Nations Play Their Chips

Nir Kshetri, The University of North Carolina at Greensboro
Jeffrey Voas, IEEE Fellow
Ralf Bebenroth, Kobe University

Countries rely on technology for the defense, prosperity, and well-being of their citizens. Here we investigate how a recent scarcity of semiconductor chips has impacted the three largest economies and spurred them into action.

The world faces a semiconductor shortage.[1] This shortage was estimated to cost the U.S. economy $240 billion in 2021.[2] In 2021, chip shortages forced automobile companies to cut scheduled production of vehicles by 11.3 million units.[3] The shortage of semiconductors seems to have recently eased due to worldwide gross domestic product declines, but it still remains a concern. An estimate has suggested that automobile companies cut scheduled vehicle production by 3.8 million units in 2022.[3]

Semiconductor production activities are highly geographically concentrated. One hundred percent of the world's highly advanced logic semiconductor (smaller than 10 nm) manufacturing capacity is in Taiwan and South Korea.[4] This makes global chip supply chains vulnerable to events such as natural disasters and geopolitical instability.[5] Unsurprisingly, governments in major economies have shown an interest in building less geographically concentrated semiconductor supply chains. These governments have also realized that public support is required to address this challenge.[6]

Here we highlight the effects of semiconductor shortages in the world's three largest economies: China, Japan, and the United States (see Table 1). We also focus on how the governments in these countries are responding. This article is the result of surveying much existing literature.

CHINA

Just like other major economies, China started facing a shortage of semiconductor chips when the COVID-19 pandemic started disrupting global supply chains. (Note that there exists a huge gray market for chips in China, which consist of many intermediaries. Second-hand or out-of-date chips may be sold at as much as 500 times the original cost.[7])

The shortage worsened after the United States imposed export-control measures, which started in October 2022, to cut off China from advanced semiconductor chips and

Digital Object Identifier 10.1109/MC.2023.3240451
Date of current version: 5 April 2023

EDITOR NIR KSHETRI
University of North Carolina at Greensboro;
nbkshetr@uncg.edu

chip-making equipment.[8] The new rules require U.S. companies such as Nvidia and AMD to stop supplying Chinese chipmakers with equipment that can produce advanced chips unless they obtain permission. Export controls have also been introduced to include some semiconductor production items.[9] Moreover, U.S. companies cannot engage in transactions with Chinese firms for some end uses of certain types of integrated circuits or chips. Companies such as Taiwan Semiconductor Manufacturing Company Limited (TSMC) are prohibited from producing sophisticated microchips in China.[10] U.S. citizens and green card holders are also banned from working on certain chip technology for Chinese entities.[9] The U.S. Department of Commerce's Bureau of Industry and Security argued that China could use these chips to "produce advanced military systems," although the chips can also be used for civilian purposes.[10]

Although China is the world's largest car producer and global leader in electric vehicles, the country relies on Europe, the United States, and Taiwan for almost all the advanced chips needed. A zero-COVID-19 lockdown further worsened the situation.[11]

POLICY RESPONSE AND POSSIBLE OUTCOMES

China is fighting back. In December 2022, the news media reported China's plan to provide a support package of more than 1 trillion yuan (US$143 billion) over a five-year period to develop its semiconductor industry. A significant part of the funding will go to the purchase of domestic semiconductor equipment for chip-producing foundries (fabs). Chinese companies will receive a subsidy of up to 20% on the cost of equipment and receive tax breaks for investing in assembly, packaging, and R&D of chips.[12]

JAPAN

Japanese companies had dominated the global semiconductor market in the 1980s.[13] However, this dominance started to diminish in the late 1980s when semiconductor designers moved toward outsourced manufacturing. In the fabless model, which involves outsourcing fabrication of the chips, a company designs and sells the hardware and semiconductor chips but relies on chip-making factories known as *foundries* to manufacture the chips. TSMC has been credited for pioneering the "foundry and fabless" model.[1]

In the past 15 years, Japanese companies have not made investments to benefit from the semiconductor production process's evolution.[5] To meet the demands of its electronic device makers, Japan has relied heavily on chips imported from South Korea and Taiwan.[13]

Industries in Japan have suffered. In September 2022, Toyota Motor Corporation announced that due to semiconductor shortages, it would reduce its production to roughly 800,000 vehicles worldwide in the following month from its original plan of 900,000 vehicles. Likewise, Honda Motor Company was forced to reduce its car production by up to 40% at two of its plants in Japan in October.[14]

This has had a clear impact on corporate bottom lines. In the second quarter (Q2) of 2022, Toyota's profit fell by 18%, compared to 2021 Q2.[15] Likewise, Honda's profit in the same period fell by 33%.[16]

POLICY RESPONSE AND POSSIBLE OUTCOMES

According to the Ministry of Economy, Trade and Industry (METI), Japan's share of the world's semiconductor market was 50% in 1990; that was reduced to 10% in 2021.[17] Japan hopes

TABLE 1. Effects of the semiconductor shortage on the world's three biggest economies and their policy responses.

	Current Situation	Response
China	• Chip shortage worsened following U.S export-control measures • A huge gray market for chips • A zero-COVID-19 lockdown worsened the situation	• December 2022: a plan to provide a support package of $143 billion over a five-year period • Tax breaks for investing in assembly, packaging, and R&D of chips
Japan	• Major industries have suffered heavily • Auto companies such as Toyota Motor Corporation and Honda Motor Company were forced to reduce their car production; profits fell significantly	• Abandoned its economic nationalism in favor of open alliances; current orientation toward development of the domestic semiconductor is in favor of international integration Cooperation • Subsidies for the construction of chip facilities
The United States	• Cost the economy $240 billion in 2021 • As of the end of 2021, 8 million fewer cars were made	• CHIPS and Science Act: a $280 billion package to develop domestic semiconductor manufacturing, including $52 billion in subsidies for research and production of semiconductors • Some states and cities have provided targeted subsidies for specific chip manufacturers

to recapture at least 20% of the global semiconductor market by 2030.[5] Japanese policymakers know that drastic measures are needed.

Prime Minister Fumio Kishida's recent engagement with his counterparts in the United States and the European Union have focused on improving Japan's global connections.[5] In May 2022, the Japanese METI minister visited the semiconductor research facility Albany NanoTech Complex in Upstate New York to discuss cooperation on developing next-generation semiconductor production technologies.[18]

The Japanese government has realized that semiconductor is an area where policy intervention and support, such as subsidies, are critical. In June 2022, METI announced US$3.5 billion subsidies for the construction of a US$8.6 billion chip factory in the Kumamoto prefecture. The factory is a joint venture between TSMC and two Japanese companies: Sony and Denso. The production will begin by the end of 2024. The factory is expected to be the most advanced production facility in Japan. Likewise, in July 2022, the Japanese government announced a US$690 million subsidy for a joint venture between Japanese company Kioxia and U.S. firm Western Digital to upgrade a chip facility in Kansai.[5]

Japanese policymakers think that investments by TSMC and partnerships with companies from allied nations such as the United States will serve as an insurance policy against the uncertainties associated with possible semiconductor supply-chain disruptions.[5]

The production capacity of these companies would satisfy only a fraction of the total chip demand. For instance, the monthly production volume for TSMC's facility is expected to be 50,000–60,000 silicon wafers a month.[5] Silicon wafers are the materials used in the production of semiconductor chips. In 2021, Japanese automakers manufactured ~16.46 million vehicles at production facilities outside Japan[19] and 7.85 million in Japan.[20] A typical car requires between 50 and 150 semiconductors,[21] and a modern car may use as many as 3,000.[22] Especially electrified vehicles and cars equipped with advanced driver-assistance systems require more semiconductors per vehicle.[14]

According to the Japan Electronics and Information Technology Industries Association, the chip sector may also face a challenge in securing enough workers to innovate and operate the factories. To fill the demand for talent required by their investments in the next 10 years, the country's eight big producers will have to hire approximately 35,000 engineers.[23] Universities have started training hundreds of new engineers to meet the industry's workforce demand.[5]

THE UNITED STATES

According to Goldman Sachs, 169 industries in the United States use semiconductors in their products. And more modern products utilize more chips. Solving the semiconductor shortage is becoming increasingly challenging due to rapidly rising demands for products utilizing chips. For instance, in 2021, demand for semiconductors was 17% higher than in 2019.[25] In 2022, U.S. semiconductor production accounted for 12% of the global total, compared to 37% in early 2010s.[26]

Due to semiconductor scarcity, U.S. automakers such as General Motors and Ford are selling vehicles with some missing convenience features, such as heating, ventilation, and air-conditioning chips and heated-seat controls.[3] As of the end of 2021, 8 million fewer cars were made in the United States, which cost automakers approximately US$210 billion in revenue.[2]

The current shortfall of chips has been even more pronounced in "less advanced" chips because the world's biggest semiconductor producers have focused on "cutting-edge" chips that offer higher profit margins.

POLICY RESPONSE AND POSSIBLE OUTCOMES

In August 2022, President Joe Biden signed the CHIPS and Science Act into law. The Act provides a US$280 billion package to develop U.S. domestic semiconductor manufacturing, including US$52 billion in government subsidies for research and production of semiconductors.[26]

In addition, some states and cities have also provided targeted subsidies for specific chip manufacturers. For instance, in 2020, the city of Phoenix approved financial incentives and support for TSMC, which included US$200 million to develop roads, sewers, and other infrastructure and US$500,000 for additional sets of traffic lights.[27] Likewise, the state of Ohio promised to provide Intel more than US$2 billion in economic development subsidies. This was reported to be the largest single-project subsidy in the state's history.[28]

These subsidies and other forms of support have shown some encouraging results. In 2020, TSMC announced a plan to spend US$12 billion to build a semiconductor plant in Arizona (known as *Fab 21*), which is expected to be completed in 2024. The facility's opening ceremony was held in December 2022.[26]

In December 2022, TSMC revealed its plan to further increase its investment in the Arizona fab to US$40 billion and build a second plant on the site. The second phase of Fab 21 will produce 3-nm chips. The production is expected to begin in 2026.[30]

The first plant will produce 20,000 5-nm advanced process wafers per month.[30] After completion of the second plant, TSMC's capacity is expected to expand to ~50,000 wafers per month.[31] TSMC will create 13,000 high-technology jobs in the area.[29] TSMC also estimated that the two plants will generate an annual revenue of US$10 billion when they open. In addition, TSMC customers are expected to have annual sales of US$40 billion from products using TSMC chips manufactured in Arizona plants.[25]

TSMC is expected to see significant cost increases in its U.S. plants. For instance, the Arizona fab's total cost of ownership (TCO) is estimated to be more than five times of its TCO in Taiwan.[32] However, on the plus side, the company has or will receive significant subsidies for its Phoenix plant. Roughly US$40 billion of the US$52 billion subsidies in the CHIPS and Science Act is allocated to provide incentives for chip manufacturers such as Intel, Samsung, and TSMC. Likewise, as mentioned, Phoenix has provided TSMC with significant financial incentives.

Similarly, in November 2021, Samsung announced a plan to build a US$17 billion semiconductor factory in Taylor, Texas.[33] In January 2023, the company's CEO reported that the facility's construction was progressing and that production will start by the end of the year. The company's plan has been to produce 3-nm chips in the beginning and move to 2-nm chips in 2025.[35] And in February 2021, Intel announced a plan to spend US$20 billion to build chip factories in Ohio. The plant is scheduled to open in 2025 and employ at least 3,000 people.[2]

The semiconductor shortage has presented significant costs to national economies. One important lesson from Taiwan and South Korea is that government support played a key role in the growth of their semiconductor industries. The governments of the world's three biggest economies are realizing that some form of public support is probably needed to develop this industry locally. ■

REFERENCES

1. J. Voas, N. Kshetri, and J. F. DeFranco, "Scarcity and global insecurity: The semiconductor shortage," *IT Prof.*, vol. 23, no. 5, pp. 78–82, Sep./Oct. 2021, doi: 10.1109/MITP.2021.3105248.
2. O. Villafranca, "Chip shortage cost U.S. economy billions in 2021," *CBS News*, Jan. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.cbsnews.com/news/chip-shortage-cost-us-economy-billions-in-2021/
3. B. Vigliarolo, "US car industry leads the world in production cuts over chip shortages," *Register*, Aug. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.theregister.com/2022/08/09/car_chip_shortage/
4. "SIA urges U.S. government action to strengthen America's semiconductor supply chain," Semiconductor Industry Assoc., Washington, DC, USA, Apr. 2021. [Online]. Available: https://www.semiconductors.org/sia-urges-u-s-government-action-to-strengthen-americas-semiconductor-supply-chai
5. B. Dooley and H. Ueno, "Japan once led the world in microchips. Now, it's racing to catch up," *NY Times*, Aug. 2022. [Online]. Available: https://www.nytimes.com/2022/08/04/business/japan-semiconductors-chips.html
6. N. Kshetri and J. Voas, "Where's the Silicon?" *Computer*, vol. 54, no. 8, pp. 11–12, 2021, doi: 10.1109/MC.2021.3055877.
7. "Woman with fake baby bump caught smuggling computer chips into China," *Bloomberg*, Dec. 2022. [Online]. Available: https://www.bloomberg.com/news/articles/2022-12-02/woman-with-fake-baby-bump-caught-smuggling-computer-chips-into-china
8. S. Mellor, "China's chip shortage is so bad a woman was just caught smuggling semiconductors inside a fake baby bump," *Fortune*, Dec. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://fortune.com/2022/12/02/china-chip-shortage-woman-caught-smuggling-semiconductors-inside-fake-baby-bump/
9. V. Harrison and M. Farrer, "What do US curbs on selling microchips to China mean for the global economy?" *Guardian*, Oct. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.theguardian.com/world/2022/oct/19/what-do-us-curbs-on-selling-microchips-to-china-mean-for-the-global-economy
10. B. Harris, "How Biden's microchip ban is curbing China's AI weapons efforts," *Defense*, Jan. 2023. Accessed: Jan. 25, 2023. [Online]. Available: https://www.defensenews.com/global/asia-pacific/2023/01/12/how-bidens-microchip-ban-is-curbing-chinas-ai-weapons-efforts/
11. "How China became ground zero for the auto chip shortage," *Reuters*, Jul. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.voanews.com/a/how-china-became-ground-zero-for-the-auto-chip-shortage-/6670710.html
12. M. Gooding, "China has a $143bn semiconductor plan to beat US chip sanctions," Tech Monitor, London, U.K., Dec. 2022. [Online]. Available: https://techmonitor.ai/technology/silicon/china-semiconductor-manufacturing-us
13. S. Hasan, "Can Japan's semiconductor industry make a comeback?" *TRT World*, Dec. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.trtworld.com/magazine/can-japan-s-semiconductor-industry-make-a-comeback-63529
14. "Toyota's October vehicle output to be weighed down by chip shortage," *Jpn. Times*, Sep. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.japantimes.co.jp/news/2022/09/22/business/toyota-oct-chip/
15. "Toyota profit down as chips shortage keeps customers waiting," *Hurriyet Daily News*, Aug. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.hurriyetdailynews.com/toyota-profit-down-as-chips-shortage-keeps-customers-waiting-175861
16. "Honda sees declining profits on semiconductor crunch," *Asahi*, Aug. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.asahi.com/ajw/articles/14692079

DISCLAIMER

The authors are completely responsible for the content in this column article. The opinions expressed here are their own.

17. M. Duchâtel, "Racing for the new rice - Japan's plans for its semiconductor industry," Institut Montaigne, Paris, France, Aug. 2021. [Online]. Available: https://www.institutmontaigne.org/en/analysis/racing-new-rice-japans-plans-its-semiconductor-industry
18. "Minister Hagiuda visits the United States of America," Ministry of Economy, Trade and Industry, Tokyo, Japan, May 2022. [Online]. Available: https://www.meti.go.jp/english/press/2022/0506_003.html
19. "Total overseas vehicle production volume of Japan's automotive manufacturers from 2012 to 2021 (in million units)." Statista. Accessed: Jan. 25, 2023. [Online]. Available: https://www.statista.com/statistics/658861/japan-overseas-automobile-production/#:~:text=In%202021%2C%20Japanese%20automakers%20manufactured,million%20in%20the%20previous%20year
20. "Total production volume of motor vehicles in Japan from 2012 to 2021 (in million units)." Statista. Accessed: Jan. 25, 2023. [Online]. Available: https://www.statista.com/statistics/675241/japan-motor-vehicle-production/
21. H. Ziady, "The global chip shortage is going from bad to worse. Here's why you should care," *CNN*, May 2021. Accessed: Jan. 25, 2023. [Online]. Available: https://www.cnn.com/2021/04/29/business/chip-shortages-smartphones-consumer-goods/index.html
22. "A tiny part's big ripple: Global chip shortage hobbles the auto industry," *NY Times*, Oct. 2021. Accessed: Jan. 25, 2023. [Online]. Available: https://www.nytimes.com/2021/04/23/business/auto-semiconductors-general-motors-mercedes.html#:~:text=One%20big%20reason%20automakers%20can,have%20more%20than%203%2C000%20chips
23. "Japan's biggest chipmakers from Toshiba to Sony brace for engineer shortage," *Financial Times*, Jun. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.ft.com/content/b90da329-a2e5-486a-860f-a20a3afc707a
24. "Results from semiconductor supply chain request for information," U.S. Dept. Commerce, Washington, DC, USA, Jan. 2022. [Online]. Available: https://www.commerce.gov/news/blog/2022/01/results-semiconductor-supply-chain-request-information
25. S. Holland and J. L. Lee, "TSMC triples Arizona chip plant investment, Biden hails project," *Reuters*, Dec. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.reuters.com/technology/biden-visit-taiwans-tsmc-chip-plant-arizona-hail-supply-chain-fixes-2022-12-06/
26. M. Kelly, "Biden signs $280 billion CHIPS and science act," *Verge*, Aug. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.theverge.com/2022/8/9/23298147/biden-chips-act-semiconductors-subsidies-ohio-arizona-plant-china
27. "Phoenix approves TSMC incentives," *Taipei Times*, Nov. 2020. Accessed: Jan. 25, 2023. [Online]. Available: https://www.taipeitimes.com/News/biz/archives/2020/11/20/2003747217
28. K. Tarczynska, "Opinion: Massive Ohio subsidy deals need transparency, accountability," *Cincinnati*, Oct. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.cincinnati.com/story/opinion/contributors/2022/10/28/opinion-massive-ohio-subsidy-deals-need-transparency-accountability/69596057007/
29. E. Huang, "TSMC's U.S. tool-in ceremony is over, what's next?" *Common Wealth Mag.*, Dec. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://english.cw.com.tw/article/article.action?id=3346
30. H. Chang, "What is TSMC doing building a fab in the American desert?" *Common Wealth Mag.*, Oct. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://english.cw.com.tw/article/article.action?id=3162
31. A. Shilov, "TSMC unveils major U.S. fab expansion plans: 3nm and $40 billion by 2026," *Anand Tech*, Dec. 2022. Accessed: Jan. 25, 2023. [Online]. Available: https://www.anandtech.com/show/18682/tsmc-unveils-major-us-fab-expansion-plans-3nm-and-40-billion
32. "Taiwan semiconductor: Trapped in costly Arizona," *Seeking Alpha*, Jan. 2023. Accessed: Jan. 25, 2023. [Online]. Available: https://seekingalpha.com/article/4569500-taiwan-semiconductor-trapped-in-costly-arizona
33. "Samsung says it will build $17 billion chip factory in Texas," *Asahi*, Nov. 2021. Accessed: Jan. 25, 2023. [Online]. Available: https://www.asahi.com/ajw/articles/14487832
34. P. Mehra, "Samsung's US chip plant to be completed by end of 2023, confirms CEO," *TechCircle*, Jan. 2023. Accessed: Jan. 25, 2023. [Online]. Available: https://www.techcircle.in/2023/01/16/samsung-s-us-chip-plant-to-be-completed-by-end-of-2023-confirms-ceo/

NIR KSHETRI is a professor of management in the Bryan School of Business and Economics, University of North Carolina at Greensboro, Greensboro, NC 27412 USA, and the "Computing's Economics" column editor for *Computer*. He is a research fellow at Kobe University, Kobe, Japan. Contact him at nbkshetr@uncg.edu.

JEFFREY VOAS, Gaithersburg, MD 20899 USA, is the editor in chief of *Computer*. He is a Fellow of IEEE, IET, AAAS, and the Washington Academy of Sciences. Contact him at j.voas@ieee.org.

RALF BEBENROTH is a professor at Research Institute for Economics and Business Administration, Kobe University, Kobe 657-8501 Japan. Contact him at rbeben@rieb.kobe-u.ac.jp.