The Impact of China's Production Surge on Innovation in the Global Solar Photovoltaics Industry

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China's subsidy-aided rise to dominance in PV manufacturing has driven prices way down, but at the cost of undermining promising alternative technological pathways. Policymakers should adopt measures to sustain greater diversity in PV and similar technologies.

KEY TAKEAWAYS

- Sustained innovation in solar photovoltaics (PV) is vital to achieve global climate goals. Experts differ on whether today's dominant PV technology can be improved to the extent required. The world needs more options; China's dominance limits them.
- China became the dominant global player in PV manufacturing during the 2010s with critical help from government subsidies.
- Excessive subsidy-powered competition from China decimated the industry in the rest of the world, eliminating many innovative companies.
- China's surge shifted the course of technological innovation: PV prices dropped, efficiency rose, and process innovation flourished. But R&D-intensity, patenting, and start-ups cratered.
- As the course of innovation shifted, alternative technological pathways that might have led to even lower prices and better performance were cut off.
- Policymakers should learn from this experience and adopt measures that would create and sustain technological diversity in PV and other climate-critical technologies, while working with allies to curb clean energy mercantilism.

INTRODUCTION

Before the advent of veterinary medicine, anyone buying a horse was supposed to first look at its teeth. Teeth were reputed to be a leading indicator of durability, with bad teeth signaling that the plow-pulling days of the horse on offer would be numbered. A gift horse, though, was a different matter. According to the old saying, "Never look a gift horse in the mouth." Any plowing it did was taken to be pure gain, and to imply otherwise by peeking at its teeth might be taken as an insult by the giver.

Yet, sometimes gifts impose costs as well as bestow benefits. Imagine a gift horse received in the fall and nourished with precious fodder through the winter proving unable to plow in the spring. So while it may be impolite, a look in the mouth may be prudent when economics is more important than etiquette.

The remarkable decline in the price of solar photovoltaic (PV) modules, which stemmed from China's subsidy-aided rise to dominance in PV manufacturing during 2010s, is a "gift" (to use a metaphor employed by Greg Nemet of the University of Wisconsin) that warrants a closer look. Between 2006 and 2013, China's global share of production of PV cells, the industry's core technology, surged from 14 percent to 60 percent. The global average price per watt of PV capacity dropped rapidly during these years, while the global market grew eighteen-fold. Prices have continued to fall since then, and China remains the dominant producer. Low prices have helped make PV 1 of only 6 technologies that are "on track" out of 46 that will be required for the world to stay well below two degrees of global temperature rise by 2050, according to a 2020 report by the International Energy Agency (IEA).[1]

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Yet, for all its evident benefits, China's "gift" imposed costs as well. Most critics of China have focused on the global distribution of manufacturing jobs created by the growth of the solar industry. An even more significant impact, though, has been overlooked: a change in the industry's pattern of innovation. Conventional indicators of product innovation, such as patenting and the ratio of research and development (R&D) to sales, dropped precipitously in the wake of the Chinese surge. The decimation of PV manufacturing outside China drove many innovative firms out of the business, in large part because they could not match the predatory prices offered by government-subsidized Chinese competitors. China's new PV giants have innovated in important ways, especially through process innovation that moved the industry's dominant technology rapidly down a steep experience curve. But the prospect of shifting to better, cheaper PV products with the potential for even greater emissions reductions over the long run, has been deferred or even lost.

This report contributes to a series of ITIF reports assessing China's impact on global innovation across a diverse set of key industries.[2] It seeks to assess the opportunity cost of the Chinese surge in PV, and explores how to weigh it against the more tangible benefits cheap PV has already brought the world and might bring it in the future. The stakes are especially high looking forward. As IEA suggests, PV looms increasingly large in scenarios that lead to a successful global transition to low-carbon energy. If this technology loses momentum due to slowed or stranded innovation, the transition would be put at even greater risk than it already is.

The report first explains why this issue matters from the climate and energy perspective. Then, building on prior ITIF research, it delves briefly into the theory of "innovation mercantilism." The particulars of the case follow, describing the history of PV manufacturing before, during, and after the Chinese surge, with a focus on the role innovation mercantilist policies played in it. It then seeks to assess the impact of the surge on innovation, reviewing key indicators and placing this data in the context of theories of dominant design and technological lock-in. This section also includes simple counterfactual models of pathways the industry might have taken if the surge had been slightly less powerful than it was.

This report concludes by arguing policymakers should take measures that would create and sustain diversity in PV technology and, by extension, in other energy and climate technologies with similar characteristics, such as batteries, carbon capture devices, and hydrogen electrolyzers. Diversity is a sensible goal given the great importance of these technologies to the achievement of global climate goals and the non-trivial risk that dominant designs may not perform as well as their proponents expect.

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As detailed in the final major section of this report, policies that would advance this goal include:

- Increased public R&D spending with an emphasis in the United States and other R&D-intensive countries on alternatives to today's dominant crystalline-silicon design;
- Market-pull policies, such as carve-outs for alternative designs within portfolio standards as well as tiered tax incentives and feed-in tariffs (FITs) that award alternatives a higher level of support;
- Public-private co-investment in manufacturing and supply chains informed by strategic analysis of technologies and markets;
- Stronger enforcement of international trade law and updating of U.S. anti-dumping rules; and
- International cooperation featuring reciprocity and transparency to strengthen learning and build open markets that support innovation.

THE VITAL IMPORTANCE OF CONTINUED INNOVATION IN SOLAR PV

Electricity will be the core resource of the clean energy system of the future. It can be generated with low greenhouse gas emissions using a variety of technologies. It is a flexible energy carrier with diverse applications today, many of which are growing rapidly, such as powering information and communications technology.[3] Looking ahead, low-carbon electricity must be substituted for higher-carbon fuels in major applications such as transportation and heating to eliminate a substantial additional fraction of emissions. In IEA's Sustainable Development Scenario (SDS), in which the goals of the Paris Agreement are achieved along with universal access to energy, global electricity supply grows by 70 percent, while use of unabated fossil fuels in vehicles and buildings shrivels.[4]

Solar PV has many qualities that make it one of the most attractive options for low-carbon electricity generation. In addition to its low and falling cost, it is modular, durable, relatively easy to site, and low in lifecycle emissions. IEA's SDS envisions 5 terawatts (TW) of PV capacity being deployed globally by 2040, ten times the total in 2018. A 2019 review in *Science* led by researchers from the U.S. National Renewable Energy Laboratory (NREL) offers an even more ambitious scenario, in which 30–70 TW of PV capacity makes this technology "a central contributor to all segments of the global energy system" by 2050.[5]

Successful deployment on such a scale will require sustained innovation in the coming decades. PV innovation may be assessed with several metrics. Most energy forecasters measure it in terms of cost reduction. Varun Sivaram and Shayle Kann, for instance, have argued that the installed cost of complete PV systems, including modules and balance of system (BOS) components, will need to fall below $0.25 per watt for ambitious global goals to be achieved by 2050.[6]

Sustained PV innovation even promises to address variability, the technology's Achilles' heel.

Industry experts disagree about how likely this goal is to be achieved with first-generation PV technology made out of crystalline-silicon (c-Si). Advanced c-Si PV cells use more-efficient architectures and require less material than current ones, which in turn reduces the required capital cost of module manufacturing. NREL's 2019 roadmap for continued innovation anticipates that the cost of c-Si modules will decline to $0.24 per watt between 2030 and 2040. As has typically been the case over the last decade, module prices have dropped much more quickly than expected since that roadmap was prepared, reaching an average of $0.36 per watt. A new roadmap under development may bring Sivaram and Kann's 2050 target within striking distance.[7]

In his 2018 book *Taming the Sun*, Sivaram advances a more holistic vision of PV innovation and its vast potential. Rather than being assembled into rigid c-Si modules, PV cells will be "printed on flexible substrates en masse." They may be made from advanced semiconductor materials such as quantum dots, organic materials, new materials such as perovskites, or hybrids of two or more of these alternatives. At a cost of just a few pennies per watt, such cells would enable massive reductions in balance of system costs, such as shipping and installation. They would open up new applications in heavy industry, hydrogen production, and direct air capture of carbon dioxide. They would bring solar power directly to cities through building integration (such as roofs and windows that generate electricity), eliminating the need to devote large land areas to solar farms, while drastically downsizing the impact on the power grid. Such innovation would be particularly beneficial for developing countries that will dominate global carbon emissions in the 21st century, which have limited available land and are urbanizing rapidly.[8]

Sustained PV innovation even promises to address variability, the technology's Achilles' heel, to some extent. PV systems generate at maximum power only when the sun is shining brightly; when the weather is cloudy, production declines. These variations create problems for the grid, which needs to balance supply and demand at all times. There are several solutions, including energy storage, larger grids, and demand response. An additional solution, overbuilding solar capacity so this resource can meet demand even during cloudy weather, will become more viable if cells become ultra-cheap along any technological pathway.[9]

Challenges hindering other low-carbon electricity-generation technologies, which scenarios such as the SDS rely on for deep decarbonization along with PV, may place even more weight on PV innovation moving forward. Nuclear power and fossil-fuel plants with carbon capture, utilization, and storage are costly and face significant public opposition. The growth of wind power may slow as the technology matures and the best sites are developed. Hydropower already faces similar constraints. Other renewables, such as concentrating solar and tidal power, have not yet been proven commercially viable. Investments in research, development, and demonstration (RD&D) that aim to break through barriers across a broad range of technologies should be sustained and expanded, but no prospect currently shines as brightly as solar PV.[10]

HOW MERCANTILIST POLICIES MAY SLOW OR STRAND INNOVATION

If PV innovation were to stall, the likelihood of the world reaching its 2050 climate goals would be significantly diminished. Yet, few solar industry observers seriously consider this possibility. The conventional wisdom is captured by IEA's judgment that PV is "on track." The virtuous cycle between market growth and cost reduction that marked the past decade, according to this view, will surely continue for three more.

But past performance does not always predict future results. Indeed, past performance may obstruct future results—if it erodes the conditions that made for past success. In this case, the mercantilist policies that powered the Chinese production surge altered the trajectory of innovation, making promising alternatives to the dominant technological paradigm in PV more difficult to pursue. This hypothesis is firmly grounded in theory, and finds empirical support across other manufacturing industries. The burden of this report is to see whether it finds support in this industry.

Mercantilism, writes Laura LaHaye, was a "system of political economy that sought to enrich the country by restraining imports and encouraging exports." It dominated European policy in the sixteenth, seventeenth, and eighteenth century, but fell into disfavor as David Ricardo's theory of comparative advantage gained sway. Britain could trade its cloth for Portuguese wine, in Ricardo's famous example, and both countries would be better off. Mercantilism, even when it is successful in relative terms, imposes opportunity costs in absolute terms, as imbibers of British wine well understand.[11]

Although no longer dominant within the economic and trade policy establishment, mercantilism never died, Ricardo notwithstanding. As ITIF research documents, the prospect of running trade surpluses that enrich the mercantilist state, while favoring supporters who can make easy profits in protected domestic markets, is a recurring temptation for governments. Sometimes, a defensible analytical case can be made for temporary "infant industry" protection that allows domestic producers to build up their capabilities before facing the full force of more-experienced global competitors. Frequently, though, such temporary measures become permanent—and sometimes they are actually intended to be so.[12]

Mercantilism is frequently contrasted with free trade "small-l" liberalism. Between these poles, however, there is a spectrum of other approaches. "National developmentalism," as ITIF's Robert

Atkinson writes, sanctions support for domestic industries, but within internationally agreed rules and norms.[13]

Mercantilism is particularly problematic in industries in which innovation is rapid. Such industries rely on continuous feedback from the market to provide both information and resources that sustain innovation. This feedback process is especially important for mass-produced products in which economies of scale drive innovation. By segmenting global markets, mercantilists impede learning through feedback. And by subsidizing domestic firms, they restrict the resources flowing to foreign competitors.[14]

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Mercantilist policies can take a number of forms beyond restricting access to the home market and subsidizing exports. The mercantilist state may countenance or even assist in theft or forced transfer of intellectual property and know-how, which deters product innovation. It may repress labor, which reduces incentives for process innovation. It may manipulate its currency, which impinges on both.[15] In the case of PV, the most important policy was the simplest: government financial support for domestic firms. These subsidies led to excessive global competition, ultimately drying up profits and investment that foreign firms needed in order to pursue innovation-oriented strategies.

The notion of excessive competition may seem paradoxical. Competition ought to be a powerful driver of innovation in market economies, as firms seek profits through new products, improved processes, better business models, and the like. And it often is, particularly when wages are high and public investments in research and education create a rich pool of knowledge and talent upon which firms can draw as they compete to address evolving markets or create new ones. For example, robust competition, including the entrance of new firms pursuing technological opportunities neglected by incumbents, helped the semiconductor industry uphold Moore's Law for more than 50 years.[16]

Yet, competition must not be so robust that it destroys profits and erodes investor confidence. Current profits and investment with the expectation of future profits provide firms in market economies with the capital they need to take risks. Innovation-oriented strategies are by definition risky and involve significant upfront costs for R&D and equipment, especially in capital-intensive industries such as PV manufacturing. They become increasingly difficult for firms to pursue when government subsidies support too many competitors in an industry.

Turning from theory to empirical analysis, the weight of the evidence suggests that "China's innovation mercantilist policies have harmed innovation in other nations," as Atkinson puts it. David Autor and his colleagues, for instance, have shown that the "China shock" that followed that country's accession to the World Trade Organization in 2001 negatively impacted not only production and jobs in the United States, but also innovation as measured by patents in the manufacturing sector as a whole.[17]

It takes time for mercantilism to impact innovation. Mercantilist subsidies are opaque and may be dimly perceived or discounted by foreign competitors. Once the threat is recognized, the most technologically advanced firms may respond to subsidized, less-advanced competitors by doubling down on innovation, seeking to differentiate their products and escape competition.[18] While this response may prove successful for some, it is ultimately limited by the patience of investors, particularly for smaller, less diversified firms, which have less margin for error. If subsidies are sustained, investor confidence crumbles and innovation-oriented firms face a reckoning. That, in short, is the story of the PV manufacturing industry outside China in the 2010s.

SETTING THE STAGE: THE SOLAR PV WORLD BEFORE THE CHINESE SURGE

The Chinese surge from the mid-2000s to the early 2010s made PV manufacturing what it is today: a large and growing sector dominated by commodity production, and composed of many firms competing on price and scale. This outcome was not inevitable. To imagine alternative pasts, we must recover the sense of possibility that existed before the surge, particularly with respect to second- and third-generation product technologies.

PV technologies are the result of decades of public and private investment in the United States, Japan, Germany, and elsewhere. The first PV device, made of silicon, was invented by scientists at Bell Labs in New Jersey in 1954. The U.S. government supported its development and deployment with policies that provided both technology push and market pull over the next quarter-century. Initial applications focused on satellites and spacecraft, wherein cost was no object to government sponsors. The oil crises of the 1970s sparked an effort to develop affordable terrestrial applications, using the tools of non-defense procurement, regulatory reform, and tax incentives along with federal RD&D spending.[19]

The Reagan administration pulled back many of these policies in the United States as oil prices dropped in the 1980s, but other countries picked up the baton. Japan made PV a top RD&D priority in the 1980s, and followed up with the "New Sunshine" policy to encourage deployment in the 1990s. When Japan cut back its program in the 2000s, Germany ramped its up. It moved into the lead in RD&D spending and invented the FIT, which induced homeowners to install PV systems by guaranteeing a high rate of return on their investments. Between 2000 and 2006, Germany's installed PV capacity grew more than 38-fold, surpassing Japan's.[20]

The United States returned to the PV playing field in earnest around the turn of the century as well. The electricity crisis in California in 2000–2001 sparked that state to adopt a renewable portfolio standard (RPS) in 2002 that mandated utilities to support solar power. Other states—to date, a total of 29—have done the same. With oil prices rising and the Middle East dominating foreign policy attention, the federal government added to the momentum beginning in 2005 by expanding the solar investment tax credit and enabling utilities and third-party "tax equity" investors to claim it. The average annual growth rate for PV installation shot up from less than 10 percent in the late 1990s to about 60 percent during the 2000s.[21]

As the global market grew, manufacturers pursued a variety of strategies. U.S.-based pioneer SunPower focused on improving the efficiency and lowering the cost of first-generation c-Si systems, which dominated the global market in the mid-2000s with a share well over 90 percent. This strategy would ultimately be pursued with great success by Chinese producers, which were just beginning to make their mark at this time.[22]

Many other competitors diversified or shifted entirely to second-generation thin film technologies (TFTs). TFTs, which can be made from a variety of materials, are less efficient in practice than c-

Si; that is, they convert a smaller portion of the solar energy falling on them into electricity. On the other hand, they can be produced in a more flexible form and thus potentially used in a wider variety of configurations than the dominant design. Most important, they were projected to be much cheaper to make in the long run.

Just because entrepreneurs and investors see opportunities to displace the incumbent technology, and even put their talent and money to work to do so, does not mean they are right.

The world's largest PV producer, Japan's Sharp, invested heavily in amorphous silicon (a-Si), a TFT that had been used since 1980 in pocket calculators. The leading German manufacturer, Q-Cells, diversified into a variety of TFTs, including cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). In the United States, a wave of venture capital flowed into TFT start-ups. AVA, HelioVolt, MiaSolé, Nanosolar, and SoloPower were among the nascent firms that raised rounds of $100 million or more in 2007 and 2008. The more established CdTe producer First Solar (founded in 1990) brought in $1 billion with its 2006 initial public offering. As TFTs' global market share began to tick up—breaching 10 percent in 2007—some analysts predicted it would grow to 25 or 30 percent within five years.[23]

A third generation of PV technology, which initially used organic materials, promised to overtake the first two by combining high efficiency with low cost. One third-generation U.S.-based firm, Konarka, reportedly raised more than $150 million in private capital and received $20 million in government grants during the 2000s. Although its cells were not very efficient, the company nonetheless claimed in 2008 that it would have 1 gigawatt (GW) in annual production capacity 2010, more than the installed PV capacity in North America at the time.[24]

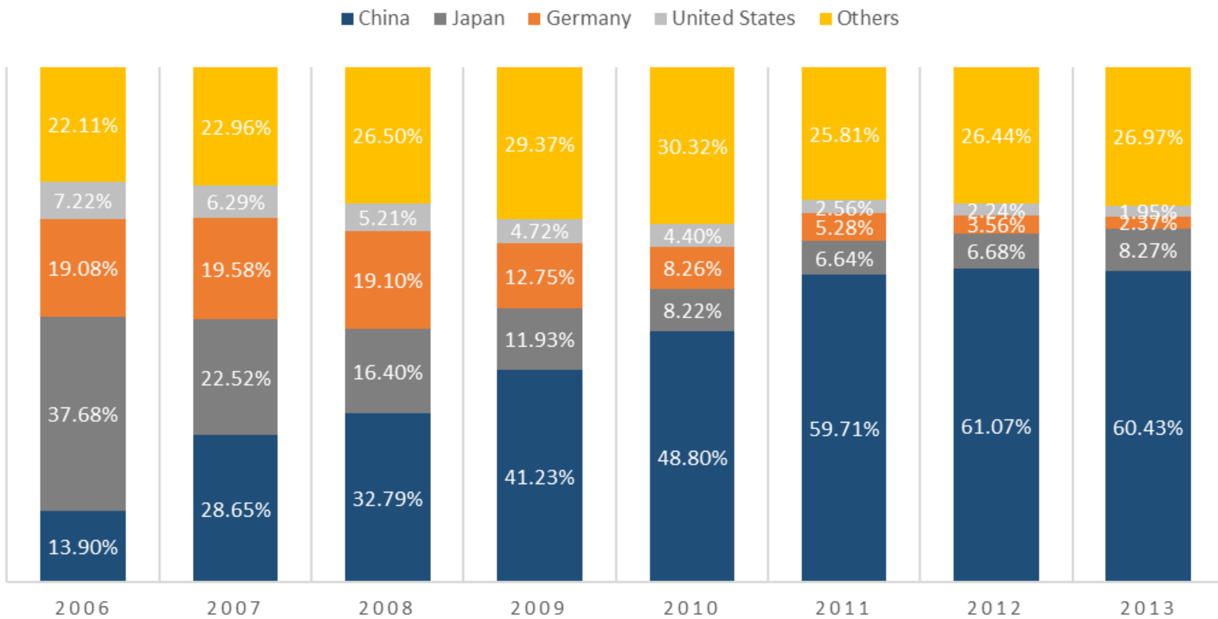
Of course, just because entrepreneurs and investors see opportunities to displace the incumbent technology, and even put their talent and money to work to do so, does not mean they are right. Misperceptions and hype drive investment waves. Old technologies often fight back and sometimes maintain their dominance. SunPower founder and industry legend Richard Swanson cautioned his colleagues in 2009 that "the competition from crystalline silicon will remain formidable." Some market players mistook an extraordinary price spike in silicon in 2007–2008, which temporarily favored TFTs, as a signal of something more permanent.[25]

In hindsight, however, it is clear that the competition among companies and technologies played out in a much different context than industry participants such as Swanson expected at the time. China put its thumb on the scale and determined the outcome. Alternative pathways that might have led to different destinations over the ensuing decade were cut off.

THE CHINESE SURGE TO GLOBAL LEADERSHIP: THE ROLE OF SUBSIDIES

China's PV manufacturing industry was miniscule before 2005. It breached 100 megawatts (MW) of cell production in that year, jumping to 7 percent of global supply from less than 2 percent in 2003. Production grew by an order of magnitude in the next two years, another order of magnitude in the following three, and doubled again in 2011, capping roughly 200x growth in a six-year span. China's share of the global market had surpassed 60 percent by 2011, and it has remained above that level since then. (See figure 1.)[26]

Figure 1: Global market share of PV cell production by country, 2006–2013[27]

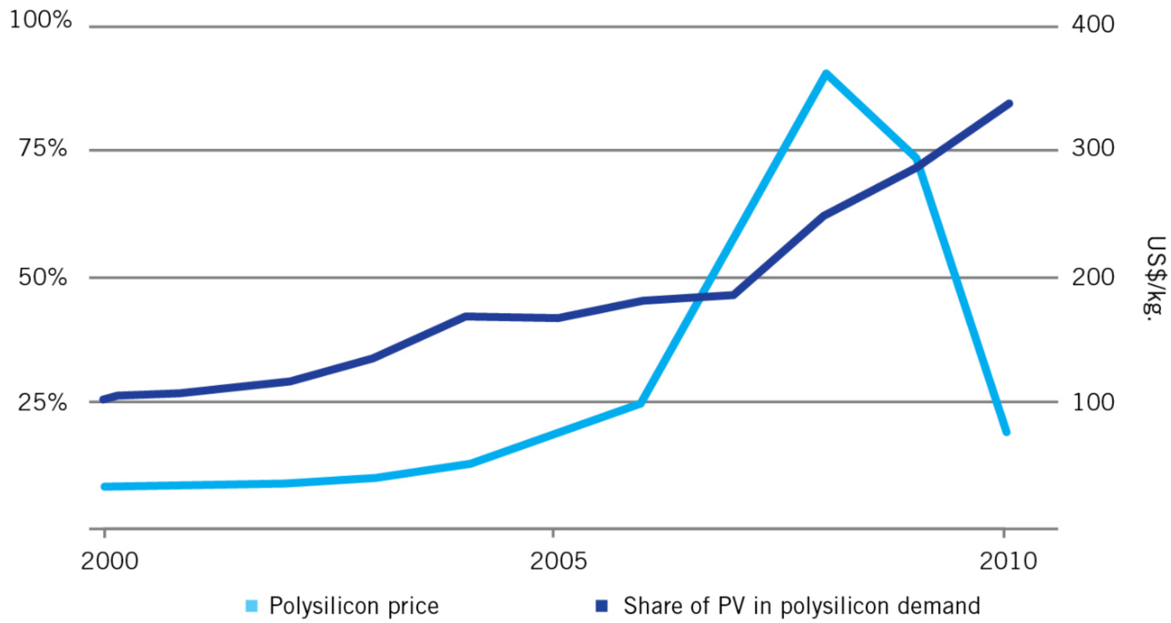


As Nemet and others have shown, the industry's initial climb to global credibility owed more to Australia, Germany, and the United States than the Chinese central government. Chinese students who had trained at the laboratory of PV pioneer Martin Green at the University of New South Wales in Sydney, and elsewhere in the West, returned home to start up or lead many of the most successful firms, such as Canadian Solar, JA, Suntech, and Yingli. U.S. investors provided many of these entrepreneurs with money, plowing some $7 billion into Chinese PV firms between December 2005 and the end of 2007 alone, a forgotten adjunct to the "cleantech" VC boom of the same period. Chinese manufacturers used some of their money to import specialized turnkey production lines from Germany that were far superior to domestic equipment at that time. And German consumers, motivated by the FIT, drove massive demand for low-cost Chinese products.[28]

Although the Chinese central government gave little direct support to PV manufacturers before 2009, "provincial and local governments were quick to get behind the new solar firms in their jurisdictions," as Kelly Sims Gallagher of Tufts University put it. These governments offered subsidized land and electricity, direct and indirect financial support, and tax relief to the emerging industry. Local state-owned banks in Wuxi, for instance, granted Suntech $3.7 billion in low-interest loans between 2005 and 2012 at the behest of the municipal government. The firm received another $1.4 billion in tax rebates and other export promotion subsidies. Success quickly bred imitation, as entrepreneurs from industries as diverse as clothing, auto repair, and firefighting equipment, based in places with no obvious locational advantages, poured into PV manufacturing with support from subnational governments.[29]

The central government did assist the industry indirectly during this early phase of the surge. China's currency was substantially undervalued relative to the dollar during this period, thereby boosting all exports to the United States. The misalignment reached an estimated 40 percent at its peak in 2009 before subsiding to the single digits by 2012, according to William Cline of the Peterson Institute. A series of national planning documents signaled to lower levels of government that the central government considered renewable energy broadly to be a strategic industry and encouraged inflows of foreign equipment and investment to it. Beijing also supported the creation of a domestic silicon industry, albeit initially to provide inputs for semiconductors rather than PV. This support proved to be fortuitous when silicon prices spiked in late 2007, which was also the first year the solar industry used more silicon worldwide than the chip industry. (See figure 2.)[30]

Figure 2: Polysilicon price (right axis) and share of PV in polysilicon demand (left axis)[31]



This spike, which lifted silicon prices by about 900 percent in the space of a few months, sent shockwaves through global PV manufacturing. It encouraged investment in TFTs, which did not use the material; prompted some c-Si firms to lock in supplies at fixed prices; and induced massive investments in silicon production. This last impact, along with the global recession that began in 2008, caused prices to recede as quickly as they rose as new production came on line.[32]

The free fall in silicon prices, which went further and faster than industry analysts anticipated, left c-Si manufacturers that had locked in fixed prices, including some in China as well as elsewhere in the world, exposed. The blow was even more devastating for firms making TFTs, which were concentrated in the United States, where they had gained a 65 percent market share by 2007. While firms were harmed by the silicon price volatility in every producing country, the heavy concentration of Chinese manufacturers in c-Si meant that China suffered relatively less when the price settled at a very low level.[33]

This outcome was not the result of a deliberate central government strategy. While there is some evidence that large state-owned silicon manufacturers subsidized the PV industry through unduly low input prices, many Chinese entrants into silicon production were privately owned, including some PV manufacturers that became vertically integrated. There were also many entrants from other parts of the world. The Chinese share of the global market for silicon inputs lagged behind its share of other segments of the PV value chain during the surge.[34]

Chinese companies also transformed the PV manufacturing equipment business with the unwitting assistance of their German competitors. Close linkages between German PV manufacturers and their domestic suppliers in the mid-2000s had allowed the latter to build dedicated machinery as the market grew, rather than repurposing semiconductor equipment as they had in the past. German equipment makers then aggressively sought markets in China. As a German expert commission concluded in 2012, the export of PV manufacturing equipment "served as the prime source of gain in know-how for Chinese companies." One German CEO put it more bluntly to a researcher: "The equipment manufacturers are to blame for the German PV [cell] manufacturers losing their competitive advantage." The tables were then turned on German equipment makers as Chinese entrants into this segment were able to beat them on price without sacrificing too much quality. Lower equipment costs became a key source of competitive advantage for the Chinese PV industry, and helped drive down end-product costs as well.[35]

The Chinese central government was far more involved in the later phase of the surge. The State Council declared PV specifically (not just renewable energy in general) to be a "strategic emerging industry" in 2010. As the global banking industry cratered, China's state-owned banks fueled the continued rapid growth of the nation's PV manufacturing industry with lines of credit worth more than $40 billion. Rainer Quitzow of the Free University of Berlin noted that such commitments "function as *de facto* repayment guarantees for commercial lenders … [which] enabled the leading Chinese PV firms to continue their aggressive investment strategies as company balance sheets around the world began suffering."[36]

Central government support for domestic demand also helped sustain the industry. China's share of global PV installations was less than 1 percent in 2008; the early phase of the surge was devoted almost entirely to exports. By 2013, that figure was nearly 30 percent, as German demand growth stalled, while the Chinese market exploded to become the world's largest. A large-scale demonstration project in 2009 authorized by Beijing was followed by both direct subsidies and FITs to incentivize adoption by Chinese customers.[37]

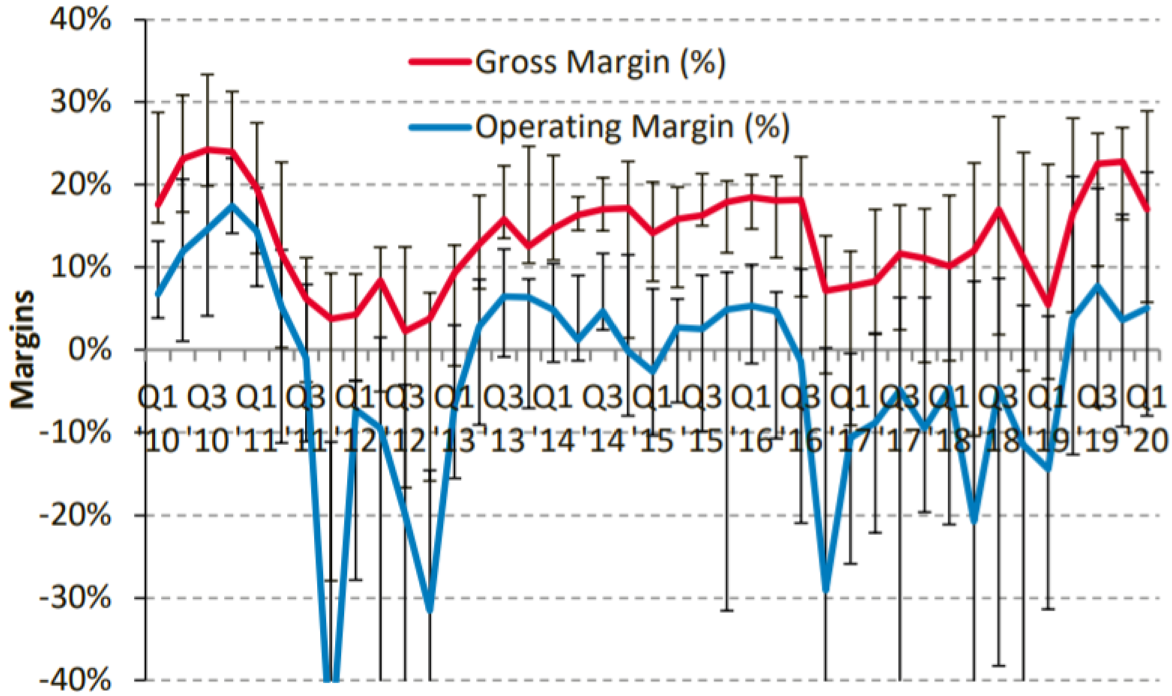
The domestic market was served almost entirely by domestic firms. Clean Energy Associates CEO Andy Klump summarized the situation this way at a 2013 industry conference: It was "possible" for foreign firms to do projects in China "as long as you partner with the right state-owned entity [SOE] or local company. But expect a much lower margin. And the payment terms are horrific." (A 2019 report by the McKinsey Global Institute concludes that Chinese producers supplied 100 percent of the domestic market.)[38]

A team from MIT and NREL found that the price of a Chinese PV module in 2012 was about 20 percent less than one made in the United States. They attributed the difference to two groups of variables: subsidies, which accounted for one-sixth of the gap, and scale/supply chain, which accounted for the rest. But this is a distinction without a difference. Without state-directed access to capital, total control of the protected domestic market, and other policies, it would have been impossible for Chinese firms to build out the PV supply chain after 2006, and to do so on a much larger scale than non-Chinese competitors could contemplate.[39]

Unfortunately, this meaningless distinction has been repeated without caveats by numerous later authors, such as MIT's John Deutch and Edward Steinfeld, and Fang Zhang and Kelly Sims Gallagher. Citing the MIT/NREL analysis, the latter wrote, "Even counting these subsidies, they actually did not substantially contribute to China's advantage over foreign countries, such as the United States." Later NREL analysis, citing the same work, is far more measured, attributing "declining U.S. market share … to Chinese government subsidies for PV manufacturing facilities and their access to low-cost debt and regional suppliers, which has since been further compounded by economies of scale."[40]

Subsidies allowed China's major PV manufacturers to sustain enormous losses during the latter part of the surge. Veteran industry reporter Herman K. Trabish captured the situation in the title of an April 2013 piece "Is China's Solar Business Not-for-Profit?" The median operating margin for a group of predominantly Chinese large manufacturers tracked by NREL fell to an estimated negative 40 percent in 2011, recovered briefly, and fell again to negative 30 percent in 2012. (See figure 3, which also includes data for U.S.-headquartered SunPower and First Solar.) These data fail to capture unprofitable smaller "zombie" companies that continued to produce at the behest of lenders or governments that did not want to acknowledge that they had failed.[41]

Figure 3: PV manufacturers' margins, 2010–2020[42]



Line represents the median, with error bars representing 80th and 20th percentiles for the following companies in Q1 2020: Canadian Solar, First Solar, LONGi, Motech Industries, United Renewable Energy, ReneSola, Shunfeng, Tongwei, Risen Energy, and SunPower. Margin data from Hanwha Q Cells, Jinko Solar, JA Solar, Trina, and Yingli are also included from Q1 2010 to Q4 2019 where available.

The fact that China's major PV manufacturers have operated for the better part of a decade without making much money (albeit with significant variations across firms and over time) suggests that subsidies continue to shape international competition in this industry. After the horrific losses of the surge period, these producers managed to do slightly better than break even in the middle of the decade, but then suffered large losses once again for several years after that.[43]

The widespread adoption of PV in China is good for the global climate and for the health of the Chinese public, particularly when it substitutes for carbon-intensive coal-fired power, which has historically dominated China's grid. China took the baton from Germany in the early 2010s to lead the international relay that built a global PV market. But non-Chinese suppliers did not benefit the way Chinese suppliers did during the German leg of the race.

As Nemet argues, entrepreneurship, creativity, and international linkages were certainly necessary factors in the Chinese PV surge. But subsidies, initially from the subnational level and later from the national level, were necessary as well. Even a sympathetic observer such as Gallagher noted that in a capital-intensive industry, “Chinese clean energy firms have enjoyed virtually unlimited amounts of capital” thanks to government policy. Similarly, Jeffrey Ball and his Stanford colleagues stated that Chinese officials acknowledge that in 2011–2012 they created “a solar manufacturing bubble [with] their easy liquidity.”[44]

EXCESSIVE COMPETITION AND THE DEMISE OF PV MANUFACTURING OUTSIDE OF CHINA

The PV manufacturing bubble is all the more remarkable given the rapid and sustained growth of global sales. After 2006, year-on-year growth of installed PV generation stayed above 40 percent until 2013, when it fell to 37.7 percent. For the 2006–2013 period as a whole, installation growth totaled an astounding 2,362 percent. Yet, supply kept pace with or even exceeded demand. Excess manufacturing capacity put intense downward pressure on prices.[45]

Chronic oversupply and hyper-competition implied a massive waste of capital, yet Chinese local leaders and entrepreneurs continued to jump into the game as they read the signals from Beijing. The central government finally took note in late 2013, decreeing that some three-quarters of the more than 500 companies in the domestic PV manufacturing value chain at that time would no longer be eligible for domestic projects. The policy not-so-subtly squeezed access to finance in an effort to drive low-quality producers out.[46]

Outside China, the shake-out was even more severe. Beleaguered manufacturers turned to their home-country governments for help. A spokesperson for SolarWorld, a German-headquartered firm with operations in the United States and elsewhere, put its complaint simply: “Pervasive and all-encompassing Chinese subsidies are decimating our industry.” The United States and later the European Commission ultimately imposed sanctions aimed at countering subsidies and below-cost dumping of Chinese PV cells and modules. But these steps—riddled with loopholes, opposed by customers, and moderated for geopolitical reasons or fear of retaliation—proved to be toothless.[47]

Western governments were not willing to match Chinese subsidies or effectively correct for distorted exchange rates, either. In the United States, the federal government offered a 30 percent tax incentive to PV manufacturers under the 2009 American Reinvestment and Recovery Act. It hit a fiscal cap in 2010 after providing just $800 million in breaks, including $10 million that went to China’s Suntech and Yingli. Four solar manufacturing projects received federal loan guarantees under the Recovery Act. But two were never used, and two others went to companies that went bankrupt in 2011–2012: Abound and Solyndra.[48]

Loan guarantees for utility-scale PV projects indirectly aided the U.S.-based manufacturer First Solar, which supplied the equipment for three of the five projects that won them. These projects, which amounted to over 1 GW of production between late 2011 and early 2015, helped the firm's bottom line. The program as a whole established the viability of large-scale solar projects, which dominated installations in the United States throughout the 2010s, ultimately benefiting Chinese suppliers more than others.[49]

The controversy over the Solyndra loan guarantee poisoned further attempts to provide additional federal support to U.S. PV manufacturers. Not long after the Tea Party revolt gave Republicans control of the House of Representatives in January 2011, its powerful Energy and Commerce Committee initiated an investigation, alleging that the company received preferential treatment. By the time Solyndra declared bankruptcy and defaulted on the loan in August of that year, the name conjured disdain among members of the majority party, which was not inclined to back this industry in any case. The only remaining federal programs after that provided a mere $20 million to $30 million per year for manufacturing R&D.[50]

U.S. states also offered incentives to locate PV manufacturing plants within their borders. But these, too, proved no match for their competition in China. In the case of Evergreen Solar, the fourth-largest solar-cell manufacturer in the United States in 2010, Massachusetts went head-to-head with Wuhan and lost. Despite loans and tax credits from the state, the company closed its Massachusetts plant in 2011 after receiving "easy access to capital" (in the words of its own executive) to move production to China. According to Usha Haley and George Haley, "Evergreen, with its partners, the Wuhan municipal and Hubei provincial governments, borrowed two-thirds of its Wuhan factory's cost (as compared to less than 5 percent of its U.S. factory's cost from the Massachusetts government) from two Chinese state-owned banks at very low interest rates with no principal or interest payments due until the end of the loan in 2015."[51]

A few states sought to jump-start solar manufacturing within their borders, for instance, by offering additional incentives for in-state production in their renewable portfolio standard. These efforts did not yield significant results. Most RPS-driven purchases—like those aided by the German FIT and the U.S. federal investment tax credit for PV installations, and unlike Chinese solar installations—were agnostic as to the source of the equipment installed.

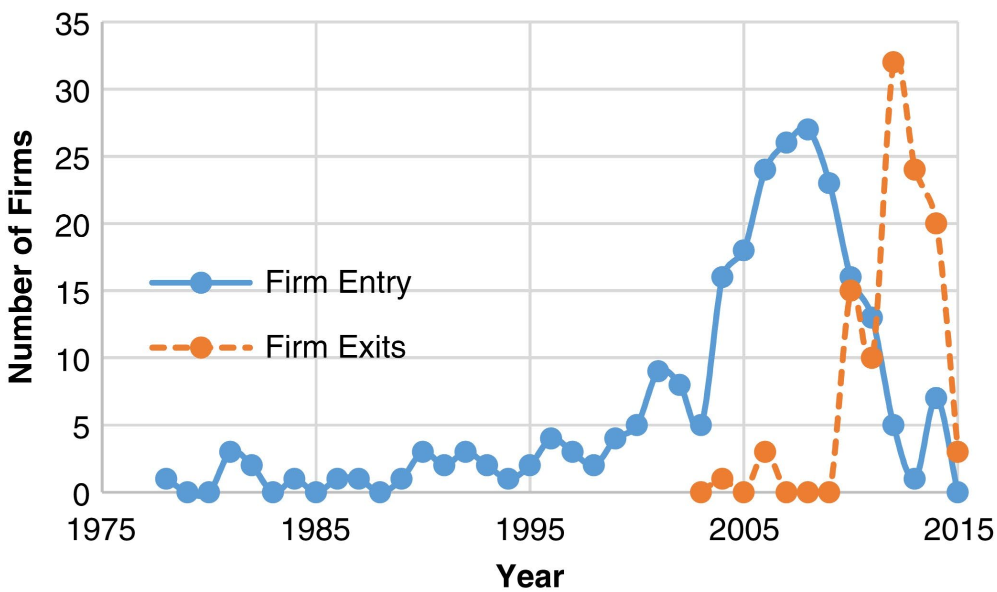
In any case, in the absence of effective trade protection, incentives offered by governments outside China to build PV manufacturing plants would simply have exacerbated the problems of excessive competition and overcapacity. Beyond seeking government help, Western producers employed a variety of strategies to try to survive the shake-out. Some continued to compete directly on price with subsidized Chinese competitors, building new facilities in Malaysia, the Philippines, and other Asian locations to cut costs. Others diversified downstream into project development. By 2014, for instance, two leading U.S.-headquartered firms, SunPower and First Solar, were deriving more than two-thirds of their revenue from downstream activities.[52]

As discussed in more detail below, these firms also sought to differentiate themselves from commodity producers through product innovation. SunPower jousted with U.S.-headquartered Solar City and Japan's Panasonic to make the world's most efficient c-Si module, while First

Solar offered the most-efficient TFT modules. The effort to escape competition is well-established in theory, and empirical research has shown that R&D-intensive manufacturing firms are less vulnerable to trade shocks.[53]

Such strategies allowed SunPower and First Solar to survive, but they were the exceptions. A study of 238 firms that entered the PV module manufacturing industry globally from 1978 to 2015 found that 104 of them exited by 2015, with the majority departing between 2012 and 2014. (See figure 4.) Chinese firms are included in these figures, as the policy decree previously noted would imply. Suntech, for instance, which was the world's largest producer in 2011, went bankrupt two years later. But the study showed that the probability of a Chinese firm exiting the industry was statistically significantly lower than a non-Chinese firm, even when many other variables are taken into account. In fact, the China variable predicting firm survival was larger in magnitude than most of the strategy variables upon which the authors concentrate.[54]

Figure 4: Firm entry and exit in PV module manufacturing, 1978–2015[55]



The bloodletting was much worse for ventures pursuing second- and third-generation technologies. Twenty-seven of the 34 TFT start-ups in the study exited, as the global market share of thin film products peaked in 2009 and fell back into the single digits by 2012. Along with Abound and Solyndra, darlings of the cleantech VC boom such as HelioVolt, Konarka, MiaSolé, Nanosolar, and SoloPower were acquired or went under. Nor were units of large companies spared; GE, for instance, sold its thin-film business to First Solar in 2014. Other buyers were Chinese. Hanergy, for instance, made a string of acquisitions, including MiaSolé (which sold for just $30 million in 2012 after having raised more than $500 million in venture funding and receiving over $100 million in federal tax incentives) and the thin-film unit of Q-Cells, Germany's leading PV manufacturer.[56]

After the shake-out, the industry settled into a pattern that persists today, notwithstanding a further round of tariffs imposed by the Trump administration. According to NREL, with the exception of First Solar and South Korea-based Hanwha Q Cells, the top ten PV manufacturers (and all of the top five) in both 2015 and 2019 were based in China or Taiwan. While many

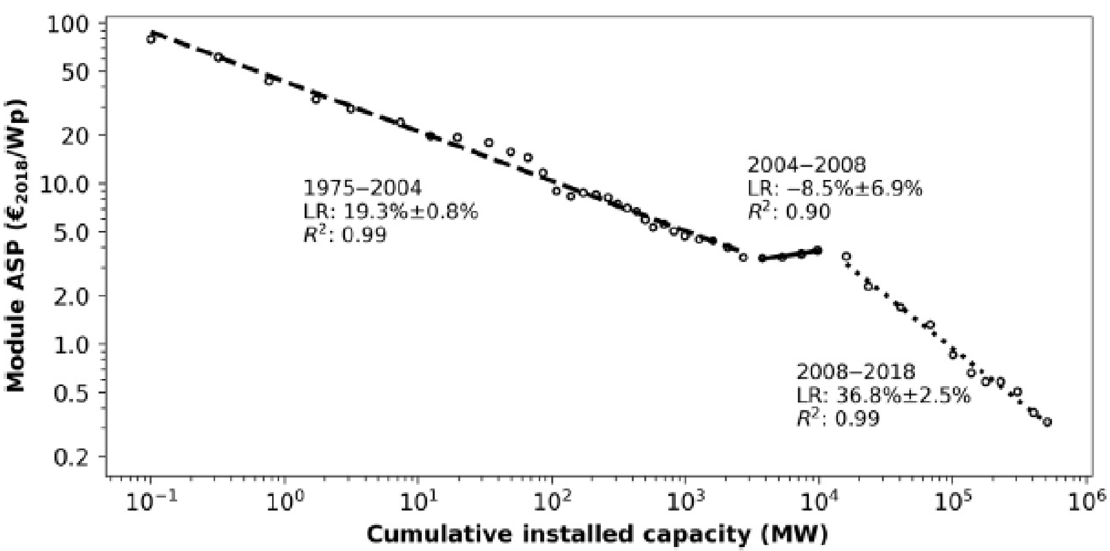
Chinese manufacturers have diversified their production locations, particularly within Asia, to lower costs and avoid tariffs, Chinese factories still produce about 60 percent of the world's PV cells and modules.[57]

PV INNOVATION SINCE 2006

The shift in the pattern of production brought with it a shift in the pattern of innovation in the PV manufacturing industry. Price pressure resulting from chronic oversupply compelled process innovation and efficiency gains in c-Si cells and modules, as managers struggled to keep costs in line with revenues. But it also squeezed profits and limited new entrants, crimping R&D spending, invention, and product innovation.

Figure 5, which maps the PV "experience curve," may be the most famous graph in energy policy this century. The y-axis measures the price for a unit of PV electricity generation capacity; the x-axis measures cumulative installed capacity. Both axes are logarithmic, that is, each evenly spaced tick on an axis represents a ten-fold difference from one unit above, below, or to the side of it. The downward slope of the line therefore describes the percentage decline in the unit price relative to the percentage growth in cumulative capacity. The relationship is often summarized as a "learning rate": for each doubling of cumulative capacity since the 1980s, according to Atse Louwen and Wilfried van Sark, the creators of figure 5, the price has declined by approximately 20 percent.[58]

Figure 5: PV experience curve, 1975–2018[59]



Global cumulative installed PV capacity has doubled approximately nine times since 2001. Applying the 20 percent learning rate, we see that the same amount of generating capacity that cost $100 in 2001 would have cost about $13 in 2018, in constant, inflation-corrected terms. However, as figure 5 shows, the path has not been smooth. Louwen and van Sark found a unique break in the series between 2004 and 2008, when prices rose, largely due to the spike in polysilicon prices. The learning rate (denoted as "LR" in figure 5) in those years was negative as a result. In the following period, from 2008 to 2018, as China came to dominate global production, the rate accelerated to about 37 percent, making up the lost ground for the series as a whole.[60]

As the term suggests, the "learning rate" was developed to assess what producers learn about cost reduction as they gain experience. Originally, it described a single factory, and captured improvements made by workers and managers making the same product with the same equipment. Figure 5 still captures learning in this sense, but because it covers an entire global industry over a long period of time, "learning" also captures economies of scale, innovations based on R&D, and many other factors that are challenging to sort out.[61]

Another challenge in interpreting the data displayed in figure 5 is that the data is based on observed prices and installations, rather than actual costs and cumulative production. The latter would map more closely to the concepts that analysts seek to measure, but tend to be proprietary. Indeed, in the case of the Chinese PV manufacturing industry, opaque subsidies call into question whether costs can be measured properly at all. Subsidies may allow prices to diverge from costs for extended periods, as firms that are losing money nonetheless survive and even expand. In addition, vertically integrated producers that develop projects using their own equipment use transfer prices to account for internal transactions, which may also diverge from costs.

Despite this uncertainty, the drop in prices since 2008 has been so steep that there is no doubt that Chinese PV manufacturers have "learned" a lot, in the broad sense of the word. Although SunPower's Swanson might not have been surprised the incumbent technological paradigm had so much possibility left in it, many others have been. Leading energy forecasters have regularly underestimated how low PV prices, led by Chinese firms, would go.

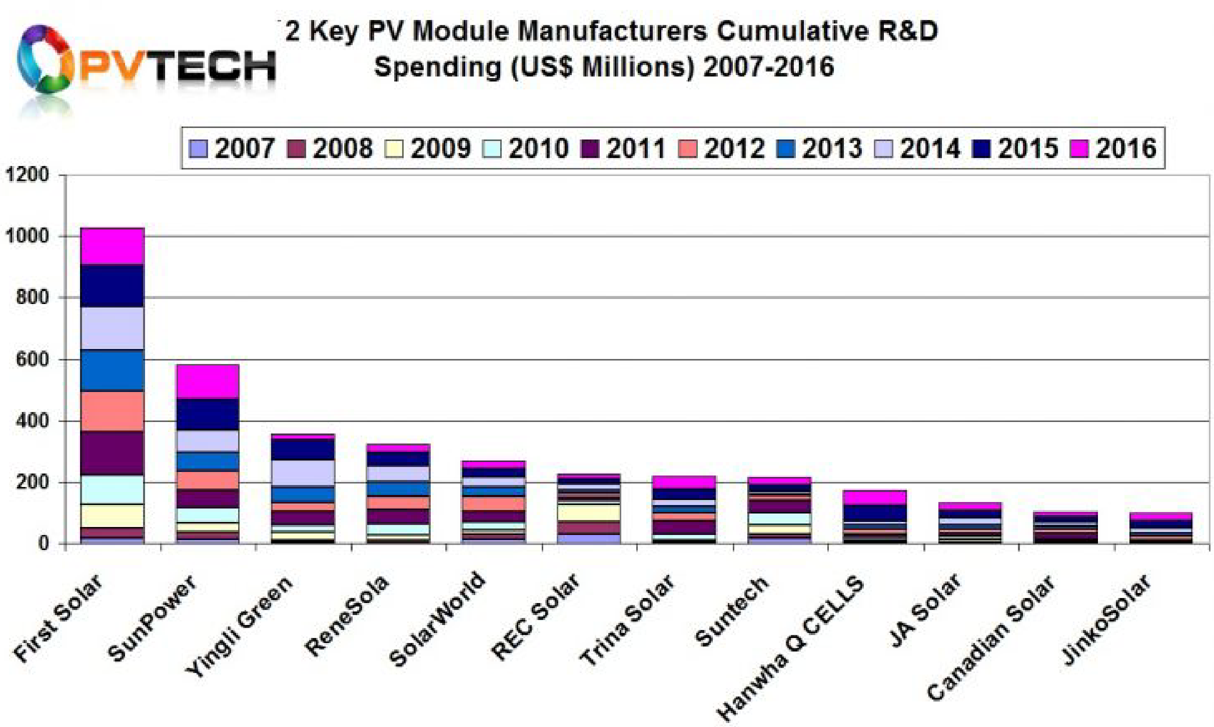
The most easily quantified factor captured by the experience curve is the steadily rising efficiency of installed c-Si modules. The average module installed in 2008 converted about 14 percent of the available energy in the light falling on it into electricity. That figure is about 18 percent now, thanks to improvements in cell design and materials. This efficiency gain boosted the capacity of the average module by about 30 percent. Gains in commercially available products are presaged by even-better-performing research cells. Although they hardly dominate NREL's chart of the highest c-Si research-cell efficiency over time, Chinese firms including Trina, Canadian Solar, and Jinko have begun to appear on it in recent years. Such firms have also forged close ties with some Western academic laboratories that have set PV efficiency records in research settings as well as with Chinese laboratories.[62]

A second facet of "learning" to which the Chinese PV industry has contributed even more significantly in the past decade involves process innovation, economies of scale, and improvements in manufacturing equipment. Jonas Nahm of Johns Hopkins University documented Chinese firms' "innovative manufacturing … to rapidly translate complex technologies into mass-manufacturable products … [including] changes to product designs to accommodate mass production requirements and to meet cost targets for final products." Close linkages between equipment suppliers and manufacturers enable this form of innovation. Belying the stereotype of labor-intensive sweatshops, many Chinese PV factories rely heavily on automation and robotics to achieve greater throughput. Yet, despite these improvements in equipment and processes, estimated capital expenditures per unit of production along the entire PV supply chain fell by a remarkable 85 percent between 2007 and 2018.[63]

The Stanford group led by Ball concluded, "China's solar industry is a textbook lesson in the power of manufacturing clusters," in which regional agglomerations of firms spanning a value chain reinforce one another's strengths through both competition and cooperation. The Chinese surge into PV manufacturing led to the creation of what Gary Pisano and Willie Shih have termed an "industrial commons … know-how, advanced process development and engineering skills, and manufacturing competencies related to a specific technology." These capabilities, along with lower wages, contribute to the international competitiveness of Chinese producers. A recent study by NREL analysts found that the difference in the minimum sustainable unit price between Chinese- and U.S.-made c-Si modules grew from 20 percent in 2012 to 32 percent in 2018, even though unit labor content shrank.[64]

As previously noted, two U.S.-based survivors in this industry, SunPower and First Solar, sought to differentiate themselves through product innovation as well as diversification downstream into project development. Their innovation strategies required spending much more on R&D (about 5 percent of revenue) than their Chinese competitors, who spent only about 1 to 2 percent. Yet, with profits and revenue growth shaved to the bone by excessive competition, both the numerator and denominator of the R&D/revenue ratio were squeezed for these firms. (The Chinese firm with the highest ratio in 2016, ReneSola, exited the PV manufacturing business in 2017.) Figure 6, compiled by *PV Tech* magazine, shows cumulative R&D spending from 2007 to 2016, and reveals how First Solar and SunPower outspent their Chinese rivals even as they lost market share. (Please note that the firms covered in figure 3 and figure 6 overlap substantially but are not the same. Hanwha Q Cells is based in Korea, while all others listed with the exception of First Solar and SunPower are Chinese.)[65]

Figure 6: Cumulative R&D spending by 12 PV module manufacturers, 2007–2016[66]

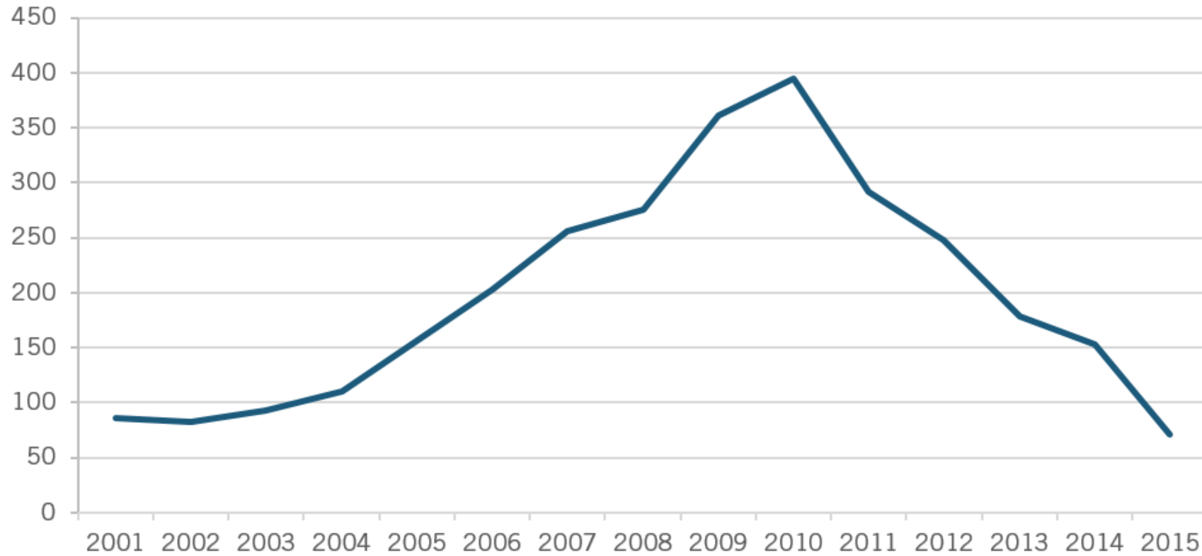


Free riding by low-spending R&D firms on high-spending ones probably deterred the latter from spending even more, particularly firms such as SunPower that focused on first-generation c-Si technology. One study of the industry concludes that in-house R&D contributed little to innovation but instead functioned “primarily as an absorption mechanism…. [A] competitive advantage generated by innovation,” therefore, “is likely to be quickly eroded.” (Theft of intellectual property may also have contributed to such erosion in the case of SolarWorld, which claimed that $60 million in R&D investment and $600 million overall was “undercut” by Peoples Liberation Army hackers who stole the firm’s technology and shared it with Chinese manufacturers in 2012.) The data for that study and others like it ends in 2011–2012, but given the continued growth of the market and the relative modesty of c-Si manufacturers’ R&D spending, it seems likely that the conclusion holds for the more recent period as well.[67]

Chinese manufacturers may also have benefited more from public R&D spending than did their counterparts elsewhere. Some received assistance to conduct highly applied research from the central government, including the co-location of national key laboratories at the headquarters of leading firms, as well as support for cooperation with international labs. The U.S. Department of Energy’s solar PV R&D spending has been far less focused on domestic industrial applications.[68]

Tight R&D spending and the intense focus by the largest PV producers on process innovation is reflected in the decline of patenting since the early 2010s. It is important to be aware that this indicator can be misleading. In their exhaustive study of 51 different selection strategies that researchers have used to measure PV innovation with patents, Stephan Bruns and Martin Kalthaus show that analytical results linking specific policies to trends in patenting are highly sensitive to the definition of the technology, the period covered, quality controls, and other variables. But at a purely descriptive level, the data tells a clear story, regardless of source or definition. PV patenting peaked globally in 2010 and then dropped below the level achieved at the beginning of the Chinese surge. Figure 7 shows a typical time series, using Kalthaus’s preferred definition of the technology and limited for quality control purposes to “triadic” patents in which applications were jointly filed to protect the same technology in the United States, Europe, and Japan.[69]

Figure 7: Triadic patents for PV inventions, 2001–2015[70]



Kalthaus, informed by his comprehensive study of the field, provides a breakdown of patent data by technological generation, which is presented for triadic patents in figure 8. The peak and decline of the overall dataset, corresponding with the Chinese surge, is evident. While there are few patents on silicon cells at any point in the series, the growing number of patents for module and encapsulation technologies through 2010 may have contributed to improvements in c-Si products. Patents for second- (thin-film) and third-generation (emerging) technologies also peaked in 2009–2010. All categories, across all generations and including module and encapsulation technologies, fell precipitously after that.[71]

Figure 8: Triadic patents for PV inventions by technology, 2001–2015[72]

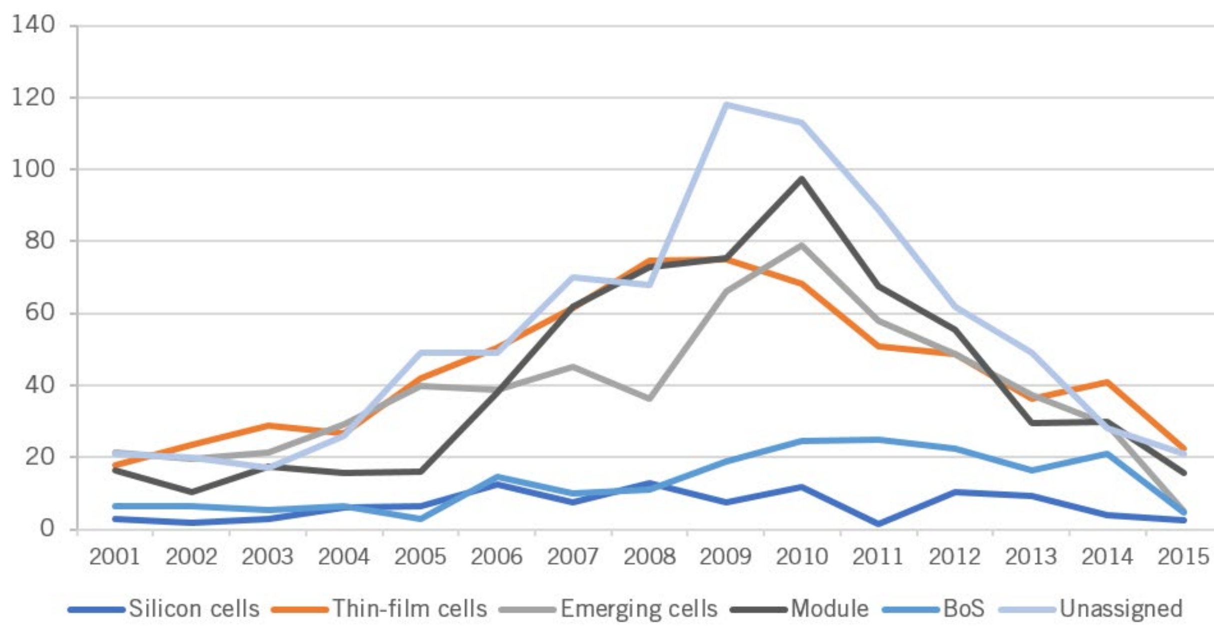
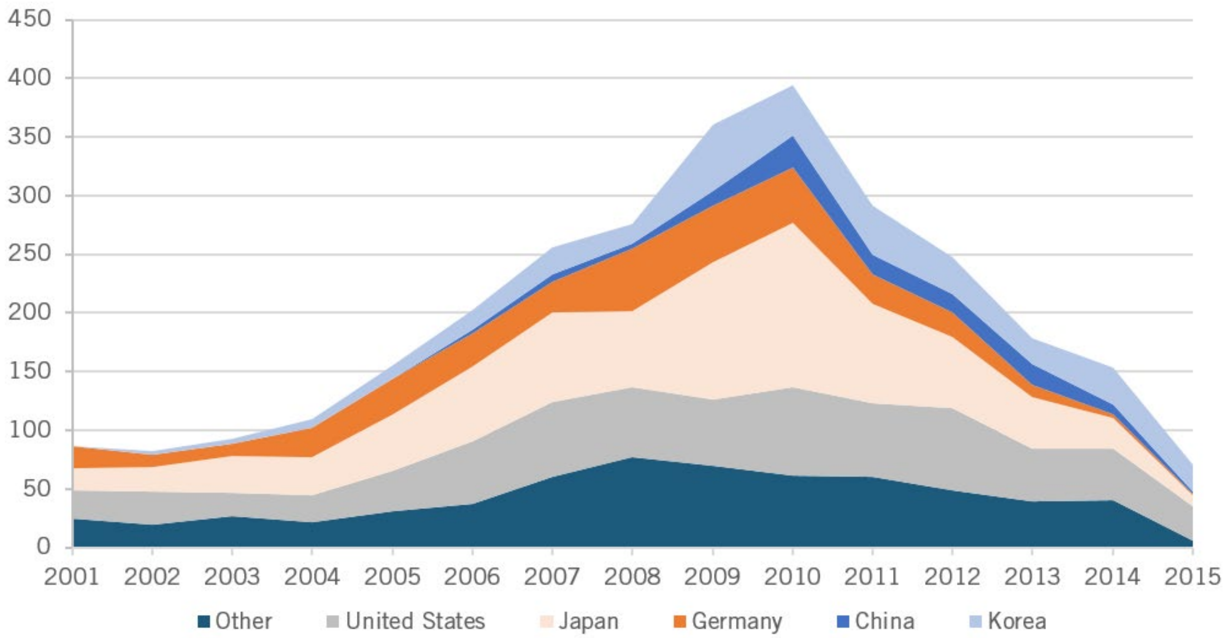


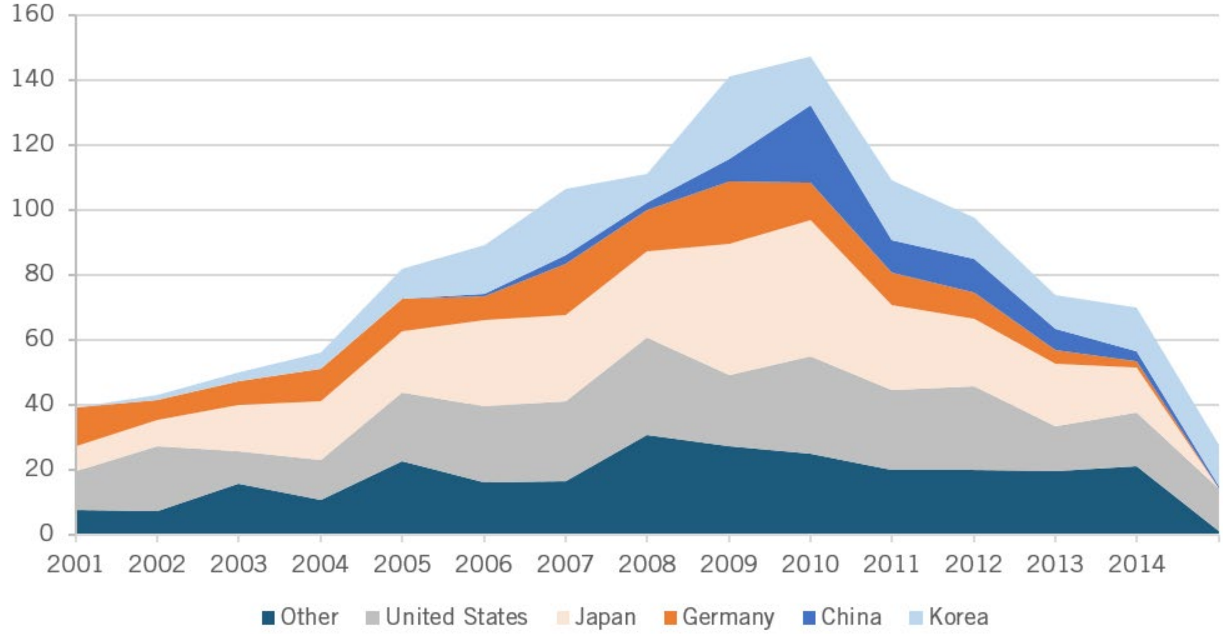
Figure 9 displays the international distribution of triadic patents from 2001 to 2015. Of the nearly 3,000 patents covered, Chinese inventors received less than 4 percent. It may be that Chinese firms have less need to win protection by patenting abroad than firms in other countries, because their main rivals are domestic. Ball and his colleagues reported that domestic patenting in China surged along with production. But these authors also suggested that the patent surge is an artifact of government incentives for firms to win patents and lax criteria for granting them. Most Chinese domestic patents are therefore probably low quality.

Figure 9: Triadic patents for PV inventions by country, 2001–2015[73]



The decline of patenting by Japanese and German inventors displayed in figure 9 is particularly striking. As formerly leading producers such as Japan's Sharp and Germany's Q-Cells lost hope of regaining market share, their home countries' patent production fell by more than 90 percent in less than five years.[74] U.S. patents, perhaps buoyed to some degree by sustained federal R&D investment, dropped only by about half. South Korean inventors, new entrants during the 2000s, experienced a less-marked drop-off. That country's sustained capacity to generate high-quality patents contrasts with China's rapid fade, especially in light of its small share of global PV manufacturing.

Figure 10: Triadic patents for second- and third-generation PV cell inventions by country, 2001–2015[75]



These trends are put into sharper relief in figure 10, wherein the data is limited to second- and third-generation technologies. While a majority of triadic patents held by Chinese inventors fell into these categories, they accounted for only about 5 percent of the global total, and declined quickly after the 2010 peak. Korean inventors held more than twice as many in total, and continued to win patents as Chinese inventors left the field.

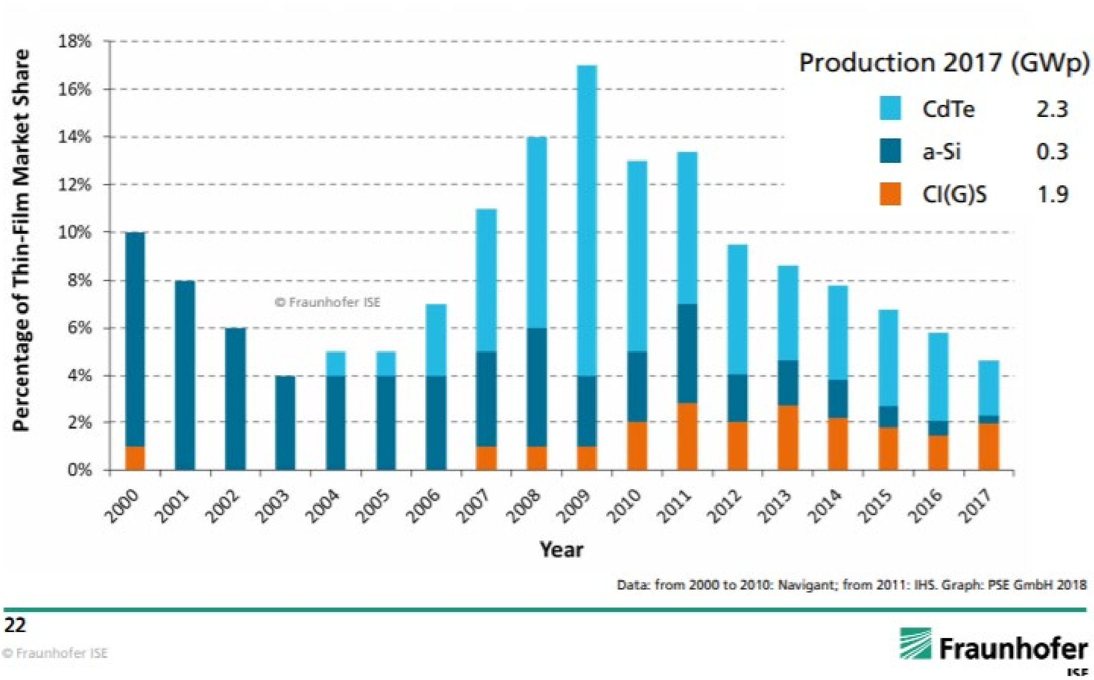
The decline in patents for second- and third-generation technologies is not surprising given the carnage among companies pursuing these technologies that was documented in the previous section. A team commissioned by the World Intellectual Property Organization (WIPO) found that many fewer companies outside of China filed patent applications after the surge. "For example, the number of unique US-based applicants having filed at least one patent in the PV sector has decreased by 71 percent between 2011 and 2014." The figure was even higher for Korean, Japanese, and German applicants.[76]

Few new applicants from these countries entered the field. Burned by their losses, and unwilling to enter a capital-intensive, low-margin business, U.S. venture capitalists turned their attention elsewhere. Bemoaning this lack of interest, Eric Wesoff of *PV Magazine*, writing in January, 2020, opined that "a silicon PV wafer and panel factory manager from 15 years ago would recognize most every step and process of today's production … far from the 'improbable pyro-nano-quantum-thingamajig technology' we were promised."[77]

INTERPRETING THE IMPACT OF THE CHINESE SURGE ON INNOVATION

The evidence leaves little doubt that the Chinese surge into PV manufacturing coincided with a shift in the trajectory of technological innovation. Prices dropped, efficiency rose, and process innovation flourished, while R&D-intensity, patenting, and new entry dived. As late as 2010, some industry analysts anticipated that TFTs' share of the global market would rise to 30 percent by 2013. Instead, it plunged into the low single digits and stayed there, as figure 11, which was prepared by the Fraunhofer Institute, shows. The market for third-generation PV has not yet gotten off the ground, although research and even some efforts to commercialize it are continuing.[78] This section interprets these trends using two theoretical lenses—dominant design and technological lock-in—with support from counterfactual analysis.

Figure 11: Global market share of thin film technologies, 2000–2017[79]



Slower Innovation Within a Dominant Design?

It is possible the shift in PV innovation would have occurred in any case when demand scaled up. Dominant design theory asserts that industries, especially those based on mass production, go through periods of ferment (when diverse product architectures are developed) and consolidation (when standardization occurs). The latter periods are associated with rapid scale-up of production and a shift in the focus of innovation to processes and production equipment. Proponents of this perspective see Chinese firms as beneficiaries of the advent of a dominant design, but not the fundamental cause of the shift.[80]

Even if one adopts this view, however, it seems likely that the nature of PV innovation would still have been different if manufacturing had remained diversified internationally, rather than concentrating in China. More R&D-intensive c-Si manufacturers such as SunPower and SolarWorld would have thrived in such a world, along with the German equipment-making industry that laid the foundation for the dominant design to succeed. The result might have been accelerated c-Si product innovation, leading to more rapid gains in efficiency and other performance characteristics than we have seen to date.

But this counterfactual trajectory also suggests a possible trade-off. A less-subsidized, more-profitable, more-internationally competitive PV manufacturing industry might not have dropped its prices as quickly. That, in turn, might have slowed demand growth, since demand in the 2010s was mostly driven by public policy around the world, which in turn was made far more attractive by the low prices of Chinese modules. That effect would have slowed PV's progress down the experience curve in figure 5.

Stranded Innovation Due to Technological Lock-In?

A second counterfactual builds on the theory of technological lock-in. This theory holds that a dominant design may emerge and be sustained not because of its intrinsically superior characteristics, but because of historical contingencies. Better designs are locked out of the market or relegated to marginal niches. Historians have found that such contingencies can account for the dominance of particular designs for many technologies, including in the energy sector.[81]

One of the best-known cases of lock-in is the light water nuclear reactor. This design became the world standard because the U.S. Navy adopted it for nautical propulsion, which led the U.S. government to promote it for power plants. Even though alternative designs would have been better for power plants, the light-water design won out because of the head start the Navy's investment gave it and the vast power of the United States government, its chief promoter. The dominant design became locked-in because its economic and political momentum reinforced one another.[82]

Historical contingencies may also have influenced the dominant design for solar panels. First-generation crystalline-silicon technology had a head start, leading the market from its inception in the 1970s. Second-generation TFTs, aided by their lower cost and greater flexibility, were beginning to make serious inroads when the financial crisis hit in 2008, as figure 11 shows. But the crisis made project lenders much more conservative, insisting on "bankability," by which they meant project developers had to be able to point to a track record of performance in order to find funding. This risk-aversion inevitably penalized designs with which developers had less experience, with knock-on consequences for upstream investors in companies and factories.[83]

The political power and deep pockets of the Chinese central government, the chief promoter of the dominant design from 2010 on, strongly reinforced this trend. At a moment when access to capital was critical to survival, the government stepped in with conviction to supply it. Its move, according to this interpretation, did more than merely allow an industry that had proven its competence with export-quality, first-generation products to survive. Like the U.S. government and light water reactors, China's government locked in c-Si cells as the dominant design for PV.

This interpretation certainly has weaknesses. TFT cells are less efficient and therefore require more space per watt generated than c-Si cells. Some require materials that are much less abundant than those used in c-Si cells. Many start-ups proved unable to master the fussy manufacturing processes required to make TFT cells at scale quickly enough to meet the competitive challenge when it arose.

First Solar, the world's major producer of CdTe TFT cells, stands as a proof case that the dominant design is not necessarily intrinsically superior. Its continued investment in innovation and its manufacturing prowess in Asia as well as the United States, along with downstream diversification and a bit of timely help from the U.S. government under the Recovery Act, have kept it among the world's top 10 PV manufacturers.

That no “Second Solar” emerged that came close to replicating First Solar’s performance may be an indictment of the management of the contenders for that title.[84] But it may also be an illustration of the historical contingency on which the lock-in theory relies. While TFTs might not have displaced c-Si as the dominant design, a healthier diversity of designs might have flourished if events had played out only slightly differently.

Modeling Plausible Alternative Pathways

While we cannot rerun the 2010s to find out precisely what would have happened in the absence of Chinese mercantilism, we can explore the second interpretation of its impact on PV innovation by utilizing experience curves.

Two Experience Curves

Figure 12 is drawn from the same source as figure 5, but breaks down the data between two types of modules: c-Si and CdTe. This division is appropriate, since some of the most important sources of learning, such as supply chain improvements and manufacturing innovation, differ between the two.

Figure 12: Experience curves for crystalline-silicon and cadmium-telluride PV modules, 1975–2018[85]

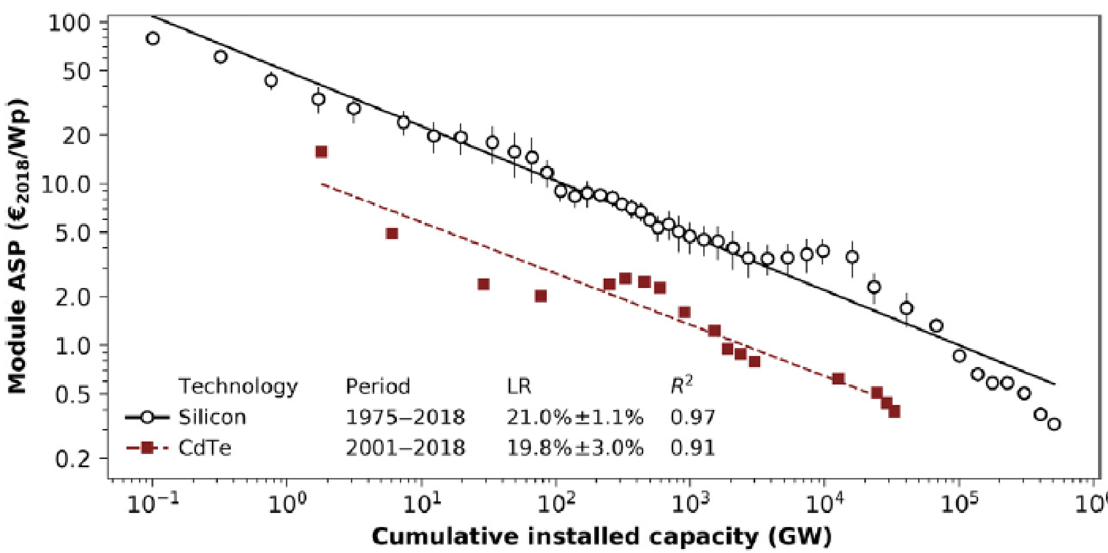
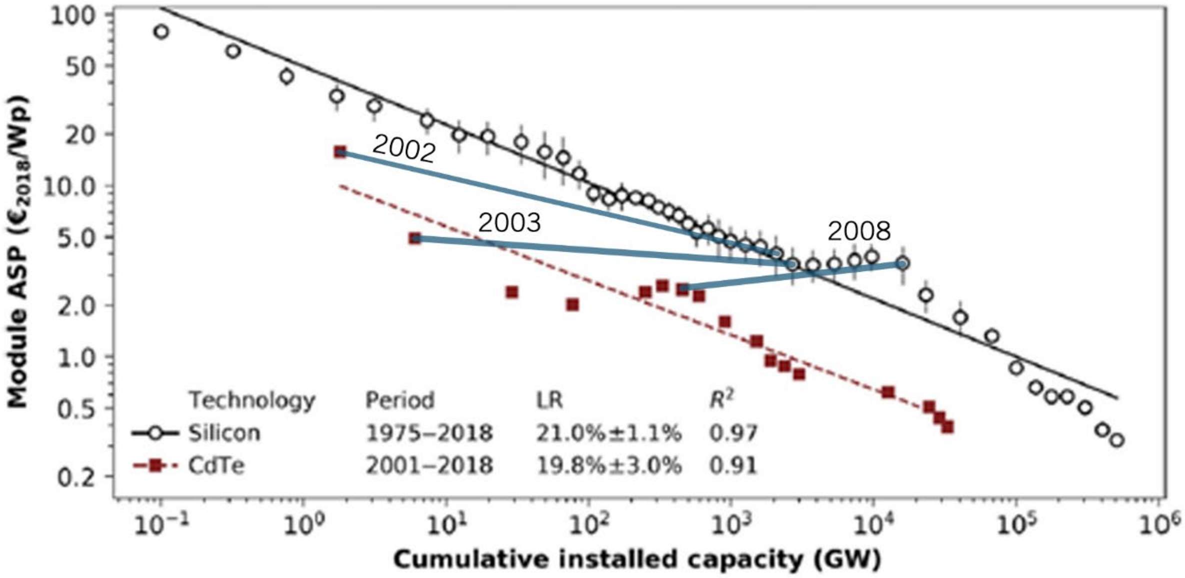


Figure 13 drills down on these concepts. The blue lines connect data points for the same year along each experience curve. For 2002, the line slopes downward, meaning that the unit price for c-Si was substantially less than for CdTe. But CdTe production grew rapidly over the next year, bringing the prices close to equal, and making the blue line nearly flat for 2003. By 2008, cumulative production of CdTe had expanded so much that the blue line slopes upward; CdTe prices per unit were lower than c-Si at that moment.

Figure 13: Comparisons of progress down PV experience curves through 2008[86]



The fact that the axes on the experience curve are log scales is crucial for understanding this comparison. Recall that each evenly spaced tick is one order of magnitude, a 10x difference. The distance on the graph from 10,000 units to 100,000 units in installed capacity, for example, is the same as the distance from 100,000 units to 1,000,000 units. Yet, the real-world challenge of scaling up by 90,000 units may be considerably less severe than scaling up by 900,000 units. That makes rapid movement from left to right on the graph more plausible the further to the left a technology is. Indeed, the points are more spaced out on the left of these figures than the right.

Figure 14: Comparisons of progress down PV experience curves through 2018[87]

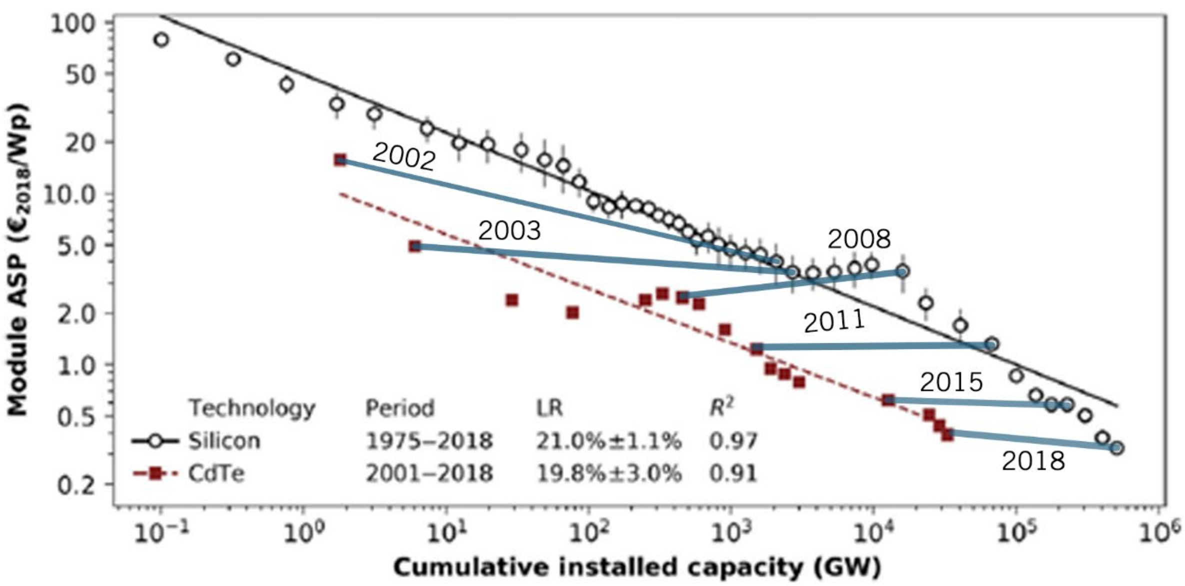


Figure 14 shows the later progression down the two curves, as the volume of Chinese c-Si module production grew so remarkably. By 2011, the two technologies' unit prices were once again close to level. By 2015, c-Si was slightly cheaper, and the price advantage grew by 2018.

This data is estimated, aggregated, and thus subject to error. Yet, the pattern of changing relative prices appears to be robust, given the magnitudes of these measurements. The reversal favoring c-Si coincided closely with the timing of the Chinese surge. If CdTe's market share, shown in figure 11, had continued to grow after 2009, as its advocates had expected, and the technology had remained on the experience curve depicted in figure 14, the experience gap would have closed, and CdTe products would have remained cheaper.

How Our Models Work

Models that use data from experience curves such as these allow us to explore this issue in a more formal way. The movement of each technology along its curve can be projected by picking a starting point and varying how the overall market and the market shares of the technologies evolve going forward from that point. These variations determine how far and how fast prices come down both in absolute terms and relative to one another.

We have created such models, using proprietary data on production and costs, which are broadly consistent with but not the same as the data displayed in figure 12. Our models start in 2006, since the Chinese surge began at about that time. We used cumulative production and average cost data to place each technology on the experience curve in that year.

For simplicity's sake, we also used real-world data for total global production for 2007 to 2016. We did not attempt to model the feedback from prices to production that we discussed above, which could change total production. Although that would not be difficult to add from a mathematical perspective, making the model dynamic in this way would require additional assumptions about firm behavior and public policy.

What we did vary in order to create counterfactuals is the share of production assigned to each of the two technologies within that fixed total. Specifically, by assigning a larger share of global production to CdTe modules, we artificially moved that technology down its experience curve more quickly than actually occurred. (We excluded two other solar PV technologies—a-Si and CIGS—which made up a small share of global production in this period, as shown in figure 11.)

Consistent with figure 12, we used a learning rate of 20 percent for both c-Si and CdTe. We varied this rate in models in order to test sensitivity.

Baseline

In 2006, our data shows that CdTe unit costs were about half those of c-Si. This difference existed even though cumulative production of c-Si was nearly 200 times larger at that time, more than two orders of magnitude, or two ticks to the right on the x-axis on an experience curve graph. In other words, the line connecting the dots on the two curves in 2006 was upward sloping in our data, just as it is for 2008 in figure 12 (which uses a different dataset). It is not surprising that venture funding was pouring into TFT start-ups in 2006, nor that the technology's market share was growing. As the Chinese surge accelerated, however, the cost gap in our data steadily narrows, with unit cost parity achieved in 2014 (which is also similar to figure 12).

Model 1: "10 Percent"

Our first model is called "10 percent." In this model, CdTe maintains a fixed 10 percent share of global production from 2007 on, with c-Si holding the other 90 percent. This is roughly the ratio between the two technologies' market shares in 2008 and 2010, and below the peak of 2009. The cost gap does not close in "10 percent" as it does in figure 14, but instead grows in favor of CdTe. By 2016, the cost per watt of CdTe capacity is 80 percent less than that of c-Si. If, as a sensitivity test, we reduce the CdTe share to 5 percent, the difference in CdTe's favor shrinks only slightly, to 75 percent. If, however, we reduce the share to 5 percent and increase c-Si's learning rate to 40 percent (as in figure 5), the gap is gone by 2014 and c-Si gains a 20 percent price advantage by 2016.

Model 2: "Share the World"

Our second model is called "share the world." In this model, 100 percent of the Chinese market is supplied by c-Si from 2007 on, but the rest of the world is split, with 30 percent going to CdTe and 70 percent to c-Si. In "share the world," too, the cost gap grows in favor of CdTe, stabilizing at about 85 percent less than c-Si through 2016, even though the Chinese market is growing rapidly after 2009 and becomes a sizable share of the global market by 2012. We test the sensitivity of this model by raising the learning rate to c-Si to 40 percent and reducing the share of the non-China market assigned to CdTe to 10 percent. In this variation, the cost gap disappears as c-Si gains a slight advantage by 2016.

Model 3: "Second Solar"

Our third model is called "Second Solar." In this model, we imagine a second CdTe company exists that produces the same amount as our data estimates First Solar actually did every year from 2007 on. In other words, we doubled First Solar's share of global production. We took "Second Solar's" portion of global production away from c-Si. "Second Solar" produces results similar to "10 percent." The unit cost of CdTe quickly settles at about 80 percent less than that of c-Si. As a sensitivity test, we raised the learning rate for c-Si to 40 percent. In this variation, the cost gap closes over time but does not disappear, reducing CdTe's cost advantage to about 15 percent by 2016.

Interpreting the Models

These models are suggestive of plausible alternative pathways for the industry. "10 percent" might be interpreted as a world in which the concern about bankability did not become as important as it did at the moment it did, and more buyers went with the lower-cost option from 2008 onward. The timing of the financial crisis is a key historical contingency according to this interpretation. "Share the world" adds the contingency of more-effective policies (whether protection or subsidies) in countries that wound up importing Chinese c-Si modules, especially the United States, which was the global center of TFT production and consumption before the surge. Such policies might have shifted not only the location of production, but also the balance of the technologies produced. "Second Solar" points to the managerial failures previously discussed. If only one new entrant out of the many that jumped into TFT production, whether a start-up or an established firm such as Q-Cells, had succeeded to the degree that First Solar did, the technological trajectory of the industry might have been altered.

In all three of our main models, CdTe's cost advantage is massive and sustained. As long as the CdTe modules proved to be durable and performed as expected, it seems likely that the issue of bankability would have quickly disappeared. While the impressive price drops of c-Si have captured the world's attention, in these models, we project prices well below observed prices, even if CdTe had won only 10 percent or even 5 percent of the global market. The biggest feel-good story in energy of the past decade could have felt even better.

To be sure, the models are sensitive to adjustments in their parameters. Doubling the historical learning rate for c-Si to 40 percent, as we have done in our sensitivity tests, for example, makes the two technologies much more competitive. It is true that figure 5 shows a learning rate at about this level between 2008 to 2018. However, our models start in 2006, and those two years make a big difference, since the learning rate was negative then.

Even more important to bear in mind is that learning rates are observations, not predictions. Cadmium is a toxic heavy metal, and ramping up CdTe production might have bumped up against environmental regulatory limits. Tellurium is relatively rare, and its price might have spiked, disrupting the curve. While First Solar has been able to replicate its manufacturing processes at new plants, other companies have never matched it. Perhaps CdTe production is too finicky to scale the way these models project.[88]

None of these very reasonable caveats should overshadow the fact that the world did not get a chance to find out if even lower prices for PV based on scaled-up CdTe production would have been achievable. China's thumb on the scale distorted what Joseph Schumpeter called the "process of creative destruction" through which well-functioning market economies discover what is possible. Because the process is evolutionary, past outcomes shape future opportunities.[89]

LESSONS LEARNED AND STRATEGIES FOR THE FUTURE

The case of PV manufacturing is not over. Nor is it unique. The threat of Chinese innovation mercantilism hangs over other, less-mature sectors, such as batteries, electrolyzers, and carbon capture devices, with the potential to reduce global carbon emissions. Policymakers should adopt measures that counter China's policies and raise the odds that alternatives to the dominant designs in PV and other key climate and clean energy technologies get a fair chance to succeed in the coming decade. Innovation and deployment of these technologies are both important goals for public policy.

Next Steps for PV Technology Policy

China dominates every stage of global PV manufacturing today. The scale and supply chain advantages of the Chinese production system are formidable. The c-Si technology at the core of this system holds over 95 percent of the global market. (See figure 11.) The ability of China's industry to continue to grow rapidly despite making little or no profits suggests that subsidies, whether actually flowing or merely serving as an implied backstop, still shape the landscape. (See figure 3.) Certainly any potential investor asked to back a new entrant, even one with advanced technology, would be remiss if they did not take state-backed Chinese competition to be a risk factor, inquire about the entrepreneur's strategy for dealing with it, and seek a higher return as compensation.[90]

Given the climate challenge facing the world, and the options available to respond to it, PV is too important a technology to fail. There is a real chance that the industry's system of innovation as currently configured will not be able to meet the challenge. The lack of product diversity is especially concerning. As Sivaram puts it, "[S]ilicon solar appears to function much more as a barrier than a bridge to the adoption of more advanced technologies." If there is to be no Second Solar, and third-generation technologies are unable to gain enough of a foothold in the market to establish their own experience curves, the fate of the climate may depend not only on the indefinite continuation of Chinese gift-giving, but also continued rapid progress in first-generation technology.

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Some experts, such as Martin Green, evince confidence that the incumbent dominant design will outrun its challengers. Thinner, more efficient and more durable c-Si modules are coming to market that will not only be cheaper themselves but also enable balance-of-system cost reductions. The alternative pathways, in his view, are hobbled by reliance on rare or toxic materials, as well as fragile designs.[91] Other experts are less optimistic about c-Si and more enthusiastic about the alternatives. Perovskites, for instance, a family of third-generation technologies, hold the promise of very-high-efficiency cells that can be made at very low cost with Earth-abundant materials. Recent research points toward progress in solving some of the problems Green identifies with these technologies and even an economically-sustainable path to large-scale production via niche markets. (Green himself holds out some hope for hybrid cells that combine c-Si with a yet-to-be-discovered thin film material.)[92]

Perhaps more important than any one expert's view is that the consensus view changes over time. Two review articles published in *Science* by large groups with the same lead author over a span of just two years, for example, reached different conclusions about the importance of improving PV's core technology. While the group was more upbeat about c-Si's prospect in 2019 than in 2017, the consensus could shift back to pessimism, especially since the actual costs of production in China are so opaque. Prudent risk management suggests, at a minimum, that policymakers should seek to create and sustain a modicum of technological diversity in case the c-Si experience curve flattens out again.[93]

Increased public investment in R&D for all three generations is necessary to do so. It would be sensible for the United States and other R&D-intensive countries other than China to focus their investments on second- and especially third-generation technologies. China, which would benefit the most from the sustained success of the first generation, could take responsibility for that technology's trajectory, particularly since China's policies are denying the industry large-enough profits to sustain adequate private R&D spending.[94]

But public R&D spending alone is far from sufficient to ensure technological diversity in PV production. Manufacturers must scale their innovations if they are to move down the experience curve. They must raise and resolve questions about manufacturability, process innovation, and other aspects of "learning" that lead to cost reduction. Operators must gain experience in the field as well in order to demonstrate new technologies' reliability and durability, ultimately demonstrating their bankability, so investors will come forward to support projects and companies without hesitation.

Policies that create demand for alternatives to the dominant design are critical to scale them up in this way. Customers must provide feedback for learning to be meaningful. Market-pull policy options include carve-outs for alternative PV technologies within renewable portfolio standards, tiered tax incentives and FITs that award them a higher level of support, and loan guarantees for project developers deploying them. These are the same tools that were used to build the PV industry that we have now.

The third component of a policy package to create and sustain technological diversity in PV production takes a lesson from China: public-private co-investment in manufacturing and supply chains for alternative technologies. These investments should be informed by strategic analysis of technologies and markets, and seek to strengthen knowledge flows between R&D and production to accelerate innovation. That may well mean concentrating resources in a few places with the potential to grow into significant industry clusters.[95]

Tariffs and other forms of trade protection, which have been ineffective in the past, may have a role to play in this package as well to counter tactics that might defeat the strategy of technological diversification. Making these policies more effective will require Congress to update anti-dumping rules to allow the U.S. government to impose countervailing duties before economic harm is done. To use another horse analogy, the current policy ensures the horse of economic damage is already out of the barn before the door allowing the damaging imports in can be closed. [96]

Foreign-headquartered firms should be eligible to participate in public R&D and manufacturing programs, and imported products should qualify for carve-outs and other demand incentives, only if their home countries offer reciprocity and transparency. Products made by companies benefiting from mercantilist policies should be excluded. China has exploited policies that were neutral with regard to where products came from, especially in the United States and Germany, providing an important lesson for policymakers today.[97]

Indeed, it would be ideal if countries committed to this strategy of encouraging technological diversity formed a coalition of the willing and aligned their policies. The larger the coalition, the larger the market, and the more opportunities to share ideas and know-how and to achieve scale. Analysts in both the United States and Europe have suggested that the time may be ripe to re-shore PV manufacturing as both labor and capital costs decrease.[98] It would be a shame if erstwhile allies balkanized the industry more than is necessary to sustain diversity, thereby slowing the learning process and the path to a low-carbon economy.

Policies to Encourage Diversity in Other Climate-Tech Sectors

Many new technologies, within and outside the power sector, will be needed to avert the worst consequences of climate change. A July 2020 IEA report finds that 75 percent of the emissions reductions in its Sustainable Development Scenario come from technologies that are not yet mature. Some of these technologies, such as PV, are modular, exhibit economies of scale, and could be standardized and commodified. These characteristics could make them vulnerable to policy and market dynamics that are similar to those experienced by PV over the past decade, including innovation mercantilism. The PV case should be drawn upon to inform clean energy innovation policy choices in the United States and its partners going forward.[99]

Batteries are an example. Many observers have highlighted the parallels between the experience curves of lithium-ion (Li-ion) batteries and c-Si solar panels. The causes are similar. Massive, subsidized investment and protection of the domestic market have helped make China the dominant player in the Li-ion battery supply chain and drive down prices. If supply outruns demand, scarce profits could limit investment in the next generation of these batteries and lock out alternatives to them.[100]

The PV case should be drawn upon to inform clean energy innovation policy choices in the United States and its partners going forward.

The parallel is inexact. Powerful, diversified non-Chinese companies such as Panasonic and Samsung SDI are leading Li-ion battery producers. Li-ion batteries have two very large potential markets—electric vehicles and grid storage—with different requirements. The customers for Li-ion batteries, particularly vehicle original equipment makers (OEMs), have a much stronger incentive to demand product innovation than do solar project developers. The OEMs are also wary of losing control of the value chain to their suppliers, as the auto industry shifts away from internal combustion engines and associated components. Grid storage is much more like solar power; indeed, the two are increasingly integrated in the same projects. But storage operates very differently than solar, which may lead to a more diversified demand profile.

Nonetheless, the stakes are high. The transportation and electricity system applications of batteries are expected to make major contributions to emissions reductions in nearly every climate model. The suite of policies that could create and sustain technological diversity in PV might also be applied to batteries. In fact, the European Union and its major member states have already taken action to build a domestic battery supply chain, including major public investments in manufacturing and R&D. (Europe may also seek to rebuild its PV industry as its Green Deal goes forward.)[101]

The United States currently does not have a strategy to do the same, even though federal loan guarantees under the Recovery Act helped create a U.S. electric vehicle industry (including Tesla) in the late 2000s. Federal investments in energy storage R&D, which are substantial, are not complemented by strategic downstream investments. States compete against one another to provide locational incentives to battery and vehicle plants without an overarching national strategy, as they have done for decades with conventional auto plants.[102]

Peering further into the future, Greg Nemet identifies devices to capture carbon directly from the air as a technology with many features similar to PV. IEA spotlights hydrogen electrolyzers similarly. These technologies also figure prominently in ambitious emissions reductions scenarios, and it is vital to our common future that they flourish.[103]

CONCLUSION

Solar PV is the star of today's clean energy economy. It has become much cheaper, much faster than almost anyone predicted a decade ago, and it has been adopted far more widely than predicted as a result. Many national and corporate plans to reduce carbon emissions in the coming decades are premised on PV continuing to rapidly decline in cost for many more years and ultimately becoming cheap enough to be virtually ubiquitous around the world.

But a look in the mouth of the gift horse suggests the need for the United States and other countries to adopt policies that would bolster the odds of realizing these expectations. While the Chinese mercantilist-backed surge into PV manufacturing was a gift that accelerated global adoption in the 2010s, it also altered the trajectory of technological innovation. Mercantilist policies helped destroy many innovative firms outside of China, constrict new entry, and limit investments in innovation by the survivors. The shift in trajectory has precluded, to date, fully exploring some technological opportunities with the potential to yield better results over the long run. Looking forward, sustained mercantilist behavior might undercut a coming wave of innovation that would otherwise allow PV to take another great leap forward.

While the Chinese mercantilist-backed surge into PV manufacturing was a gift that accelerated global adoption in the 2010s, it also altered the trajectory of technological innovation.

Policymakers should act to create and sustain technological diversity—that is, to ensure worthy innovations are not unduly slowed or stranded—in PV. A collaborative effort among China's competitors would be the best way to implement such steps. That collective effort should then be extended to sustain innovation in other climate-critical technologies that are similarly at risk.

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About ITIF

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