, this is costly in the near term. BloombergNEF estimates that the EU and the United States would need to spend $98 billion and $82 billion each in initial manufacturing construction alone to meet domestic battery demand in order to cut their market reliance on China.[556] The EU further estimates it will need to spend an additional $412 billion (€382 billion) across the entire battery supply chain to eliminate its reliance on Chinese battery imports and achieve self-sufficiency by 2030.[557] As a result of China's dominant position in EV battery making, most global EV makers are set to continue to depend on China—at least in the short term—including Tesla, which relies on China for 40 percent of its battery supply chain.[558]

Major Chinese EV manufacturers, like BYD, have capitalized on China's battery manufacturing advantages.[559] Unlike U.S. competitors, BYD controls nearly all aspects of its battery supply chain.[560] The firm, which was founded as a battery manufacturing business, owns over 20 battery-making plants in China, including one of the world's largest battery-making plants with a 24-gigawatt-hour (GWh) capacity in Qinghai Province.[561] BYD's stakes in resource mining allow the firm to lock in discounts in sourcing raw materials to make batteries.[562] Like other Chinese firms, BYD has benefited from strong government support, with direct subsidies of over $3.7 billion between 2018 and 2022, according to the Kiel Institute.[563] Amid this generous state support, BYD has plans to open more battery factories and consolidate much of its upstream battery-manufacturing sourcing, including gaining ownership stakes in lithium mining operations, exploring joint ventures in nickel mining, and developing sodium-ion batteries.[564]

Chinese firms are now poised to dominate global sales of EVs. One estimate finds that Chinese EVs are set to account for one-third of global market share by the end of this decade, increasing market share outside of China from 3 percent in 2024 to 13 percent in 2030.[565] BYD has become a major player in the global EV market, dominating domestic and foreign firms in China's EV market while surpassing Tesla in global sales of battery EVs in the last quarter of 2023, thanks to Chinese government support and strong domestic supply chains.[566] Other Chinese EV firms already operating at home in what is the world's largest automotive market have established beachheads abroad and are surging in

China's Dominance in EVs—*Continued*

international EV markets. Hangzhou-based Geely Auto reported a 48 percent year-on-year increase in 2023 EV sales, with more than 270,000 Geely EVs sold outside of China.[567] State-owned SAIC reported an 18.8 percent increase in its 2023 overseas EV sales year-over-year and has unveiled plans to begin promoting 14 new EV models for foreign markets by 2025.[568]

Many countries will gladly accept China's low-cost EVs, indicating that China's market share is likely to increase and ultimately displace existing suppliers in those markets, a development likely to cut into the revenue of U.S. automakers from sales overseas. Some countries have resisted them over concerns that China's massive subsidies for the sector have created unfair competition. The United States and Canada in 2024 both announced a 100 percent tariff on EVs imported from China, and the EU imposed tariffs ranging from 17 to 38 percent on top of the existing 10 percent tariff on all imported cars.[569] Brazil, which became the largest import market for Chinese EVs in 2024, is in the process of gradually increasing tariffs on imported vehicles from zero to 35 percent by 2026 in order to protect domestic industry.[570]

Batteries as Key Components of Global Electrical Grids

Chinese batteries also play a crucial role in providing electrical storage equipment for power grids worldwide, including in the United States. China is increasingly supporting and subsidizing what it calls "new-type energy storage systems" (NTESS), energy systems that use novel technologies to store and distribute power, such as battery energy storage systems (BESS), compressed air energy storage, and flywheel systems, among others.[571] As of 2023, China's installed NTESS capacity stood at 13.1 gigawatts (GW), with lithium-ion batteries utilized in these systems accounting for 28.7 percent of the world's total deployed power capacity for lithium-ion batteries.[572] These energy storage systems are central to China's five-year plans at both the national and provincial level, with targets to reach 100 GW in cumulative battery storage capacity by 2030.[573] In contrast, the United States had a total energy storage system capacity of 17 GW by the end of 2023.[574] With China the global leader in energy storage systems, the United States imported a record 841,573 metric tons of lithium-ion batteries in 2023, mostly from China.[575] This constituted a 32.9 percent rise from 2022 and marked the third straight year U.S. battery imports have risen by over 30 percent.[576]

Utility-scale batteries are increasingly necessary to support U.S. energy storage stations, especially as they integrate more power generated by alternative energy like wind and solar.[577] Leading China's entrance into U.S. battery energy storage systems is Fujian-based battery firm CATL, whose battery-backed energy storage systems are being rapidly installed into the U.S. electric grid.[578] According to Craig Singleton, China program director and senior fellow at the Foundation for Defense of Democracies, several CATL-supported BESS projects are under construction or have already been complet-

ed in the United States, including a March 2022 CATL battery-supported BESS project in Florida and an August 2022 project near Richmond, Virginia.[579] Nevada-based firm Primergy Solar entered into a sole battery supply agreement with CATL in October 2022, which is set to be among the largest solar and storage projects in the United States.[580]

CATL's rapid expansion in the U.S. electrical storage market comes at a time when energy storage batteries are increasingly key to the U.S. grid's function.[581] In the second quarter of 2024, energy companies connected nearly 4 GW* of battery storage to the United States grid, up 87.3 percent year-on-year and bringing total capacity to 23.8 GW.[582] CATL batteries are well positioned to underpin Texas's power grid, where battery storage makes up nearly 60 percent of new energy projects seeking to connect to the grid, far more than any other energy storage source.[583] This battery dependency in energy grids is only expected to grow. Texas currently has 4 GW of energy battery storage for its grid; this will rise each of the next two summers to reach a total of 12–14 GW.[584] CATL has major contracts in Texas, including an agreement with Texas-based HGP Storage to produce up to 5 GWh† of energy to support the Texas power grid.[585]

Mr. Singleton argues that the integration of CATL batteries into the U.S. electrical grid creates potential vulnerabilities to hacking, intelligence gathering, and disruption from China.[586] Due to vulnerabilities in EV charging networks, EVs themselves, and BESS-related systems, hardware manufacturers could compromise EVs, charging networks, electric grids, and industrial control systems.[587] Mr. Singleton acknowledges that "it is challenging to ascertain the precise likelihood of such attacks, [but] the potential exists."[588] Another report from Aon, a cybersecurity advisory firm, similarly identifies vulnerabilities in BESS systems, finding that their operating systems and components can be out of date and lacking in sophisticated security measures.[589] Should these vulnerabilities be exploited, they could be deeply disruptive to the energy systems in which they are embedded.[590] In his report, Mr. Singleton indicates that previous cyberattacks have already targeted energy systems, such as a 2022 ransomware attack on India's Tata Power, one of the country's largest integrated power companies.[591] He warns that in the worst-case scenarios, such attacks could carry grave consequences, including potential blackouts of critical industrial areas and major financial hubs.[592] The Aon report further identifies risks of lithium-ion batteries themselves that underpin BESS systems. These batteries require careful oversight and control for their voltage and temperature.[593] Should a threat actor interfere, these battery cells could rapidly degrade or, in the case of extreme interference, a remote attack could trigger a significant fire or explosion at the site of the BESS system with potentially broader consequences for the local grid, a point echoed by Dr. Jeffrey Nadaner, former Deputy

*One GW is equivalent to 1,000 megawatts and represents roughly the same energy output of two coal-fired powerplants, enough to power 750,000 homes in the United States. Mary Pressler, "The US Installs 15.1 Gigawatts of Generation So Far in 2022," *Quick Electricity*, September 1, 2022; Dana Hull, "California Hits Renewable Energy Milestone: 1 Gigawatt of Solar Power Installed to Date," *Mercury News*, November 8, 2011.

†A gigawatt hour (GWh) is a flow measurement of electrical output over one hour. 1 GW of installed capacity produces 1 GWh of electricity in an hour, 168 GWh in a week, and 8,760 GWh over one year.

Assistant Secretary of Defense for Industrial Policy, in testimony before the Commission.*[594]

These battery storage systems are complemented by other Chinese equipment also being installed in the U.S. power grid. As Joe Weiss describes in *Control*, from 2006 through 2023, the United States has imported around 450 transformers over 10,000 kilo-volt-amperes (kVA) from China.[595] More than 360 of these Chinese-made transformers were large transmission systems over 100,000 kVA that are key to operating the electrical grid.[596] Mr. Weiss warns that despite some executive action† to limit foreign influence in the electrical grid, U.S. utility firms continue to buy Chinese equipment, including more than 125 large Chinese transformers since 2020.[597] Chinese energy storage batteries and related equipment are increasingly installed in U.S. power networks.

Batteries Linger in U.S. Networks

Despite efforts to remove Chinese batteries from some U.S. critical networks, such as the U.S. military's ban on buying Chinese batteries, Chinese-produced batteries remain critical parts of the supply chain for the U.S. government.[598] According to Dr. Nadaner's testimony before the Commission, between 2018 and 2023, 1,503 battery suppliers to U.S. government agencies relied on Chinese components in their supply chain, more than double Japan (462) and Germany (392), the second and third leading component suppliers.[599] Last year, Chinese-produced industrial batteries were unplugged at Camp Lejeune due to congressional concerns of the potential risks these batteries posed to disrupting the military installation's power supply and energy infrastructure.[600] Experts claim that a BESS system such as the one installed at Camp Lejeune requires frequent remote operation and that telecommunications equipment connected to the batteries could be vulnerable to hacking attempts.[601] Preceding the batteries' removal, 27 lawmakers signed a letter warning that "CATL could introduce malware into large-scale power storage stations, threatening the U.S. energy grid" and that the presence of CATL batteries in U.S. military installations and critical infrastructure "raise[s] several concerns that a malicious actor, or government, could seek to exploit."[602] Mike Casey, director of the National Counterintelligence and Security Center, further warns against the risks introduced by Chinese battery storage systems: "We encourage power companies interested in using these industrial battery energy storage systems from China to think beyond the short-term cost savings they may realize and consider the potential long-term vulnerabilities and how to mitigate them."[603]

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*The simultaneous detonation of Hezbollah devices in Lebanon in September 2024 demonstrated the feasibility of prepositioning in a network and carrying out a coordinated remote sabotage strike. Though the context in which this attack occurred and the tactical approach are unique, the event underscores the imperative to ensure remote backdoor capabilities are not built into battery systems in U.S. networks, given these systems' inherent explosive quality. Bruce Schneier, "Israel's Pager Attacks Have Changed the World," *New York Times*, September 22, 2024; Craig Singleton, "Beijing's Power Play," *Foundation for Defense of Democracies*, October 23, 2023.

†Executive Order 13920, signed May 1, 2020, by the Trump Administration, directed the U.S. Department of Energy to lead interagency efforts to ensure purchases of bulk power systems used in the U.S. electrical grid from entities controlled by a foreign adversary did not pose unacceptable national security risk. The executive order has since been suspended by the Biden Administration. Joe Weiss, "The U.S. Electric Industry Is Not Responding to Cyber-Vulnerable Chinese Equipment," *Control*, February 29, 2024; Executive Office of the U.S. President, "Securing the United States Bulk-Power System," *Federal Register* 85:26595 (May 4, 2020).

U.S. Efforts to Restrict Chinese EVs

With greater U.S. investments to transition from carbon-based energy sources, the Biden Administration is moving to prevent U.S. firms from opting for widely available Chinese-made energy technology, particularly in the transportation sector. In December 2023, the Administration explicitly restricted Chinese EV suppliers from receiving tax credits and incentives from the Inflation Reduction Act by designating them as a Foreign Entity of Concern (FEOC).*[604] The raft of tariff increases the Administration announced in May 2024 brings the rate on Chinese EVs under Section 301 up from 25 percent to 100 percent and on Chinese batteries from 7.5 percent to 25 percent, citing unfair subsidies and rapid growth of Chinese exports as threatening to U.S. producers.[605]

Despite growing scrutiny, U.S. firms have maintained partnerships with Chinese battery producers. For example, Ford announced in February 2023 that it would start producing low-cost lithium-ion batteries by 2026 at its plant in Michigan using technology licensed from CATL.[606] This illustrates one of the main challenges for U.S. industries seeking to reduce reliance on Chinese batteries. Even if the United States reduces dependencies on physical Chinese batteries, China continues to dominate battery supply chains and even research in battery technology, publishing about half of the world's research on battery efficiency.[607] As a result, Chinese firms often maintain an edge over U.S. competitors in technology, IP, and know-how in battery manufacturing.[608] Ford is therefore in an unenviable position of licensing state-of-the art CATL technology and IP, even as the Administration seeks to limit the reach of Chinese battery makers in the United States.[609] The planned partnership appears set to proceed amid bipartisan congressional concerns and the Administration's new rules, which do not directly prohibit the Ford-CATL agreement.[610]

Internet of Things (IoT) Raises Growing Concern

There is rising concern of potential security threats to U.S. networks associated with Chinese-made devices.[611] In recent years, the Federal Communications Commission (FCC) has placed ten Chinese companies—including Huawei, ZTE, and Hangzhou Hikvision Digital Technology—on its Covered List that prevents the marketing, sale, or operation of any equipment within the United States due to national security risks.[612] Recent attention has focused on cellular modules produced by Chinese companies, which connect IoT† devices to the internet that have the potential to be remotely accessed and controlled from China.[613] Chi-

*Under the rules set to be implemented over 2024, companies will be denied tax credits if vehicle batteries contain components that were manufactured or assembled by an FEOC. Beginning in 2025, the rules expand in scope to disqualify any vehicles whose batteries contain any critical minerals extracted, processed, or recycled by an FEOC. U.S. Department of the Treasury, *Treasury Releases Proposed Guidance to Continue U.S. Manufacturing Boom in Batteries and Clean Vehicles, Strengthen Energy Security*, December 1, 2023.

†An IoT device could connect any electronic device to the internet, such as vehicles and home appliances. David Shepardson, "US FCC Chair Says China's Quectel, Fibocom May Pose National Security Risks," *Reuters*, September 6, 2023; U.S. House of Representatives Select Committee on the Strategic Competition between the United States and the Chinese Communist Party, *Letter to FCC Chair on Chinese Internet Connectivity Modules*, August 8, 2023.

Internet of Things (IoT) Raises Growing Concern—*Continued*

na's government has sustained policies to boost IoT development, including accelerating IoT research and applications in the State Council's "Made in China 2025" plan released in 2015.[614] China is one of the largest producers of IoT equipment globally, with three Chinese companies, Quectel (37.1 percent), Fibocom (6.9 percent), and China Mobile (6.8 percent), collectively holding about half of the global market as of the first quarter in 2024.[615] In September 2023, the FCC reportedly raised security concerns about two Chinese IoT module companies, Fibocom and Quectel, to U.S. government agencies with the relevant authority to consider whether they pose national security risks.*[616]

The United States is separately considering measures to address potential privacy, data security, and cyber security concerns associated with Chinese-made EVs. Similar to the concerns raised by Mr. Singleton, independent cybersecurity researchers have demonstrated the ability of Chinese-made EVs and EV charging equipment to collect and transmit data back to China and install malware.[617] In February 2024, the Commerce Department issued an Advanced Notice of Proposed Rulemaking to address threats stemming from "connected vehicles" from China.[618] On September 23, 2024, BIS released a Notice of Proposed Rulemaking to address security concerns from connected vehicles that, if finalized, will prohibit the sale or import of certain types of Chinese hardware and software integrated into vehicle connectivity systems and automated driving systems to take effect for model years 2027 and 2030, dependent on the type of technology.[619]

Implications for the United States

U.S.-China technology competition is foundational to both U.S.-China economic competition and national security. China has realized the importance of technology supremacy for decades and consistently implemented policies designed to gain an edge in technologies of the future. If China surpasses the United States in the development and deployment of these technologies at scale, industries critical for the United States and its allies could become overly reliant on China, and the balance of regional and global power could shift in the PLA's favor. The United States has already begun to take aggressive steps to ensure continued U.S. technological leadership in these sectors through domestic investments, export controls, and investment restrictions, and it is considering other policies, but some hurdles remain.

Advanced computing technology, including AI, is at the forefront of U.S.-China technology competition. AI will add tremendous value to the global economy and reshape a swath of industries. AI also has

*Quectel refuted concerns raised regarding the security of its modules. In a press release, Quectel Wireless Solutions stated that "Quectel customers own the data, and [Quectel has] no access to any of the data collected." *Business Wire*, "Quectel Response to FCC about IoT Module Security," September 7, 2023; David Shepardson, "US FCC Chair Says China's Quectel, Fibocom May Pose National Security Risks," *Reuters*, September 6, 2023.

the potential to transform the military balance between the United States and China by helping both militaries improve their data analysis, accelerate battlefield decision-making, and more effectively target the adversary.[620] One key to AI competition is advanced semiconductors, where the United States has a lead but China is investing heavily to catch up. Separately, there is a risk that China may flood the world with cheap legacy semiconductors, forcing prices down, which may threaten the viability of other countries' legacy semiconductor industries and provide China with significant global economic leverage. Another aspect of competition in AI is the quality and performance of AI models. Amid a vigorous debate within the AI industry over whether open source or closed source models are the better approach, entities in China have been using U.S. open source models as the basis for some of their technological advances. There is not currently a U.S. policy framework that focuses on the differences between the two approaches for U.S.-China technology competition. Moreover, experts have also expressed concern over the need to address cloud computing, a key potential workaround that could allow Chinese firms or even the PLA itself to access highly advanced AI and quantum computing capabilities located in different countries and delivered remotely via the cloud.[621] While existing controls on AI have limited such access to a certain extent, technological change, developments in global markets, and evolving Chinese policy responses all underscore the importance of regularly reviewing U.S. export controls and related policies.

While practical breakthroughs from QIS are generally yet to be realized, the potentially profound economic and national security implications of such technologies require close scrutiny. The country that has the edge in quantum technologies will be able to protect its communications networks from eavesdropping and interception, break adversaries' encryption methods, bolster its scientific research, and deploy advanced sensing capabilities to detect enemy military assets.[622] To date, the U.S. export control policy response for QIS has been limited, at least in part because defense applications have been viewed as less achievable within the short to medium term for most aspects of QIS other than quantum sensing.[623] Unlike the advanced semiconductor controls used for AI, U.S. quantum technology controls primarily only target specific Chinese end users instead of the other enabling technology categories. Questions remain regarding the effectiveness of the end user approach, the utility of broader controls on enabling technologies and access to R&D and know-how, and potential opportunities for multilateral cooperation with allies.[624]

U.S.-China competition in biotechnology will have significant economic impacts in terms of capabilities in numerous technologies and manufacturing industries of the future, and for some applications it will have direct national security implications. In addition, genomic-related biotechnologies raise concerns about data collection, including access to sensitive health and genetic data on U.S. citizens and abuse for surveillance purposes. At the same time, many applications of biotechnology would provide overall benefits to healthcare, medicine, and related technologies, and traditionally, cooperative scientific research in such fields has been supported. While the

United States leads in many areas of innovation in biotechnology, Chinese biotechnology companies such as BGI and WuXi have become integral in U.S. genomic and pharmaceutical supply chains, raising concerns over dependency for medical and agricultural products. Furthermore, these companies are obtaining advantages over time due to their access to sensitive data and proprietary commercial information, an area of particular concern given their alleged ties to the PLA.

Finally, the rapid expansion and dominant position China has attained in the global battery industry presents an expansive challenge for policymakers in an emerging technology with major implications for the transition to clean and renewable energy systems. With China's overwhelming presence throughout the battery production supply chain, Chinese companies are poised to maintain substantial advantages and market share for powering clean energy technologies that rely on batteries, likely requiring U.S. manufacturers to rely on suppliers and IP from China at least for the short and medium term.[625] Moreover, the proliferation of Chinese batteries within U.S. networks, including vital energy infrastructures, creates cyber security-related concerns, vulnerabilities to remote manipulation, and sabotage. Experts indicate that Chinese-made batteries heighten the risk of espionage or unforeseen energy supply disruptions and system failures as they become further integrated into critical U.S. operations.[626] Recent U.S. policies have taken limited steps to address these challenges, specifically provisions in the Inflation Reduction Act incentivizing domestic production of clean energy vehicles and the recent Advanced Notice of Proposed Rulemaking to study risks from connected vehicles and associated systems.

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