EIRP ENERGY INNOVATION REFORM PROJECT

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DIVERSIFY, DOMESTICATE, AND DISRUPT:

STRENGTHENING AMERICA'S NASCENT EFFORT TO BUILD A RESILIENT AND ROBUST SOLAR PV SUPPLY CHAIN

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01

Introduction

If the United States, South Korea, and the world are to achieve ambitious climate and energy security goals, solar photovoltaics (PV) must play a major role. Does it matter where the PV supply chain is located? It might. All of its stages are highly concentrated in China now. This concentration leaves China's trading partners, including the United States and South Korea, vulnerable to disruption and predation. It may also limit opportunities for process and product innovation that could unlock more rapid cost declines and more diverse applications that accelerate PV adoption worldwide. The United States has taken steps to build a more resilient and robust PV supply chain, but until recently, these steps have been disjointed and tentative. The Inflation Reduction Act (IRA) of 2022 is a game-changer, but it falls short of creating an integrated strategy. The United States should adopt such a strategy, which would combine support for technologically advanced domestic PV manufacturing with diversified international trade in collaboration with allies and partners, such as South Korea. Such a strategy would be costly in the short run (although perhaps less costly than the IRA) and must be weighed against alternative priorities. But it could pay dividends in the long run by reducing risk and potentially sparking a positive disruption in PV technology.

02

Solar Future: The Role of PV in the Energy Transition

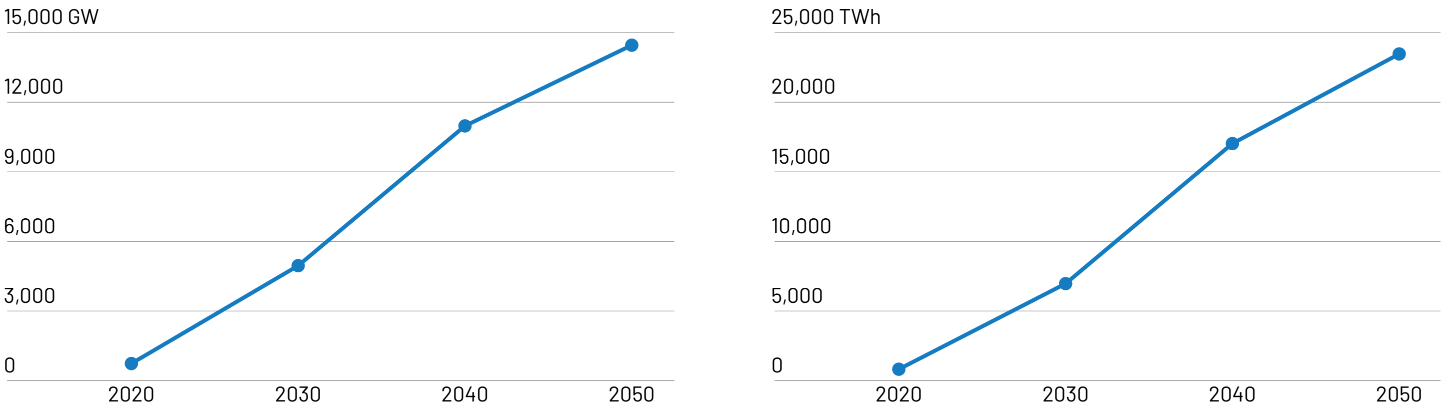
Electricity will be the core resource of the clean energy systems of the future. It is a flexible energy carrier with diverse applications today and great potential to be decarbonized. Looking ahead, low-carbon electricity will be substituted for carbon-intensive fuels in major emission sectors such as transportation and heating, further expanding demand. The Intergovernmental Panel on Climate Change notes that the literature on "net-zero energy systems almost universally calls for increased electrification,"[1] and the Net-Zero Emissions by 2050 scenario (NZE) of the International Energy Agency (IEA) expects electricity demand to grow by more than 2.5 times globally. Electrification moves even more quickly in the NZE in advanced economies like the United States and South Korea.[2]

PV will play a prominent role in the global transition to low-carbon electricity. At the turn of the 21st century, few forecasters expected such a role, but the sustained drop in PV prices since then has pushed this technology to the forefront. In addition to its low cost, PV is modular, durable, relatively easy to site, and low in life-cycle emissions; the same cannot be said for mature low-carbon competitors like nuclear power,

1 Intergovernmental Panel on Climate Change, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. P. R. Shukla et al. (Cambridge and New York: Cambridge University Press, 2022), 676, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf.

2 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA, 2021), 99, https://www.iea.org/reports/net-zero-by-2050.

Figure 1: Global Solar PV Installed Capacity and Electricity Generation in the IEA's NZE Scenario



Source: IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector (IEA, 2021), 198, https://www.iea.org/reports/net-zero-by-2050.

fossil fuel plants with carbon capture, hydropower, and even wind turbines. Solar power has also gained wide public acceptance and has received policy support in more than 130 countries.[3] In the NZE, PV generating capacity grows 20-fold, and it produces a third of the electricity used worldwide in 2050.[4] See figure 1.

At the national level, PV's role in the electricity systems of the future will vary. In the United States, which is blessed with rich renewable resources, solar and wind power dominate the representative pathways to net-zero emissions in the Biden administration's long-term strategy.[5] South Korea's PV demand forecast is cloudier, with current government plans favoring a larger role for nuclear power in the coming decade.[6] Even so, non-hydro renewable capacity and output will continue to grow, nearly tripling their

3 Ibid., 116.

4 For growth in generating capacity, see ibid., 118; for share in worldwide use of electricity in 2050, see ibid., 198. See also Felix Creutzig et al., "The Underestimated Potential of Solar Energy to Mitigate Climate Change," *Nature Energy* 2: 17140 (2017), https://www.nature.com/articles/nenergy2017140.

5 US Department of State and Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (Washington, DC: US Department of State and Executive Office of the President, 2021), 29, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

6 US Energy Information Administration (EIA), "South Korea" (accessed August 17, 2023), https://www.eia.gov/international/analysis/country/KOR.

projected contributions to Korea's power system over that period.[7]

If PV is to fulfill its potential in the global energy transition, supply will have to continue to grow rapidly to meet demand. The NZE estimates that between 2020 and 2030, production capacity would double at each stage of the supply chain for today's dominant crystalline-silicon (c-Si) technology—polysilicon, ingots, wafers, cells, and modules (the supply chain stages are described in box 1). An important question facing world leaders is where this capacity will be located. Currently, China's share at each stage approaches and exceeds 80% (see figure 2).[8] This imbalance did not always exist, nor need it exist in the future.

Box 1: Crystalline-Silicon Solar PV Supply Chain

Polysilicon originates in quartz, which is refined in stages to form ingots. The ingots are sliced into wafers, which are very thin plates with semiconducting characteristics. Wafers are processed into solar cells, which can generate electricity from light, but are individually too small for most applications. Assembling cells into modules (by wiring them together and enclosing them for protection) turns them into usable products. Groups of modules form panels that are sold to PV system customers.[9]

7 Jae-hyuk Park, "US Benefits from Korea's Disinterest in Solar Power Industry," *Korea Herald*, January 13, 2023; Jae Ho Yun and Chinho Park, "South Korea's Solar Power Industry: Status and Prospects," Energy Innovation Reform Project, October 2023.

8 IEA, "Special Report on Solar PV Global Supply Chains," August 2022, 8, https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf.

9 Yun and Park, "South Korea's Solar Power Industry."

03

Invent Here, Produce There: The Hollowing Out of US PV Manufacturing

The first PV device was created by scientists at Bell Labs in New Jersey in 1954.[10] The US government was the main driver of the technology's early development, and most production was domestic. Initial applications focused on satellites and spacecraft, where cost was no object. The oil crises of the 1970s sparked an effort to develop affordable terrestrial applications with a policy mix that combined federal government procurement and electricity regulatory reform with tax incentives and research, development, and demonstration (RD&D) spending.[11]

The Reagan administration pulled back many of these policies as oil prices dropped, but other countries picked up the baton. Japan made PV a top RD&D priority in the 1980s, and its New Sunshine Project encouraged deployment in the 1990s. When Japan cut back its program in the 2000s, Germany ramped its program up. It moved into the lead in RD&D spending and massively expanded installed capacity through a generous feed-in tariff. The United States reentered the picture in the 2000s; California and other US states imposed renewable portfolio standards (RPSs) on utilities that accelerated PV adoption, an effort augmented by federal tax policies starting in 2005.[12]

The global distribution of PV manufacturing up to that point reflected this history. In 2006, Japanese manufacturers held about 40% of the global PV cell market, German manufacturers about 20%, and American manufacturers less than 10%. Within five years, however, the combined share of these three fell to less than 14%. Chinese manufacturers, meanwhile, raised their share from 14% to 60%. South Korean producers also joined the industry, gaining a 3% global market share (see figure 2).

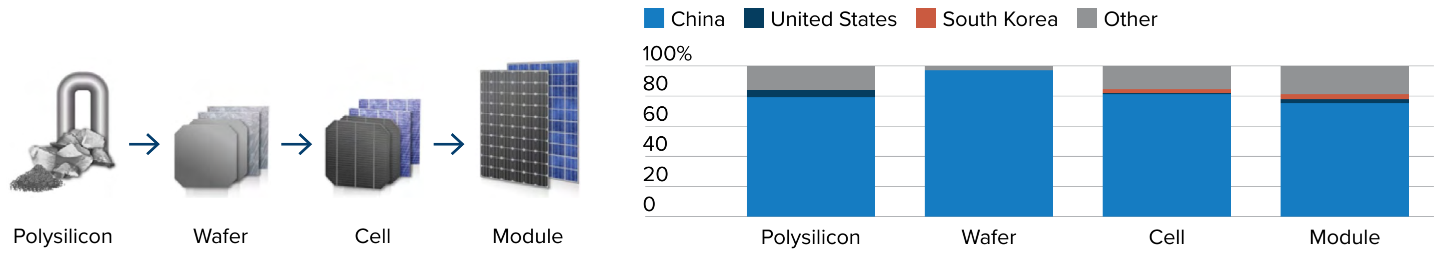
The rise of Chinese PV manufacturing was not centrally planned. The industry initially owed far less to the central government than to entrepreneurs who had returned to China from western countries and were backed by western investors and provincial and local governments. Once these start-ups began

10 This section draws on David M. Hart, "The Impact of China's Production Surge on Innovation in the Global Solar Photovoltaics Industry," Information Technology and Innovation Foundation (ITIF), October 2020, https://itif.org/publications/2020/10/05/impact-chinas-production-surge-innovation-global-solar-photovoltaics/.

11 Details are in Wolfgang Palz, ed., *Solar Power for the World* (Singapore: Pan Stanford, 2014); Gregory F. Nemet, *How Solar Energy Became Cheap* (Routledge, 2019), chapter 4; David M. Hart and Kurt Birson, "Deployment of Solar Photovoltaic Generation Capacity in the United States," paper prepared for DOE Office of Energy Policy and Systems Analysis, June 2016, https://davidhart.gmu.edu/wp-content/uploads/2016/11/PV-GMU-case-study-final-9-19-16.pdf.

12 This history is described in Nemet, *How Solar Energy Became Cheap*, chapters 5–6; Hart and Birson, "Deployment." For a focus on Germany, see Staffan Jacobsson, Bjorn A. Sanden, and Lennart Bangens, "Transforming the Energy System—the Evolution of the German Technological System for Solar Cells," *Technology Analysis & Strategic Management* 16: 3–30 (2004), https://doi.org/10.1080/0953732032000199061.

Figure 2: Production Capacity in the Crystalline-Silicon Solar PV Supply Chain



Source: IEA, "PVPS Trends in Photovoltaic Applications 2022," Photovoltaic Power Systems Programme, 43–48, https://iea-pvps.org/wp-content/uploads/2023/02/PVPS_Trend_Report_2022.pdf.

to prove themselves, however, Beijing moved to support them. The State Council declared PV to be a "strategic emerging industry" in 2010. As the global banking industry foundered during the financial crisis, China's state-owned banks fueled the country's PV manufacturers with cheap credit. The central government also subsidized domestic demand, raising China's share of global PV installations from less than 1% in 2008 to nearly 30% by 2013. This market was served almost entirely by domestic producers, which leveraged this privileged position to cement their global dominance.[13]

13 Nemet, *How Solar Energy Became Cheap*, chapter 7; Kelly Sims Gallagher, *The Globalization of Clean Energy Technology: Lessons from China* (Cambridge: MIT Press, 2014); Ping Huang et al., "How China Became a Leader in Solar Photovoltaics: An Innovation System Analysis," *Renewable and Sustainable Energy Reviews* 64: 777–89 (2016), https://doi.org/10.1016/j.rser.2016.06.061.

04

A Disjointed Response

The demise of international competition in PV manufacturing in the 2010s sparked a disjointed response in the United States. Falling hardware prices, amplified by tax incentives for buyers, accelerated PV deployment. Aspirational targets, such as state-level RPSs, were met with surprising ease and frequently raised and extended. PV project developers and installers benefited. As this domestic downstream industry grew, it sought to maintain supportive policies. Displaced manufacturers cried foul, but to little avail.

The first complaint, in October 2011, alleged that Chinese manufacturers were selling below cost and were supported by excessive government subsidies. The US government responded the next year by imposing tariffs on PV cells and modules imported from China. The tariffs were broadened to include Taiwan in 2015 after Chinese-based firms relocated production there.[14] Production then shifted to other Asian locations, prompting the Trump administration to impose tariffs across a wide range of countries in 2018. This action indiscriminately swept South Korean producers in as well, although bilateral negotiation later exempted some of this trade. The Trump tariffs were extended by the Biden administration in February 2022.[15]

The primary impact of US tariffs has been to raise costs as domestic PV hardware prices diverged from the global norm.[16] Demand for imports nonetheless remained strong through the 2010s, while the domestic supply chain barely budged (figure 4.) Trade protection induced a few module-assembly operations to open or expand in the United States, aided by the annual exemption from the 2018 tariffs of 2.5 GW of imported cells (the main input to modules). The exemption was raised to 5 GW by the Biden administration. Bifacial modules, which comprise a majority of module imports, have also been exempted from the Trump/Biden tariffs.[17]

First Solar, the only remaining large US-headquartered PV manufacturer, is the main exception to these

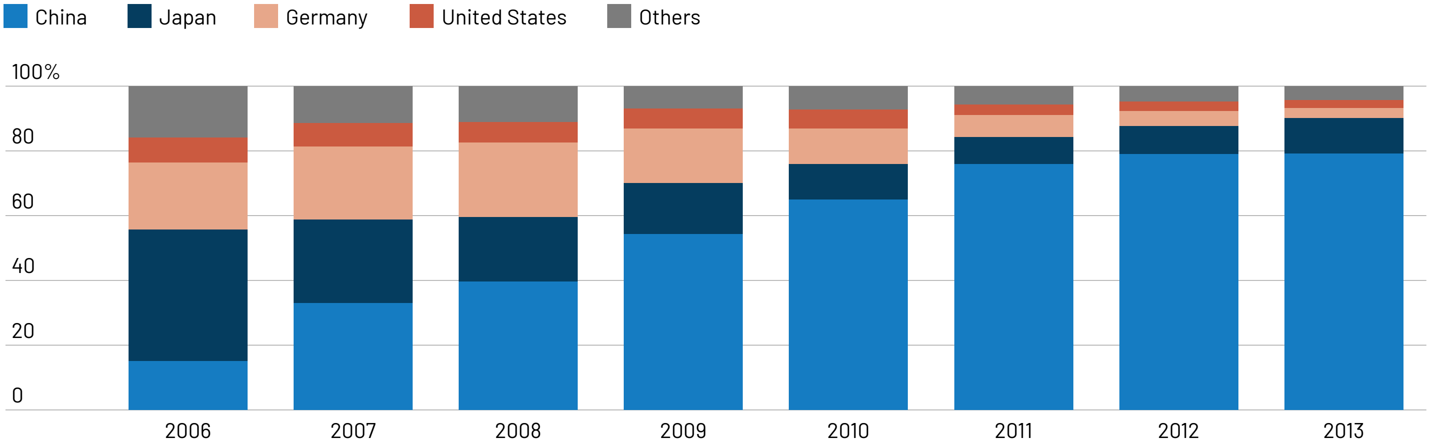
14 Brittany Smith et al., "Solar Photovoltaic (PV) Manufacturing Expansions in the United States, 2017–2019: Motives, Challenges, Opportunities, and Policy Context," National Renewable Energy Laboratory, NREL/TP-6A20-74807, April 2021, https://www.nrel.gov/docs/fy21osti/74807.pdf.

15 Michael Copley, "A Decade into Tariffs, US Solar Manufacturing Is Still Deep in Asia's Shadow," *S&P Global Market Intelligence*, May 23, 2022, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/a-decade-into-tariffs-us-solar-manufacturing-is-still-deep-in-asia-s-shadow-70236202.

16 For an overview of tariff impacts, see Solar Energy Industries Association (SEIA), "The Adverse Impact of Section 201 Tariffs: Lost Jobs, Lost Deployment and Lost Investments," December 2019, https://www.seia.org/sites/default/files/2019-12/SEIA-Tariff-Analysis-Report-2019-12-3-Digital_0.pdf; Copley, "A Decade into Tariffs."

17 David Feldman et al., "Winter 2023 Solar Industry Update," National Renewable Energy Laboratory, January 26, 2023, 40, https://www.nrel.gov/docs/fy23osti/85291.pdf; Smith, "Solar Photovoltaic (PV) Manufacturing Expansions"; Liam Stoker, "Biden Administration Confirms Section 201 Extension, Bifacial Exemption," *PVTech*, February 4, 2022, https://www.pv-tech.org/biden-administration-confirms-section-201-extension-bifacial-exemption/.

Figure 3: Transformation of Global PV Cell Manufacturing, 2006–2013



Source: Earth Policy Institute Data Center, "Climate, Energy, and Transportation" (accessed August 17, 2023), https://www.earth-policy.org/data_center/C23.

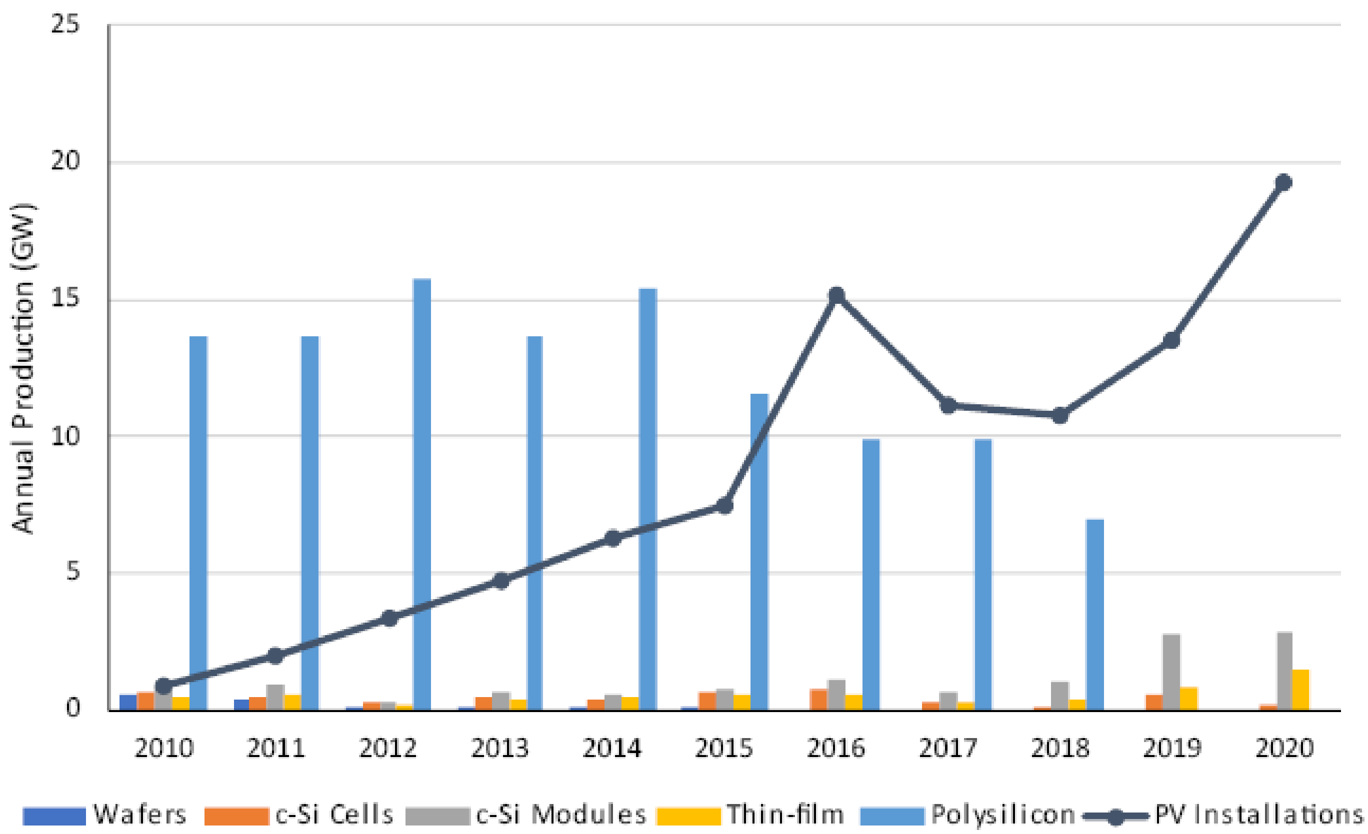
domestic market dynamics. It began expanding aggressively near the end of the decade. It is the only major producer worldwide of cadmium-telluride (CdTe) thin-film cells, an alternative to c-Si, and its supply chain was untouched by the tariffs.[18] (Box 2 briefly describes the main types of PV cells.) But domestic PV production overall satisfied a miniscule share of domestic demand in the 2010s; indeed, retaliatory Chinese tariffs helped decimate the US polysilicon industry, a segment of the PV supply chain that US producers had dominated in the first half of the decade (see figure 4).[19] South Korean polysilicon manufacturers suffered the same fate. While South Korea became an important supplier of cells and modules during this decade, China remained the ultimate source of the bulk of US imports.[20]

18 DOE, "Building a Bridge to a More Robust and Secure Solar Energy Supply Chain," February 2023, 3–5, https://www.energy.gov/sites/default/files/2023-03/Building_a_Bridge_to_a_More_Robust_and_Secure_Solar_Energy_Supply_Chain.pdf.

19 Congressional Research Service, "US Solar Photovoltaic Manufacturing," Report R47093, May 5, 2022, https://crsreports.congress.gov/product/pdf/R/R47093. Notwithstanding generally increasing installations, U.S. polysilicon production plummeted in the second half of the 2010s.

20 Yun and Park, "South Korea's Solar Power Industry."

Figure 4: US Solar PV Demand and Supply, 2010–2020



As of Feb. 24, 2022.
Thin-film solar technology does not rely on the crystalline silicon supply chain, which China dominates.
Source: U.S. Energy Department

Source: DOE, "Solar Photovoltaics: Supply Chain Deep Dive Assessment," February 24, 2022, 6, https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf.

Box 2: Solar PV Cell Technologies

Several types of PV cells are currently available.[21]

- **Crystalline-silicon** cells use materials like those in computer chips. The lattice structure of the silicon crystal makes the conversion of light into electricity efficient. Silicon is abundant. Crystalline-silicon cells have long dominated the market and are used in about 95% of solar panels sold today.
- **Cadmium-telluride** cells use less abundant materials and are less efficient than crystalline-silicon cells, but they are less expensive to manufacture, largely because the photovoltaic material can be deposited as a thin film on a low-cost support. CdTe is the most common thin-film material in the PV market.
- **Perovskite** cells are made from a variety of materials that share a common crystalline structure. They have the potential to combine the low cost of thin-film production with light-to-electricity conversion efficiencies that match or exceed crystalline-silicon. However, the durability and reliability of perovskite cells have not been established in real-world conditions.
- **Other types** of cells include copper indium gallium diselenide (CIGS) thin film, organic, quantum dot, and multi-junction III-V cells. Most of these cell types remain a focus of R&D; some occupy specialized market niches. Cell types can also be combined to make tandem and alternative multi-junction cells.

In June 2022 the Biden administration postponed further tariff increases for two years, preempting administrative proceedings that were headed in that direction. Framing the pause as a "bridge" to a reinvigorated domestic manufacturing industry, the White House authorized federal investments in the PV supply chain under the Defense Production Act and initiated the creation of "super preferences" for domestic content in federal PV procurement.[22] The 2021 bipartisan infrastructure law also made up to $750 million in grants available to small and medium-size manufacturers of various clean energy technologies, including those along the PV supply chain.[23]

21 DOE, "Solar Photovoltaic Cell Basics," https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics.

22 Eric Wesoff, "Biden to Halt Solar Tariff Threat for Two Years," *Canary Media*, June 6, 2022, https://www.canarymedia.com/articles/solar/biden-to-halt-solar-tariff-threat-for-two-years-let-solar-industry-restart; The White House, "President Biden Takes Bold Executive Action to Spur Domestic Clean Energy Manufacturing," June 6, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/06/fact-sheet-president-biden-takes-bold-executive-action-to-spur-domestic-clean-energy-manufacturing/.

23 DOE, "Advanced Energy Manufacturing and Recycling Grants," https://www.energy.gov/mesc/advanced-energy-manufacturing-and-recycling-grants.

05

The Risks of Supply Chain Concentration

These modest steps reflected rising concern in the United States about the risks of excessive dependence on PV imports from China. Recent reports by the IEA and the US Department of Energy (DOE) have catalogued these risks. One set of risks relates to geography. Xinjiang Province, for instance, houses 42% of global polysilicon manufacturing capacity; a single facility there accounts for 14%. Earthquakes shake this province frequently, and climate change threatens its water supply while raising the likelihood of extreme rainfall events. Natural disasters or plant accidents there could disrupt the base of the supply chain.[24]

Xinjiang is also the epicenter of Chinese human rights abuses, including the use of forced labor. "Numerous credible reports" of such abuses in the PV supply chain were acknowledged by the US Solar Energy Industries Association (SEIA)[25] and prompted Congress to pass the Uyghur Forced Labor Prevention Act in late 2021.[26] The act "presumptively prohibits" importing products originating in Xinjiang.[27] Similar ethical risks, along with geopolitical disputes between China and the United States and its allies, will be an enduring threat to any supply chain that is highly concentrated in China.[28]

The combination of supply chain concentration in China with Chinese policies also presents economic risks. While Chinese companies have acquired impressive production capabilities, they still depend on government subsidies. The strongest evidence for this dependence lies in these companies' ability to survive and even expand while capacity utilization is low and profits are near zero, if not negative. "Sudden changes to subsidies," in the IEA's assessment, "would increase the bankruptcy risk for all companies, even the most competitive."[29]

Any change in Chinese government policies that disrupted the Chinese PV industry's growth or exports would ripple through the world energy system. DOE's supply chain analysis notes that constraints due to trade frictions and COVID-19 disruptions slowed installations and raised prices in the United States. As more nations pursue solar-heavy net-zero strategies, competition among them may tighten

24 IEA, "Special Report on Solar PV Global Supply Chains," 58–60. For more on weather-related risk facing Xinjiang Province, see Qian Wang, Pan-Mao Zhai, and Da-He Qin, "New Perspectives on 'Warming-Wetting' Trend in Xinjiang China," *Advances in Climate Change Research* 11: 252–60 (2020), https://www.sciencedirect.com/science/article/pii/S1674927820300678.

25 SEIA, "Supply Chain Ethics and Sustainability," https://www.seia.org/initiatives/supply-chain-ethics-sustainability.

26 Copley, "A Decade Into Tariffs."

27 DOE, "Solar Photovoltaics: Supply Chain Deep Dive Assessment," February 24, 2022, 79, https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf.

28 SEIA, "Supply Chain Ethics and Sustainability."

29 IEA, "Special Report on Solar PV Global Supply Chains," 70; Feldman et al., "Winter 2023 Solar Industry Update," 31.

supply constraints.[30] China has shown a willingness to use its export leverage to advance geopolitical aims, most visibly in a dispute with Japan over rare earths in 2010.[31] While less immediately damaging than an embargo on fuel, export controls on PV supplies would threaten thousands of downstream installation jobs and could slow the low-carbon transition.

A final risk of PV supply chain concentration is that the world will continue to miss out on product innovations that might accelerate cost reductions and performance improvements. China's emphatic entrance into PV manufacturing locked in the c-Si paradigm and wiped out companies pursuing alternative product technologies, including in South Korea, Germany, and the United States. First Solar is a rare survivor.[32] The specter of a similar fate continues to hang over would-be innovators outside of China. Yet a new or at least complementary technological paradigm at scale may well be needed to sustain the deployment of PV at the pace required to achieve global net-zero goals. C-Si cells are hitting efficiency limits, embody more carbon than alternatives, and are mostly deployed in rigid products.[33] History suggests that a paradigm shift is unlikely to come from today's dominant companies, especially those backstopped by government support.

These risks must be balanced against the benefits that China's massive investments in the PV supply chain have yielded for the world. Chinese companies have played the main role in sustaining the remarkable PV experience curve, driving price declines of about 25% through each of roughly eight cycles of cumulative production doubling since 2006.[34] Beneath this simple regularity lie impressive scale economies, learning by doing on the shop floor, and innovations in production equipment. According to one estimate, the lower cost of manufacturing PV in China rather than the country where it was installed may have saved customers in the United States and Germany more than $30 billion between 2006 and 2020.[35]

30 DOE, "Building a Bridge," 4–5.

31 Lazard, "Critical Materials: Geopolitics, Interdependence, and Strategic Competition," May 2023, 5, https://www.lazard.com/research-insights/critical-materials-geopolitics-interdependence-and-strategic-competition.

32 Hart, "The Impact of China's Production Surge."

33 Billy J. Stanbery, Michael Woodhouse, and Jao van de Lagemaat, "Photovoltaic Deployment Scenarios toward Global Decarbonization: Role of Disruptive Technologies," RRL Solar, April 2023, https://doi.org/10.1002/solr.202300102; Nancy M. Haegel et al., "Photovoltaics at Multi-Terawatt Scale: Waiting Is Not an Option," Science 380, no. 6640: 39–42 (April 6, 2023), https://doi.org/10.1126/science.adf6957.

34 Fraunhofer Institute for Solar Energy, "Photovoltaics Report," February 2023, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

35 Nemet, *How Solar Energy Became Cheap*; John Paul Helveston, Gang He, and Michael R. Davidson, "Quantifying the Cost Savings of Global Solar Photovoltaic Supply Chains," *Nature* 612: 83–87 (October 26, 2022), https://doi.org/10.1038/s41586-022-05316-6.

06

Looking forward, China's low-cost, high-throughput production system is largely responsible for PV's preeminent place in the projected net-zero pathways summarized above. The IEA expects its dominance to "persist or even expand."[36] Yet as every modeler knows well, past performance does not predict future results. China's PV supply chain has surprised to the upside over the past decade and a half, but the downside risks are considerable in the years ahead.

The Inflation Reduction Act: A Break from the Past

US concerns about the risks of PV supply chain concentration prompted a much more assertive and somewhat more coherent response in the Inflation Reduction Act, which passed unexpectedly in August 2022. Under the IRA, US manufacturers of polysilicon, wafers, cells, and modules, along with manufacturers of inverter and tracking system components, gained the option of claiming a production tax credit (known as 45X after the pertinent section of the tax code) or benefiting from an investment tax credit claimed by developers who purchase from them (48C).[37] The 45X credit is expected to be more lucrative, covering roughly half the cost of a module sourced entirely domestically.[38] Funding for the 45X credit is also uncapped, whereas 48C applicants must compete with manufacturers from other industries for a $10 billion pool. Both credits are available as a direct payment (rather than only a reduction of taxes owed) and may be transferred. The 45X credit is scheduled to be phased down between 2030 and 2032.[39]

36 IEA, "Special Report on Solar PV Global Supply Chains," 18.

37 For more detail on the tax credits, see DOE, "Federal Tax Credits for Solar Manufacturers," https://www.energy.gov/eere/solar/federal-tax-credits-solar-manufacturers; Peter Henderson, Rob O'Neill, and Irina Antonache, "IRS Provides Guidance for Advanced Energy Project Tax Credits," Moss Adams, March 2, 2023, "https://www.mossadams.com/articles/2023/03/ira-energy-project-tax-credits-guidance.

38 Eric Wesoff, "Can the US Manufacture Enough Solar Panels to Meet Its Surging Demand?," *Canary Media*, June 7, 2023, https://www.canarymedia.com/articles/solar/can-the-us-manufacture-enough-solar-panels-to-meet-its-surging-demand.

39 Boston Consulting Group, "Impact of IRA, IIJA, CHIPS, and Energy Act of 2020 on Clean Technologies: Solar PV," April 2023, https://breakthroughenergy.org/wp-content/uploads/2023/04/Solar-Cleantech-Policy-Impact-Assessment.pdf.

The IRA also added a 10% domestic content bonus to the investment tax credit (ITC) or production tax credit (PTC) received by PV developers, which is separate from 45X and 48C. Module buyers will be eligible for the bonus for projects begun before 2025 if at least 40% of the cost of manufacturing modules was incurred domestically. That share will step up to 55% by 2027.[40] According to some analysts (though not to all), projects using modules with imported cells will meet this requirement as long as other components are made in the United States. The provision would be ineffective otherwise, since "there is no domestic supply of polysilicon-based solar cells."[41] Buyers of First Solar's CdTe systems will likely be eligible, too. (Nonetheless, the IRS guidance was criticized by leading Democrats for being too permissive of Chinese imports.)[42]

The SEIA predicted that the IRA will "spark a flood of investment in American-made clean energy equipment and components."[43] The flow has begun; 155 GW of new capacity across several layers of the domestic supply chain was announced in the first year after the law passed.[44] If it is all built, the total would far surpass SEIA's 2030 goal of 50 GW of capacity and DOE's stated target of 100 GW.[45]

A large share of the new investment comes from South Korea–based firms. Hanwha Q Cells has been in the forefront of this movement, investing billions to create a vertically integrated supply chain in the United States. Overall, though, projected module production has outpaced upstream segments of the supply chain and comprises a plurality of the total announced capacity. The Boston Consulting Group and Credit Suisse both posit that the IRA's incentives

40 The bonus is discussed in DOE, "Federal Tax Credits for Businesses," https://www.energy.gov/eere/solar/federal-solar-tax-credits-businesses; The White House, "Treasury Releases New Guidance Strengthening Incentives for Domestic Clean Energy Manufacturing," May 12, 2023, https://www.whitehouse.gov/cleanenergy/clean-energy-updates/2023/05/12/treasury-releases-new-guidance-strengthening-incentives-for-domestic-clean-energy-manufacturing/; Steve Hanley, "US Treasury Announces New Tax Credit Guidance: Who's Happy?," Clean Technica, May 13, 2023, https://cleantechnica.com/2023/05/13/us-treasury-announces-new-solar-tax-credit-guidance-whos-happy/; Sylvia Leyva Martinez, "US Solar: The Long and Winding Road to Domestic Module Procurement," Wood MacKenzie, May 25, 2023, https://www.woodmac.com/news/opinion/us-solar-domestic-module-procurement/.

41 Hanley, "US Treasury Announces New Tax Credit Guidance."

42 Rachel Frazin, "Manchin, Wyden, Kaptur Blast Biden Guidance on Solar Panels," *The Hill*, May 15, 2023, https://thehill.com/policy/energy-environment/4005434-manchin-wyden-kaptur-blast-biden-guidance-on-solar-panels/.

43 SEIA, "Solar and Storage Industry Responds to Treasury Dept. Guidance," May 12, 2023, https://www.seia.org/news/solar-and-storage-industry-responds-treasury-dept-guidance-domestic-content-provisions.

44 SEIA, "Impact of the Inflation Reduction Act," https://www.seia.org/research-resources/impact-inflation-reduction-act.

45 SEIA, "SEIA Calls for Ten-Fold Increase," June 21, 2021, https://www.seia.org/news/seia-calls-ten-fold-increase-american-solar-manufacturing-capacity-50gw-2030; DOE, "Building a Bridge," 13.

could make the United States into a module exporter by 2030.[46] Even if such a scenario comes to pass, the United States would remain dependent on imported polysilicon, wafers, and cells for c-Si modules.[47]

More diversified global production could complement expanded domestic production as a hedge against the risks of supply chain concentration. India, for instance, has introduced PV manufacturing support policies that are on track to meet its domestic demand and turn to exports by 2026.[48] The US government made a modest contribution to this initiative by funding a 3.3 GW First Solar plant in Tamil Nadu through its International Development Finance Corporation (DFC) in 2021.[49]

This investment advances a second complementary approach as well, technological diversification. First Solar's survival shows that its CdTe technology is already competitive with the dominant c-Si design under some conditions. Canny management, along with tariff policy and sporadic federal project funding, allowed First Solar to withstand the massive subsidies provided to its Chinese competitors and the resulting scale and learning economies that they have achieved.[50]

On the other hand, DOE's Loan Programs Office (LPO) suffered losses when it aided PV manufacturers pursuing alternatives to c-Si, most famously Solyndra. This aid was extended before the tariffs kicked in, and the political firestorm that engulfed LPO snuffed out further deals. LPO has not yet funded any PV manufacturers under the current administration.[51] DOE's Solar Energy Technologies Office has been able to provide only about $15 million in R&D support annually

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46 Credit Suisse, "US Inflation Reduction Act: A Catalyst for Climate Action," November 30, 2022, https://www.credit-suisse.com/about-us-news/en/articles/news-and-expertise/us-inflation-reduction-act-a-catalyst-for-climate-action-202211.html; Boston Consulting Group, "Impact of IRA, IIJA, CHIPS, and Energy Act of 2020," 5.

47 Julian Spector, "The US Clean Energy Manufacturing Boom Has Begun. Now What?," *Canary Media*, June 5, 2023, https://www.canarymedia.com/articles/clean-energy-manufacturing/the-usclean-energy-manufacturing-boom-has-begun-now-what.

48 Jyota Gulia et al., "India's Photovoltaic Manufacturing Capacity Set to Surge," Institute for Energy Economics and Financial Analysis, April 4, 2023, https://ieefa.org/resources/indias-photovoltaic-manufacturing-capacity-set-surge; IEA, "Will New PV Manufacturing Policies in the United States, India, and the European Union Create Global PV Supply Diversification?," December 2022, https://www.iea.org/reports/will-new-pv-manufacturing-policies-in-the-united-states-india-and-the-european-union-create-global-pv-supply-diversification; Stu Woo and Phred Dvorak, "U.S. Strikes India Deal in Bid to Loosen China's Grip on Solar Panels," *Wall Street Journal*, December 7, 2021, https://www.wsj.com/articles/u-s-strikes-india-deal-in-bid-to-loosen-chinas-grip-on-solar-panels-11638883800.

49 Woo and Dvorak, "U.S. Strikes India Deal."

50 Hart, "The Impact of China's Production Surge."

51 Information Technology and Innovation Foundation, "US Energy Department RD&D Budget: Interactive Dataviz" (accessed August 18, 2023), https://itif.org/publications/2022/05/13/energy-department-rdd-budget-interactive-dataviz/; DOE Loan Programs Office, "Portfolio Projects" (accessed August 18, 2023), https://www.energy.gov/lpo/portfolio-projects; Joseph McCabe, "The End of Abound Solar: What Have We Learned," Renewable Energy World, October 9, 2012, https://www.renewableenergyworld.com/solar/the-end-of-abound-solar-what-have-we-learned/#gref.

over the past 12 years to advance the next generation of PV materials and manufacturing processes,[52] although it plans to invest $36 million in CdTe and perovskite projects this year.[53] Technological and global diversification remain in the shadow of trade and tax policies that may quickly bump up against the limits imposed by Chinese dominance of the PV supply chain, despite the encouraging signs today.

Toward an Integrated Strategy

The IRA overcomes the high barriers to entry posed by China's massive and sophisticated PV supply chain through the brute force of tax incentives, with an assist from tariffs. This approach is not sustainable in the long term. Indeed, the "subsidy buffet," as Bloomberg New Energy Finance labels it, may try legislators' patience well before its scheduled phaseout if the government's costs mount too quickly.[54] Alternatively, if an impending phaseout merely ushers in lobbying to continue the free lunch, the PV manufacturing policy regime of the 2020s will have failed as well. True success depends on using the breathing space provided by subsidies and protection to create an industrial ecosystem that matches or beats Chinese and other global competition on price and performance.[55]

This task is already tough and will get tougher. While the IRA-fueled build-out is underway, domestic PV products may remain more expensive than imports, even imports subject to tariffs and ineligible for the domestic content bonus. As US producers reach global

52 Thanks to Hoyu Chong of the Information Technology and Innovation Foundation for these data.

53 DOE, "Notice of Intent: Up to $36M in Funding for Industrial Thin-Film Photovoltaic Research, Development, and Demonstration," June 14, 2023, https://www.energy.gov/eere/solar/articles/notice-intent-36m-funding-industrial-thin-film-photovoltaic-research.

54 Bloomberg NEF, "Localizing Clean Energy Value Chains Will Come at a Cost," November 7, 2022, https://about.bnef.com/blog/localizing-clean-energy-value-chains-will-come-at-a-cost/. The boom and bust pattern suggested here has played out numerous times with solar installation incentives. See David M. Hart, "Making, Breaking, and (Partially) Remaking Markets: State Regulation and Photovoltaic Electricity in New Jersey," *Energy Policy* 38: 6662–73 (2010), https://doi.org/10.1016/j.enpol.2010.06.036.

55 Martinez, "US Solar: The Long and Winding Road"; Robin Gaster, Robert D. Atkinson, and Ed Rightor, "Beyond Force: A Realist Pathway through the Green Transition," Information Technology and Innovation Foundation, July 10, 2023, https://itif.org/publications/2023/07/10/beyond-force-a-realist-pathway-through-the-green-transition/.

scale and seek to compete on an unsubsidized basis, they will have to overcome today's energy, labor, and capital cost disadvantages by raising productivity through automation, integration, and innovation.[56] In the meantime, the IEA projects that continued expansion of the Chinese PV supply chain will "cause a major glut by 2027," slashing capacity utilization and pushing global hardware prices down.[57] The *Global Times*, presumably reflecting official sentiment in Beijing, labels the effort to circumvent China "an impossible mission."[58] Longtime solar analyst Jenny Chase put it this way in a tweet: "y'all know this business [PV manufacturing] is horrible right?"[59]

The federal government could enhance US industry's odds of proving these doubters wrong by adopting a more nuanced and flexible approach that integrates the policy tools at its disposal into a coherent strategy. This strategy would aim to diversify the PV supply chain geographically and technologically, bringing some but not all segments home, while seeking to disrupt the c-Si paradigm by accelerating product innovation. Allies and partners, such as South Korea, would play important roles in creating and executing this strategy (summarized in box 3).

Box 3: Key Elements of an Integrated PV Manufacturing Strategy

- Better targeted and more flexible tariffs
- More diversified imports
- Stronger collaboration with allies and partners to support import diversification
- Better-targeted and more flexible tax incentives
- Much more robust supply and demand support for advanced technologies

Tariffs are the bluntest tools in the current toolbox. Most tariff rates and coverage are long standing and are locked in. The legal or administrative institutions that can adjust rates are isolated from strategic policy considerations and depend on technical case-by-case investigations. The policy timeline for making such adjustments is typically disconnected from market and geopolitical circumstances as well. The White House can intervene, as it has under both Trump and

56 Martinez, "US Solar: The Long and Winding Road"; Karan Mistry et al., "Two Paths to US Competitiveness in Clean Technologies," Third Way, Breakthrough Energy, and BCG, March 2023, 14–15, https://thirdway.imgix.net/pdfs/override/Two-Paths-to-US-Competitiveness-in-Clean-Technologies-Report.pdf; Boston Consulting Group, "Impact of IRA, IIJA, CHIPS, and Energy Act of 2020."

57 IEA, "Will New PV Manufacturing Policies."

58 "US Efforts to Isolate China from Solar Industry to End in Futility," Global Times, December 8, 2021, https://www.globaltimes.cn/page/202112/1241013.shtml?id=11.

59 Jenny Chase (@solar_chase), tweet posted May 31, 2023, https://twitter.com/solar_chase/status/1663804633406402561.

Biden, but such moves are usually constrained by US trade law and international commitments.

If Congress were to authorize it, the executive branch could use tariffs and other trade policy tools to provide limited and temporary protection for those segments of the PV supply chain that offer domestic manufacturers the best chance of becoming globally competitive over the long run. Imports in these segments would be exempted in quantities calibrated to fill the gap between domestic supply and demand. South Korea might be a privileged supplier in this context; it could build on the exemptions that it currently holds to sustain its position in the global market, rather than hollowing out its PV supply chain.[60] Similar "friend-shoring" tactics could be applied to the European Union and other international partners. While the gap between domestic supply and demand would shrink over time, exempted imports would provide a global standard against which domestic producers would be measured.

Domestic producers are unlikely to succeed in every segment of the PV supply chain, especially labor-intensive segments. Global supply chain integration that reflects national comparative advantage will remain an important opportunity to reduce overall costs. In segments where US producers face long-term disadvantages, US policymakers would seek to coordinate with allies and partners to diversify imports and expand international competition with China. These moves might be supplemented by international investments like the DFC's support for First Solar in India, a "repeatable blueprint" that has not yet been repeated.[61]

Tax incentives are another blunt instrument as currently deployed. Rates are set by law and are not responsive to market conditions. The IRA subsidizes all segments of the PV supply chain. And it is generous: First Solar expects 45X to account for nearly 90% of its operating income this year.[62] A better approach would be to coordinate tax incentives with tariff protection, focusing on the same segments and using declining tax rates along with import competition to apply cost-cutting pressure. The IRA's two-year phaseout beginning in 2030 is a gesture in the right direction, but history suggests that a phaseout in law is often a mirage, receding under industry pressure as it draws nearer. Congress might delegate the pace of

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60 IEA, "Special Report on Solar PV Global Supply Chains," 34; Yun and Park, "South Korea's Solar Power Industry."

61 Woo and Dvorak, "U.S. Strikes India Deal." See also "Joint India-US Effort Needed to Address State-Subsidised Dominance of China's Strategic Industries: First Solar CEO," *Economic Times of India*, June 19, 2023, https://energy.economictimes.indiatimes.com/news/renewable/joint-india-us-effort-needed-to-address-state-subsidised-dominance-of-chinas-strategic-industries-first-solar-ceo/101093401.

62 Jeff St. John, "Manufacturing vs. Deployment: The Clean Energy Tax-Credit Conundrum," Canary Media, June 7, 2023, https://www.canarymedia.com/articles/clean-energy-manufacturing/manufacturing-vs-deployment-the-clean-energy-tax-credit-conundrum.

the phaseout to the executive branch, essentially tying its own hands and reducing the temptation of annual extensions, while allowing the incentive to decline along with costs.

Technological diversification would be the final and possibly most potent element of an integrated PV supply chain strategy.[63] Beyond First Solar's CdTe technology, perovskites and other advanced materials for solar cells hold out the prospect of even lower costs as well as easier integration into buildings and other structures.[64] Although modules comprise only a minority of total PV system costs, every marginal drop in cost aids diffusion. Easier integration could become particularly important if local resistance to the siting of large solar farms continues to rise in the United States.[65]

An integrated policy strategy should carve out a niche for advanced PV product technologies that is large enough to prove whether they can deliver on their promise at scale in the coming decade. In addition to tax incentives and tariffs, such a strategy should use tools like targeted RD&D investments and procurement by federal agencies. A collaborative effort to coordinate the use of such tools with South Korea and other allies and partners would strengthen the strategy considerably.

Tandem cells that combine c-Si with new materials are entering the market now.[66] Hanwha Q Cells announced in May 2023 it would open a pilot production line in South Korea to make them.[67] Whether these cells will perform well enough to win over customers concerned about their durability and reliability, much less pave the way for a disruptive new production paradigm, remains to be seen. The reward could be immense: accelerated global deployment and a reshaped competitive landscape, benefiting the United States, South Korea, and the global energy transition as a whole. The risk would be hedged by the main thrust of the strategy: building out elements of the c-Si PV supply chain domestically and diversifying it away from China internationally.

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63 DOE, "Building a Bridge," 7.

64 Tina Casey, "New Perovskite Solar Cells: How Low (and How Fast) Can Solar Go?," Clean Technica, May 22, 2023, https://cleantechnica.com/2023/05/22/new-perovskite-solar-cells-how-low-and-how-fast-can-solar-go/.

65 Robert Bryce, "Renewable Rejection Database" (accessed August 18, 2023), https://robertbryce.com/renewable-rejection-database/; Matthew Eisenson, "Opposition to Renewable Facilities in the United States: May 2023 Edition," 2023, https://scholarship.law.columbia.edu/sabin_climate_change/200/.

66 Eric Wesoff, "Perovskites Can Make Solar Panels More Efficient than Silicon Alone," Canary Media, October 19, 2022, https://www.canarymedia.com/articles/solar/perovskites-can-make-solar-panels-more-efficient-than-silicon-alone; Tim Hornyak, "A Bill Gates–Based Photovoltaic Technology That May Be Solar Energy's Future," CNBC, May 20, 2023, https://www.cnbc.com/2023/05/20/a-bill-gates-based-photovoltaic-tech-that-may-be-solar-powers-future.html.

67 Petra Hannen, "Qcells Builds Pilot Line for Perovskite-Silicon Tandem PV Cells in South Korea," PV Magazine, May 18, 2023, https://www.pv-magazine.com/2023/05/18/qcells-builds-pilot-line-for-perovskite-silicon-tandem-pv-cells-in-south-korea/.

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Bridges to Cross: Caveats and Next Steps

The United States should not undertake an integrated PV strategy lightly. Indeed, it probably could not do so, since the proposed delegation of authority to the executive branch would require careful consideration by key members of Congress. Given the mistrust and conflict between the two parties, and hence between the two branches whenever control is divided, unwillingness to delegate authority could preempt further progress. If Congress was persuaded of the strategy's virtues, the executive branch would be challenged to gain a sophisticated understanding of the global PV industry and to act nimbly on it across agency lines and in concert with international allies and partners.

Implementing an integrated PV strategy might be less expensive than implementing the policies in the IRA, but it would still require significant investment and sustained resolve. The impending glut of Chinese production capacity is likely to increase the premium paid for domestic supply for at least a few years, prompting familiar pressure for relief from PV developers and installers, along with some environmental organizations. China could increase the pressure further, economically and diplomatically, to preserve its dominant position. Federal policymakers should also consider whether this industry should be a focal point for such an effort relative to others that may be more tractable, like electric vehicles.

On the other side of the ledger, the emerging consensus around industrial strategy writ large is bipartisan and focused squarely on competing with China. The administration has already taken important steps to strengthen interagency cooperation in energy and climate policy implementation. Cooperation with European and Asian nations may be rebuilt, now that the shock of the IRA's passage has been absorbed. South Korea is primed to be a leading US partner, given its strengths in PV manufacturing, the important role of South Korea–headquartered manufacturing companies in the United States, and the shared global interests of the two countries.

The most likely opportunity to move an integrated PV strategy forward will be in 2025 after the next national election. The costs and flaws of the IRA will become evident by then. The pattern of moderating and sharpening a too-ambitious policy is familiar; numerous jurisdictions have shifted from overly generous solar feed-in tariffs to more effective and efficient auction mechanisms, for instance.[68] In the meantime, the Biden administration and colleagues in the domestic and international policy communities should analyze the options, articulate the opportunity, and lay the groundwork for future collaboration.

68 Benjamin Attia, Shayle Kann, and Morgan D. Bazilian, "How Auctions Helped Solar Become the Cheapest Electricity in the World," *Georgetown Journal of International Affairs*, February 24, 2020, https://gjia.georgetown.edu/2020/02/24/part-i-how-auctions-helped-solar/.

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