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Wind and Solar Invention in the United States

Driving along Interstate 10 from Los Angeles to Palm Springs gives the viewer a panoramic view onto one of the largest experiments in the commercial generation of renewable energy. As the freeway crosses into the Coachella Valley past an outlet mall and the Cabazon dinosaur museum, the California desert opens up to one of earliest wind farms in the United States. First installed in the 1980s, some 4,000 turbines remain today of the original 6,000 that once dotted the moonlike landscape in the narrow channel between the San Gorgonio and San Jacinto peaks. The remnants of first-generation wind turbines—with their tripod-like towers and two-blade designs—remind the visitor of the technological ambition possessed by US engineers, a drive to create that long buttressed America's reputation as a seedbed for technological innovation. Yet the turbine parts strewn across the California desert also evoke the rapid end of the first wind energy boom—a frustrating closure caused by technical difficulties and a changing political environment in the mid-1980s. Despite American strengths in aerospace design, US-made turbines remained inferior to imported models in efficiency and reliability. Foreign manufacturers reaped most of the benefits from the initial wind farms in California.[1]

Three decades after the first wind turbines were installed on the San Gorgonio pass, the United States once again became one of the largest markets for wind and solar power in the world. In 2015, the United States accounted for 17 percent of global wind turbine installations and 11 percent of installed solar photovoltaic (PV) capacity.[2] Not unlike in the 1980s, US renewable energy industries maintained strengths in the invention of new technologies but established few capabilities in commercialization and production. To a far greater degree than in Germany or China, wind and solar sectors in the United States were populated by high-technology firms that spun off from universities and research institutes. By 2009, out of 100 solar photovoltaic firms in the United States, at least 73 were start-ups, and many of these were racing to commercialize thin-film technologies that broke with the conventional use of silicon as the basic raw material for solar

[1] Gipe 1995, 31–36.
[2] GWEC 2017; IEA 2016.

cell production.[3] In the wind industry, US firms developed turbines that abandoned traditional designs, including gearless drivetrain concepts and small-scale turbines based on jet engine technologies.[4] Small in size and boasting advanced technological capabilities, these firms built up strengths in early-stage research and development, but rarely did they establish capabilities in scale-up and mass manufacturing. US multinational companies, which also entered American renewable energy industries, maintained a similar focus on inventing new technologies in their home operations, while offshoring or outsourcing much of their production to locations abroad. US industrial capabilities in renewable energy industries strongly targeted early-stage R&D, without establishing the full range of skills necessary to bring new products from lab to market.

By 2008, the United States accounted for more than 61,000 renewable energy patents filed in US, European, and Japanese patent offices, roughly double the number of patents filed by German entities.[5] In 2016 alone, US entities filed some 5,000 clean energy patents with the US Patent and Trademark Office (USPTO), compared to 1,800 European patent applications and 300 from China.[6] Still, local content rates for US wind turbines hovered around a modest 40 percent, as high-value components—gearboxes, metal castings, and turbine blades—were imported from abroad. As late as 2017, local content rates for many internal components of the turbine remained as low as 20 percent.[7] A 2011 study by the American Wind Energy Association (AWEA) estimated that European wind turbine manufacturers created three to four times as many jobs per megawatt of installed wind turbine capacity as their US counterparts, as local supply chains in Europe obviated the need for imported components.[8] In the solar sector, where US firms and research institutes developed the foundations for virtually all of the main solar technologies in production today, US firms accounted for less than 5 percent of global manufacturing in 2010. New technologies were brought to market in other parts of the world, and key components for domestic solar PV manufacturing—including wafers, thin film feedstock, and inverters—were imported from abroad.[9]

The emphasis on early-stage research and development (R&D) in US wind and solar industries is particular striking when we compare it to the manufacturing-based capabilities in Germany and China. German and Chinese renewable energy sectors attracted firms with a wide range of production skills, including

[3] Knight 2011, 176.
[4] Bullis 2008.
[5] Bierenbaum et al. 2012, 6–7. Bolinger 2013, 18–19.
[6] Helveston and Nahm 2019, 796.
[7] Wiser 2017, 20.
[8] AWEA Manufacturing Working Group 2011; David 2009.
[9] Data compiled by Earth Policy Institute, 2020. The US maintained a positive trade balance in the production of manufacturing equipment and silicon feedstock. See GTM Research 2011.

those specializing in component and equipment manufacturing, scale-up, and mass production. At the most basic level, scholars have evoked theories of comparative advantage to explain American strength in invention and not production.[10] Proponents of this view have frequently cited examples like Apple, a company that used strengths in upstream R&D to generate economic benefits in the United States, even if production activities were mostly located in Asia.[11] Policymakers and industry representatives, meanwhile, claimed that the cost of labor in the United States prevented competitiveness in manufacturing. This argument was often made in conjunction with calls for trade barriers, following accusations that China and other Asian economies lowered their production cost through subsidies and lax environmental regulations.[12] Yet this same argument, when posed against a German backdrop, failed to play out: for all the competition from China and other economies with low factor prices—competition that led to a series of high-profile bankruptcies among German solar PV manufacturers—Germany still retained a supply chain of highly specialized small and medium-sized wind and solar suppliers with manufacturing facilities. And it did so while remaining a high-wage environment, in which hourly compensation for manufacturing workers in 2012 was nearly 50 percent above manufacturing wages in the United States.[13] At the very least, then, the case of Germany suggests that high-wage economies can in principle retain domestic production activities even in emerging high-tech sectors. So why have US wind and solar supply industries built capabilities in early stage R&D without adding complementary skills in scale-up and mass production?

In this chapter, I trace the development of US renewable energy sectors to show that new opportunities for collaboration in global supply chains made the co-location of innovation and production activities in the United States unnecessary for the commercialization of new technologies. New options for industrial specialization in the global economy allowed German and Chinese firms to maintain manufacturing-based industrial specializations; in the United States, they had the opposite effect, helping firms cut ties with the domestic manufacturing economy. US investments in R&D and demand-side subsidies created domestic jobs in the installation and maintenance of wind farms and solar parks, but left a far smaller industrial footprint than the German and Chinese renewable energy sectors.

In the wind and solar sectors, American firms responded to renewable energy policies set at state and federal levels by creating R&D teams as spinoffs from

[10] Kraemer, Linden, and Dedrick 2011; Mankiw and Swagel 2006.
[11] See, for instance, Bonvillian and Weiss 2015, 11–12; Kraemer, Linden, and Dedrick 2011; Sturgeon 2002.
[12] US International Trade Commission 2011.
[13] Levinson 2014, 14.

Actions	New opportunities for collaboration in the global economy	→ *Specialization* ←	Firms: Startups, declining manufacturing sector	→ *Repurposing* ←	Institutions for tech transfer, venture capital, R&D institutions
Out	Collaborative innovation and production		Startups specialize in the *invention* of energy technologies		Adapted but persistent institutions

Figure 6.1 Industrial Specialization in the United States

universities and research institutes and focused these teams on the *invention* of new technologies. I show here that firms made use of domestic institutions for technology transfer, including the Bayh-Dole act of 1980 and subsequent legislation that permitted the licensing of federally funded research. They also repurposed funding institutions for R&D activities, often the only sources of income for start-ups that had not yet found a pathway to commercialize their technologies. Firms were able to use such institutions, set up long before the growth of renewable energy industries, because collaborative advantage allowed them to enter the wind and solar sectors without domestic capabilities in mass production. A weak supplier base in adjacent industries reduced the number of firms with capabilities in scale-up and mass production that could enter wind and solar supply chains.[14] The United States' industrial specialization in invention and its ability to collaborate with global partners thus left firms less willing to revitalize domestic institutions within the manufacturing economy (Figure 6.1).

The chapter proceeds with a discussion of structural trends in the US economy that favored the creation of start-ups over the diversification of existing manufacturing businesses into renewable energy industries. It then describes the technological capabilities of these rapidly proliferating start-ups before highlighting the role of collaboration in allowing these firms to use federal R&D institutions to shape the development of US renewable energy sectors. The conclusion returns to the political implications of this particular industrial specialization and argues that their small industrial footprint prevented these wind and solar firms from becoming forceful advocates for stable clean energy legislation.

[14] Pisano and Shih 2012, 8–13.

Innovation without Production

Measured purely in terms of public financial support, the United States spent more than any other advanced economy on wind and solar R&D.[15] Many of the technological advances underlying traditional silicon-based solar cells and thin-film PV applications emerged from federally funded R&D institutes and enterprise laboratories, making possible the spread of solar technologies from their initial application in the space industry of the 1950s to the grid-connected solar PV models widely available today. Even in the wind sector, where European researchers made many of the critical contributions that enabled the gradual increase of turbine capacity, research consortia led by US corporations made efforts to leapfrog to the design of large-scale wind turbines in the wake of oil crises in the 1970s. These costly investments were almost entirely funded through federal government programs.[16]

Government support for R&D activities in universities, research institutes, and the private sector rested on two broad assumptions about the links between innovation and economic outcomes.[17] First, public investments in R&D assumed that market failures justified state intervention. Since technological innovation creates spillovers that firms often have a hard time appropriating, the private sector is assumed to underinvest in innovation in the absence of government intervention.[18] In light of innovation's central role in maintaining technological leadership, economic growth, and national competitiveness, the federal government in the postwar decades faced strong incentives to support technological innovation in the domestic economy.[19]

Second, underlying US public R&D spending in the postwar decades was a notion that a linear relationship existed between innovation and industrial development. The invention of new technologies—from this perspective, largely a function of sufficient investments in basic research—was expected to trickle into the market by way of applied research and commercialization in domestic industries. Although the exact origins of this linear model are difficult to trace, the "belief that scientific advances are converted to practical use by a dynamic flow from science to technology has been a staple of research and development (R&D) managers everywhere."[20] A linear view of the relationship between innovation

[15] International Energy Agency (IEA) 2008, 31. National Science Board 2018, Figure 6–35.

[16] On the contributions of European research, see Heymann 1998. The role of US conglomerates is discussed in Righter 1996, 149–69.

[17] In addition to such economic objectives, the United States of course also pursued environmental concerns unique to the renewable energy industries examined here. Particularly in the postwar decades, much R&D spending pursued military goals that I do not examine here in detail, although early solar PV technologies found military applications in satellites, for instance. On the military origins of Silicon Valley, see, for example, Lécuyer 2007.

[18] Mazzucato 2016, 143.

[19] Boskin and Lau 1992; Romer 1994; Schumpeter 1934; Solow 1956.

[20] Stokes 1997, 10.

and application also applied to the international division of labor. According to the theory of the product cycle, introduced by Vernon in the 1960s, only firms in advanced economies possessed the engineering capabilities required to develop new technologies and to manage challenges in commercialization. Such firms further benefited from sophisticated domestic markets and consumers able to afford price premiums commanded by new technologies. Implicit in this theory was the assumption that close geographic and managerial linkages between invention and production were required in the early stages of product development. Only once products were reliable, manufacturing processes standardized, and price premiums gained from initial technological advantage had been depleted—in other words, once products were fully commodified—only then would manufacturing activities shift to developing economies with lower technical capabilities and less sophisticated market demand.[21]

In the wind and solar industries, public investments in basic research and government support for R&D peaked after the 1970s oil shocks but remained ahead of other nations from the postwar decades to the present. In the early 1980s, supported by bipartisan agreement on the need to diversify the US energy supply, federal investment in renewable energy R&D peaked at USD 1.3 billion.[22] This unprecedented level of R&D funding for renewable energy technologies encouraged research into wind and solar technologies in universities, supported a growing governmental research infrastructure for energy technology (in the form of national research laboratories), and funded research activities in US conglomerates from the aerospace, energy, and defense industries.[23] While the programs failed to yield a single commercially viable turbine—design flaws, manufacturing problems, and structural failures had cut short the operating hours of most of the turbines, and even when turbines did operate reliably, their efficiency remained far below expectations—federal funding for research continued at levels far above those of other countries (Table 6.1).[24]

Although renewable energy budgets decreased during the Reagan presidency in the 1980s, national institutions for energy research that had been created during the oil crises survived the chopping block. SERI, the federal Solar Energy Research Institute, continued to advance renewable energy research throughout the 1980s despite budget cuts. In 1991, its broad mandate beyond solar PV earned it the designation as the National Renewable Energy Laboratory (NREL), one of seven such laboratories set up by the Department of Energy (DOE).[25]

[21] Vernon 1966, 1979.
[22] Martinot, Wiser, and Hamrin 2005, 3.
[23] Righter 1996, 158.
[24] Ackermann and Söder 2002.
[25] NREL 2002, 2.

Table 6.1 Select Industrial Policies for US Wind and Solar Sectors

	United States
Technology Push	**1973–1988** US Wind Research Program **1991–2000** PVMaT R&D Program **Since 1990s** NREL R&D Grants **2008** American Recovery & Reinvestment Act: Loans **Since 2009** ARPE-E Program
Market Pull	**1978** Public Utility Regulatory Policies Act (PURPA) **1992** Production Tax Credits (since then renewed 7 times) **Since 1997** Renewable Portfolio Standards (30 states by 2012)

NREL subsequently established a National Wind Technology Center in Boulder, Colorado, in 1993.[26] The national laboratories provided demonstration sites, test centers, and accreditation for manufacturers, who came to rely on their highly specialized staff for technical expertise.[27]

The continuation of federal R&D funding and the maintenance and expansion of the energy national laboratories allowed the United States to maintain a global lead in renewable energy research (see Figure 6.1). Technological advances that originated in the federal R&D programs of the late 1970s, for instance, decreased the cost of solar PV technologies from USD 300 per watt in 1980 to USD 4 per watt in 1992.[28] The price for wind turbine installations dropped from USD 4,040 per kW in the early 1980s to an average of USD 1,340 per kW in the early 2000s, at least partially as a result of technology improvements.[29]

Between 1974 and 2008, the US federal government spent USD 3.3 billion on solar PV research alone, significantly more than Japan (USD 2.1 billion) and Germany (USD 1.9 billion), the largest solar PV market in the world at the time. By 2018, the DOE had spent over USD 28 billion on renewable energy research, or roughly 18 percent of the research spending by the DOE.[30] Such funds were awarded through a number of technology-specific programs. Between 1991 and 2008, for instance, the DOE invested USD 289 million in R&D for new solar technologies as part of the so-called Photovoltaic Manufacturing Technology (PVMaT) program. A separate program targeted research on thin-film technologies.[31] In the wind sector, the DOE invested in research on offshore wind

26 See http://www.nrel.gov/wind/nwtc.html (accessed March 25, 2014).
27 Harborne and Hendry 2009, 3582.
28 Loferski 1993, 74.
29 Wiser and Bolinger 2008, 21; Wiser, Bolinger, and Barbose 2007, 81.
30 Clark 2018, 3–4. Critics have argued that such funds nonetheless are insufficient to combat the climate crisis. See Sivaram et al. 2020.
31 O'Connor, Loomis, and Braun 2010, 3–14.

turbine technologies, next-generation turbine technologies, and research to improve turbine reliability and grid integration.[32]

Although public investments in research allowed the United States to remain at the forefront in the invention of new technologies, broad structural changes in the US economy undermined the linear model that underpinned such public spending. Beginning in the 1970s, the decline of manufacturing sectors in the United States drastically reduced the number of domestic firms that possessed technological capabilities with potential application in wind and solar industries. Between 1999 and 2010 alone, the number of manufacturing establishments in the United States declined by 14 percent.[33] The number of manufacturing plants that employed more than 1,000 workers dropped by half between 1977 and 2007.[34] Losses were particularly strong in the aerospace, semiconductor, machine tool, and automotive components sectors—precisely the type of industries from which suppliers had entered wind and solar sectors in Germany.[35] Between 1998 and 2010, nearly 1,200 plants closed in the semiconductor industry, a decline of 37 percent among facilities with more than 500 employees and a loss of 41 percent of medium-sized plants with 100–500 staff.[36] In the machine tool sector, foreign penetration of the US market rose from 30 percent in 1983 to 72 percent in 2008, with subsectors, including metal forming, reaching import rates of 91 percent. Domestic shipments for metal forming machines dropped by more than 50 percent between 1990 and 2009. Over the same period, the US aerospace industry lost 10 percent of mid-sized firms and 28 percent of large firms with more than 500 employees.[37] Although the United States remained one of the world's largest manufacturers—second only to China by dollar value of its output, and ahead of both Germany and Japan—by the time renewable energy sectors became sizable global industries, much US manufacturing activity was concentrated in the hands of a few multinational firms. Growth in technology- or resource-intensive sectors such as pharmaceuticals, medical devices, and petrochemicals masked declines in other industries.[38]

A multitude of factors contributed to these changes in the American manufacturing economy. China's accession to the World Trade Organization (WTO) in 2001 increased import competition.[39] Other factors were homegrown and far preceded the shifts in the global economy caused by China's WTO accession.

32 Department of Energy 2006, 2017b.
33 US Census Data cited in Yudken 2010, 2.
34 Holmes 2011, 6.
35 Pisano and Shih 2012, 8–13; Whitford 2005, 2012.
36 Yudken 2010, 7.
37 Pisano and Shih 2012, 11–12; Yudken 2010, 6–12.
38 Ramaswarmy et al. 2018, 21.
39 For a discussion of the impact of changing US–China trade relations on American manufacturing sectors, see Autor, Dorn, and Hanson 2012; Berger 2013b, 41–44; Pierce and Schott 2014.

Over the course of the 1970s, financial markets in the United States had rewarded large firms for outsourcing non-core production activities; and falling tariffs and trade barriers subsequently permitted US multinationals to look to low-cost economies to find suppliers.[40] The declining number of suppliers in the US economy had its basis, at least in part, in the difficulties small and medium-sized firms faced when they tried to adapt to the reorganization of production in the global economy and the lack of state institutions that could facilitate such adjustment. For instance, after decades during which metalworking manufacturers in the American Midwest essentially served as production buffers for larger firms, many were ill-equipped to meet the new requirements in design and customization imposed by their customers in the 1990s. Although in principle, small and medium-sized firms were capable of making investments in new technological capabilities and design skills, they shied away from doing so in the face of economic uncertainty, an absence of guaranteed markets, and little public institutional support for technological upgrading in manufacturing.[41]

The accounting standards required to claim R&D tax credits, for instance, had traditionally favored technological innovation developed in traditional R&D departments over the type of incremental manufacturing innovation that would be involved in retooling a production facility for application in new sectors. Claiming federal R&D credits was an onerous reporting process, and many small and medium-sized firms lacked designated R&D departments. For all the R&D funding available for early-stage R&D, little public funding existed to upgrade existing technological capabilities.[42] Few banks wanted to fund manufacturing investments in the absence of order guarantees, a reluctance that compelled suppliers who were willing to enter new sectors to rely on retained earnings for financing.[43] Many struggled to do so. Firms willing to invest in emerging renewable energy industries also struggled to find qualified staff trained to handle increasingly complex machinery. In a survey on skills and training in manufacturing establishments, smaller firms with high-skill demands reported significantly more difficulty filling vacancies, suggesting that those firms willing to move into new emerging high-tech sectors were not served well by existing skills, training institutions, and local community colleges.[44]

Among those that weathered the decline in the number of manufacturing establishments in the semiconductor, machine tool, and automotive supply industries, few were able to make the investments required to enter renewable

[40] Davis 2009, 87–96, 195–200.

[41] Whitford 2005, 95–120; 2012, 259.

[42] Author interviews: CEO of metal-forming manufacturer, October 24, 2012; CEO of aerospace supplier, April 27, 2012.

[43] Berger 2013b, 115–16; Cetorelli and Strahan 2006, 459.

[44] Osterman and Weaver 2013, 33–35.

energy industries. One steel manufacturer seeking to diversify into the wind industry stated that a contract to supply parts for a local offshore wind park would necessitate a USD 20 million investment in a new manufacturing facility, a risky investment in the absence of any guarantees that a contract would ultimately be awarded to the firm. Even with such guarantees, bank loans would be difficult to obtain, and the manufacturer's only hope of finding external financing involved federal loan guarantees. At the time of my interview with this steel manufacturer, legal challenges and debates over subsidies had left the offshore project in limbo, yet this small manufacturer with fifty employees had already spent USD 1 million of retained earnings to prepare a bid.[45] By the time construction commenced on the offshore wind park a few years later, a different supplier had been chosen, leaving the metal fabrication firm without a viable path to pay for its manufacturing facility.[46]

By comparison, a German manufacturer of similar components, whom the steel firm relied on for technical advice, received a USD 45 million grant for a USD 90 million facility from the German government and was able to secure three years of guaranteed orders from German turbine manufacturers prior to making the investment. Asked if any competitors were also trying to enter the wind industry, the steel manufacturer recounted how all twelve of his local competitors had gone bankrupt over the past two decades, as their core markets eroded and they failed to diversify into growing industries.

As I chronicled in Chapter 4, German suppliers from legacy industries entered the wind and solar sectors by applying core capabilities to new applications in renewable energy—the production of components, materials, and manufacturing equipment required to bring new technologies to scale. In the United States, the declining number of manufacturing establishments had left fewer firms that could potentially do the same, particularly in sectors where firms had industrial strengths applicable to wind and solar. Among those who remained, slim margins often prevented investments in new skills. Weak institutional support for repurposing and reinventing existing industrial capabilities—these included the absence of local banks, training institutions, and collaborative research funds that had enabled suppliers in Germany to enter the renewable energy industries—further prevented firms from entering new economic sectors.

Because broad structural change in the US economy had reduced the number of supply firms with industrial capabilities applicable to the wind and solar sectors, US wind and solar supply chains remained considerably less diverse than those in Germany and China. US strength in early-stage research and development manifested in large numbers of high-technology start-ups, yet the failure

[45] Author interview, CEO of steel manufacturing firm, October 24, 2012.
[46] Cardwell 2014.

of small and medium-sized manufacturing firms to mobilize and enter the renewable energy supply chains left large gaps in the types of industrial capacities that could be accessed domestically. Ultimately, top-down investments in technological innovation in universities and research institutes led to vibrant start-up activity but were not matched by an equally forceful mobilization of skills in commercialization and production.

Inventing Wind and Solar

The primary benefactors of public investments in research and development were start-up firms with technological capabilities in the invention of new technologies. Even before legislation created the first domestic markets for wind turbines or solar panels, firms built on the strength of US research and development activities by spinning off from universities and government research institutes in an attempt to commercialize recent discoveries. In contrast to the aerospace and defense conglomerates that had begun working on large-scale wind turbines with the help of federal programs beginning in the 1970s, these new firms were small and specialized, growing directly out of publicly funded research. In 1974, entrepreneurs Stanley Charren and Russell Wolfe founded US Windpower as a spinoff from MIT's Lincoln Lab. The MIT laboratory provided the core technology and the company's chief engineer. US Windpower, later named Kenetech, began building a demonstration wind farm on Crotched Mountain in New Hampshire, long before the first large wind markets were created in the United States.[47] Six years later, ESI, another turbine manufacturer, was established by two government engineers working at a wind turbine testing site set up as part of the national wind energy program in Rocky Flats, Colorado. The engineers left to launch their own company and licensed the technology from the federal government.[48] In the 1980s, Zond began building variable-speed wind turbines based on a technology developed at and in collaboration with NREL. The firm was one of the few who had survived the rapid end of California's wind energy boom in the 1980s; Enron eventually purchased it in 1997.[49]

In the solar sector, small firms produced solar PV cells for niche applications and benefited from state funding for utility-scale demonstration projects.[50] Former employees of Spectrolab, a firm that had supplied solar modules for

[47] Jeff Ackerman, 1981, "Putting the Wind to Work; Breeze Power Is Serious Business for Founder of Farm in N.H.," *Boston Globe*, May 3. See also: MIT Lincoln Lab, "Spin-Off Companies," http://www.ll.mit.edu/about/TechTransfer/spinoffs.html (accessed March 27, 2014).

[48] Gipe 1995, 71.

[49] Department of Energy 2003.

[50] West 2014, 7.

space applications since the 1950s, founded Solec International in 1976. It was located in proximity to Caltech and NASA's Jet Propulsion Lab in Pasadena, and it collaborated with both institutions on the improvement of terrestrial solar technologies throughout the 1980s.[51] Solar Technology International, also founded by former Spectrolab employees, similarly participated in joint research with Caltech and the Jet Propulsion Lab to improve its solar PV technologies.[52]

With the exception of a brief period in the early 1980s, during which a combination of federal and state-level subsidies created short-lived demand for wind power installations in California, renewable energy firms struggled with a lack of market demand. Even though California's wind energy boom was not replaced by new domestic markets for renewable energy technologies until the early 2000s, new wind and solar firms continued to be founded on technologies originating in federally funded research. The first generation of terrestrial solar PV firms specialized in traditional silicon PV modules derived from earlier products for space applications. Beginning in the 1990s, a second generation of solar firms launched research on new solar PV technologies designated for grid-connected, civilian applications.

In the early 2000s, both California and Texas passed renewable portfolio standards that required utilities to meet ambitious renewable energy targets, leading to large local markets for wind turbine installations.[53] Fueled by regional investments in renewable energy, in addition to federal production tax credits, the United States ballooned to become the largest market for wind turbines in 2005.[54] A federal solar investment tax credit of 30 percent was passed as part of the 2005 Energy Policy Act and renewed in 2006 and 2008; together with state-level policies such as the 2007 California Solar Initiative, this tax credit led to a surge in US domestic demand for solar PV after decades of stagnation.[55] By then, the introduction of generous subsidies for solar PV installations had created the world's first large solar market in Germany. Other nations, most notably Spain and Italy, bolstered domestic solar demand in the years that followed.[56]

The expansion of global markets prompted a new wave of industry entry. In the solar sector, many of the new firms revolved around the attempt to commercialize thin-film solar cells. Although thin-film cells promised to replace costly silicon as the basic raw material in solar cell production, complex manufacturing processes had kept thin-film technologies prohibitively expensive. Firms such as Nanosolar and Nanosys, both founded in California in 2001, were testing

[51] Colatat, Vidican, and Lester 2009, 5.

[52] Solar Technology International was purchased by the oil firm ARCO in the late 1970s and changed its name to ARCO Solar. Colatat, Vidican, and Lester 2009, 5; West 2013, 6.

[53] Bird et al. 2005, 1401–2.

[54] Wiser et al. 2008, 4.

[55] Colatat, Vidican, and Lester 2009, 7; Solar Energy Industries Association 2014.

[56] Campoccia et al. 2009, 290–91.

alternate deposition technologies that could potentially reduce the cost of thin-film manufacturing. Heliovolt, established in Austin, Texas, in 2001, and Day Star, founded in Halfmoon, New York, in 2006, sought to solve the same problem. Konarka was founded in Massachusetts in 2001 as a spinoff from the University of Massachusetts, Lowell, to fabricate solar cells from flexible plastics.[57] Scientists from NREL founded Solyndra in 2005, a company that used a deposition technology developed by NREL to build cylindrical, higher efficiency cells.[58] In 2007, Emanuel Sachs spun off a new company, 1366 Technologies, to introduce new production processes for solar wafers.[59] By 2009, at least forty-six solar PV start-ups were operating in California alone.[60]

The wind sector also attracted a growing number of start-ups. In 2001, former employees of the legacy wind turbine manufacturer Zond founded a new turbine manufacturer, Clipper Windpower, in California. Clipper proposed replacing a single turbine generator with several smaller generators to increase efficiency and reliability.[61] In Florida, a manufacturer of superconducting magnets, diversified into the wind energy business in 2002 and began developing gearless wind turbines.[62] Ogin, a spin-off from the aerospace sector, began designing new wind turbine technology in 2008, borrowing principles from jet engines to increase turbine efficiency.[63] In 2009, NREL employees founded Boulder Wind Power to commercialize an alternative gearless wind turbine technology.[64]

Although American strengths in science and technology remained the envy of policymakers around the world, American capabilities in large domestic manufacturing sectors did not. Start-ups were far more specialized than the vertically integrated firms that had formed the main engines of technology commercialization in previous decades. They shared with those older firms similar abilities in the invention of new technologies, yet few possessed skills in the commercialization and production of wind turbines and solar panels.[65] In the postwar decades, public investments in R&D had, at the very least, led to domestic manufacturing facilities for early product generations of new technologies. But these domestic links, which fueled the assumption that a linear connection existed between the invention, commercialization, and production stages, were finally

[57] Morton 2006, 21.
[58] David R. Baker and Carolyn Said, 2011, "Solyndra: Energy Superstar's Rapid Rise and Fall," *San Francisco Chronicle*, September 18.
[59] Kevin Bullis, 2010, "Making More Solar Cells from Silicon," *Technology Review*, March 4.
[60] Colatat, Vidican, and Lester 2009, 6.
[61] Goudarzi and Zhu 2013, 199.
[62] Angela Lazazzera, 2009, "New Innovations in 19th Century Technology," *Spacecoast Business Magazine*, May.
[63] Gertner, 2013.
[64] See www.boulderwindpower.com (accessed March 29, 2014).
[65] SunPower and First Solar were an exception to this rule and invested in sizable manufacturing facilities in the solar sector.

undermined—as firms that specialized in the invention of new technologies were not accompanied by firms with equally strong capabilities in scale-up and mass production.

In contrast to Germany and China, where large numbers of domestic manufacturers entered renewable energy industries in response to growing global markets, few domestic suppliers with diverse industrial capacities populated the US wind and solar sector markets; and despite a number of notable exceptions, few large domestic manufacturers did, either. In part, uncertainty over domestic markets generated this reluctance within existing manufacturing firms. The patchwork of federal and state-level regulations and the volatility of the US demand-side policies deterred these firms from entering wind and solar industries. Faced with a costly retooling of their existing plants, the need to acquire new skills to customize products for renewable energy industries, and supplier qualification processes lasting twelve months more, many small and medium-sized manufacturers decided that investing in renewable energy sectors was a bet they'd rather not place.[66] A study by the Lawrence Berkeley Laboratory on the effects of policy volatility in wind power found that uncertainty "in the future scale of the U.S. wind power market has limited the interest of both U.S. and foreign firms in investing in wind turbine and component manufacturing infrastructure in the U.S." Short-term extensions to policy support "may lower the willingness of private industry to engage and invest in long-term wind technology R&D that is unlikely to pay off within a one-to-two year [cycle]," the report concluded.[67] Renewable energy firms showed particular reluctance to invest in states that had previously shown policy volatility in energy market regulation, a problem exacerbated by uncertainty over federal policy support.[68] Wind turbine manufacturers, which sought to localize component production to reduce transportation costs and currency risks, conceded that they were unable to guarantee long-term order volumes necessary to attract local suppliers.[69]

The existence of global sectors with highly specialized skills—including the German renewable energy suppliers focused on complex componentry and China's firms with skills in commercialization and mass production—absolved firms from having to co-locate activities that used to be located within the four walls of the firm. Many firms that successfully entered US wind and solar supply chains were multinational corporations, less reliant on any particular market and able to draw on global supply chains for parts and manufacturing expertise. Such firms included the multinational equipment manufacturer Applied Materials, the silicon producer Hemlock, and the global bearings manufacturer Timken.

[66] Rogowsky and Laney-Cummings 2009, 13–14.
[67] Wiser, Bolinger, and Barbose 2007, 81.
[68] Fabrizio 2012.
[69] Baker 2010; Spada 2010.

Their core competitors, however, resided outside the United States. Independent US suppliers operated only three out of ten blade manufacturing facilities located in the United States in 2009, with the majority of blade plants run by European wind turbine manufacturers who serviced the growing US market.[70] Although more than 10,000 metal casting firms existed in the United States in 2010, not a single firm had retooled its manufacturing facilities to supply metal castings for wind turbines—a gap that required turbine manufacturers to source castings for turbine hubs in Europe and Asia.[71] Only two American firms were manufacturing wind turbine generators.[72] Likewise, in the solar sector, the majority of suppliers were multinational corporations that had diversified into renewable energy industries. In addition to Applied Materials, which entered the solar sector through a series of acquisitions beginning in 2006, one firm, GT Solar, offered domestically manufactured turnkey production equipment.[73] More suppliers existed in glass manufacturing, wire production, laser technology, and other areas in which products required little or no customization for the solar PV sector.

In the face of difficulties faced by small manufacturers, many firms that successfully entered US wind and solar supply chains from existing industries were multinational corporations, less reliant on any particular market and able to invest in new facilities without the need for external financing. Multinational corporations frequently entered the renewable energy sector through acquisitions of start-up firms with promising technologies for select wind and solar components and production equipment. GE, perhaps the most visible example, entered the wind sector in 2003 by purchasing Enron's wind turbine division in the aftermath of Enron's accounting scandal and bankruptcy in 2003.[74] Applied Materials, a multinational firm with forty years of experience in producing manufacturing equipment and software for the semiconductor industry, decided to enter the solar PV industry in 2006. The firm had already modified some of its semiconductor equipment for manufacturers of conventional silicon-based solar cells. Anticipating growing markets for thin-film solar technologies, it embarked on a series of acquisitions to establish a solar PV division that could serve both traditional silicon and thin-film solar manufacturers. In 2006, Applied Materials invested USD 464 million to purchase Applied Films Corp, a producer of thin-film deposition equipment.[75] In 2007, it acquired two

[70] Rogowsky and Laney-Cummings 2009, 11.
[71] Spada 2010. See also Brian Rogal, 2012, "Foundries Twisting in Breeze over Wind Tax Credit," *Midwest Energy News*, March 27.
[72] Baker 2010; Rogowsky and Laney-Cummings 2009, 9–10.
[73] Platzer 2012a, 7.
[74] Lewis 2013, 95; Windpower Monthly 1997.
[75] Mark LaPedus, 2006, "Applied Materials Enters Solar Gear Markets," *EE Times*, May 4. http://www.eetimes.com/document.asp?doc_id=1161175 (accessed November 14, 2020).

European manufacturers of solar PV production equipment.[76] In 2009, the US start-up Advent Solar joined the Applied Materials portfolio.[77] In addition to these acquisitions, the firm's in-house venture capital fund, Applied Ventures, invested smaller sums in start-up companies whose technologies were not yet mature.[78]

Other multinationals followed Applied Materials' diversification into renewable energy sectors. In 2011, Dupont Chemical bought the Silicon Valley start-up Innovalight to expand its materials portfolio for the solar industry. As I mentioned earlier, Innovalight had previously received funding from NERL and the DOE to develop a silicon ink and first commercialized the technology through a joint development agreement with the Chinese firm JA Solar. Dupont's acquisition thus occurred after the technology was fully commercialized, thereby allowing Dupont to benefit from a decade of R&D activities without incurring technology risk.[79] Dow Chemical, which had participated in federally funded research consortia to develop building-integrated solar PV technologies and had received USD 20 million from the DOE for research into new types of solar arrays, struggled with delays in the commercialization of its technologies. In 2013, Dow Chemical acquired NuvoSun, a California start-up producing solar shingles for rooftop applications. NuvoSun's technology was ripe for commercialization, but the firm had struggled to fund the expansion of its manufacturing facilities to achieve scale economies.[80]

In the wind industry, growing domestic markets encouraged foreign wind and solar manufacturers to set up production facilities in the United States. Some of these manufacturers persuaded their European suppliers to join them. The Spanish wind turbine producers Acciona and Gamesa were among the first foreign wind firms to open manufacturing plants in the United States.[81] Siemens,

[76] Katie Fehrenbacher, 2007, "Applied Materials to Buy Italian Solar Equipment Maker for $330M," *Gigaom*, November 19. http://gigaom.com/2007/11/19/applied-materials-to-buy-italian-solar-equipment-maker-for-330m/ (accessed April 14, 2014).

[77] Josie Garthwate, 2009, "Applied Materials Buying Advent Solar Assets, Cheap," *Gigaom*, November 6. http://gigaom.com/2009/11/06/applied-materials-buying-advent-solar-assets-cheap/ (accessed April 14, 2014).

[78] Applied Ventures Brochure, 2014. See http://www.appliedmaterials.com/sites/default/files/AV_Handout_0812.pdf (accessed March 27, 2014). In its solar business, Applied Materials bet almost entirely on the future success of thin film solar technologies, which ultimately were unable to compete on price with the rapidly falling cost of traditional silicon-based PV technologies. See Nemet 2019, 126.

[79] Nahm and Steinfeld 2014, 297. See also Kevin Bullis, 2011, "DuPont Inks a Deal to Improve Solar Cells," *MIT Technology Review*, August 1.

[80] Department of Energy, 2008, "DOE Selects 13 Solar Energy Projects for up to $168 Million in Funding," http://energy.gov/articles/doe-selects-13-solar-energy-projects-168-million-funding (accessed March 27, 2014.) Ucilia Wang, 2013, "Dow Chemical Buys NuvoSun for Making Solar Shingles," *Forbes*, March 7. Emma Hughes, 2009, "New Product: Dow Chemical Introduces Solar Shingle BIPV," *PV-Tech*, October 09. www.pv-tech.org/product_reviews/new_product_dow_chemical_introduces_solar_shingle_bipv.

[81] Rogowsky and Laney-Cummings 2009, 4.

which had opened a manufacturing site for turbine blades in Iowa in 2007, established a full assembly plant in Kansas in 2010, one year after the American Recovery and Reinvestment Act had extended federal support for wind turbine deployment. Nordex of Germany started local production in the same year.[82] A number of European suppliers of turbine components established US manufacturing plants in the years that followed. These multinational suppliers included the blade producer LM, the gearbox manufacturers Winergy, Hansen, and Moventas, and the Portuguese tower firm Martifer. Local manufacturers that diversified from other industries—such as machine tool firm K&M, transmission firm Brad Foote, and blade manufacturer TPI Composites—remained the exception.[83]

Global Partners

US wind and solar firms made inventing new technologies a priority despite the absence of large domestic supply chains that could provide matching technological capabilities, components, and production experience. Where clusters of renewable energy firms emerged in the United States, they were frequently made up of start-ups pursuing similar strategies, not functionally diverse groups of firms with complementary skills. In Northern California, for instance, the density of venture capital funds and research universities created advantageous conditions for start-ups; but the area did not attract a network of vertically differentiated suppliers.[84] Instead, collaborative advantage—and the ability to specialize because of new opportunities for collaboration—allowed wind and solar firms in the United States to work with global partners on technology commercialization and the scale-up to mass production. In the best case, America's research and development infrastructure brought its fruits to market through such collaborative relationships, benefiting not just US firms and institutions but a range of global actors, each of which contributed skills and bore associated risks. In the worst case, start-up firms failed to find complementary capabilities in global supply chains, abruptly ending the trajectory from lab to market even for promising technologies.

In the hunt for global partners, large multinational firms—many of which had acquired start-ups to enter renewable energy—enjoyed an advantageous position. Many already benefited from global supply networks and possessed resources to manage their global links. Large firms could also internalize tasks

[82] Platzer 2012b, 32.
[83] Platzer 2012b, 32; Rogowsky and Laney-Cummings 2009, 9–10.
[84] Böttcher 2010, 16–24; Colatat, Vidican, and Lester 2009, 5–7.

that they could not find in global supply chains or that local institutions did not support. GE, for instance, the only large US wind turbine manufacturer, entered the wind energy sector through the purchase of Enron's wind turbine division during Enron's bankruptcy in 2003.

This acquisition gave GE immediate access to the turbine technologies under Enron's portfolio, including those of Zond, US Windpower, and the German manufacturer Tacke.[85] Zond's variable speed wind turbines, which had originally been developed at the University of Massachusetts, Lowell, and matured through collaboration with DOE and the national wind power program at NREL, provided the foundation for GE's turbine business. Enron's foreign assets, including the German manufacturer Tacke, further contributed patents, technologies, and supplier networks.[86] In addition to taking on 1,600 employees and production facilities in Germany and Spain, where large wind energy markets already existed, GE's purchase of Enron's wind energy division included turbine technologies that had been developed over decades of federal R&D support: GE was able to build on three decades of federally funded wind turbine R&D without incurring any of the initial technological risks itself.[87]

Despite having ceased the in-house development of utility-scale wind turbines when federal research support dried up during the 1980s, the purchase of Enron's wind assets allowed GE to quickly become one of the largest wind turbine manufacturers in the world. By 2005, GE held 61 percent of the US market for wind turbines.[88] To further improve its wind turbine technology, GE conducted both in-house R&D and acquired start-ups with specialized technologies. In 2011, for instance, GE purchased the tower manufacturer Wind Tower Systems LLC, to access its proprietary technology for the construction of low-cost wind turbine towers of more than 300 feet.[89]

GE retained the relationships with German gearbox suppliers such as Eickhoff, Winergy, and Bosch Rexroth, which had previously supplied Tacke. GE continued to source generators from VEM Sachsenwerke and maintained an R&D facility in Munich, Germany, to coordinate the development of new components with its European suppliers. Its membership in the German Engineering Federation's (VDMA) wind chapter allowed GE to participate in collaborative research activities conducted among German suppliers.[90] At the same time, GE began expanding its global supplier network, sourcing blades from Brazil and

[85] Mazzucato 2013, 148.
[86] Lewis 2013, 95; Windpower Monthly 1997.
[87] Mazzucato 2013, 148–49.
[88] Gleitz 2006, 1.
[89] Ehren Goossens, 2011, "GE Acquires Wind Tower Systems to Build Taller Wind Turbine Towers," *Bloomberg,* February 11.
[90] VDMA website, http://wind.vdma.org/en/article/-/articleview/599526 (accessed March 15, 2013). Author interview, German Engineering Federation, May 25, 2012.

metal castings and gearboxes from China, where it also maintained an R&D facility.[91] Strong institutional and financial capabilities allowed GE not only to systematically identify potential suppliers and collaborators, but also made possible the assignment of engineering staff to the production facilities of its partners. A Chinese manufacturer that developed gearboxes in collaboration with GE reported a permanent presence of GE design and manufacturing engineers on site to improve product designs and supervise manufacturing processes.[92] Even as it advertised itself as the "American" wind turbine manufacturer, GE's local content rates were among the lowest in the industry.

The resources to manage a global supply chain allowed GE to focus on assembly and research in the United States while sourcing the majority of components internationally. Local content rates for GE turbines assembled in the United States remained lower than those of its foreign competitors, many of which had established local component production.[93] As a consequence, approaches to reduce gearbox wear through novel lubricants, which GE's predecessor, Zond, had developed in collaboration with NREL, were introduced and carried out in Chinese gearbox manufacturing plants.[94] GE continued to participate in federally funded research—collaborating, for instance, with NREL and Virginia Tech on developing new blade designs through a project funded by ARPA-E—yet it was less dependent than other manufacturers on finding local partners for implementation of the results.[95]

Large suppliers such as Applied Materials maintained similarly global relationships to commercialize their products. In 2009, Applied Materials opened a solar technology R&D center in China, not primarily to source components, but to improve solar PV production technologies in collaboration with China's growing number of solar manufacturers.[96] With US startups working on disruptive technologies not yet in mass production, Applied Materials looked to China's 120 solar manufacturers to partner on the incremental improvement of silicon and thin-film solar PV technologies. In 2011, Applied Materials announced a new selective emitter product developed in its

[91] Author interview, head engineer of Chinese gearbox manufacturer, August 26, 2011. "Tecsis Signs US$1bn Wind Turbine Blade Deal with GE," *Business News Americas*, December 4, 2006, http://www.bnamericas.com/news/electricpower/Tecsis_signs_US*1bn_wind_turbine_blade_deal_with_GE (accessed April 14, 2014).

[92] Author interview, head engineer of Chinese gearbox manufacturer, August 26, 2011; December 5, 2016.

[93] Rogowsky and Laney-Cummings 2009, 9, 20.

[94] NREL, 2010, "Wind Turbine Design Innovations Drive Industry Transformation," http://www.nrel.gov/docs/fy10osti/47565.pdf (accessed March 27, 2014).

[95] NREL, 2013, "Fabric-Covered Blades Could Make Wind Turbines Cheaper and More Efficient," http://www.nrel.gov/wind/news/2013/2066.html (accessed March 27, 2014).

[96] Katherine Bourzac, 2009, "Applied Materials Moves Solar Expertise to China," *MIT Technology Review*, December 22.

R&D facility in China. The Italian firm Baccini, acquired by Applied Materials in 2007, contributed the underlying production technology, but this technology was subsequently tested and fine-tuned in the manufacturing plants of Chinese PV producers, who used components and materials developed by Honeywell in the United States.[97]

Applied Materials found less success developing manufacturing technologies for thin-film lines. A plan to build turnkey production lines for thin-film cells—based on the core technologies of several US start-up firms it had acquired—failed when falling silicon prices bolstered the competitiveness of conventional silicon cells.[98] The firm's 2010 exit from the thin-film business effectively ended research and development on a technology that had received USD 300 million in federal research funding.[99] Because its thin-film division was based on global relationships, the consequences of Applied Material's exit reverberated far beyond the United States. With few prospects for further technology improvements, early adopters of Applied Materials' thin-film production lines, such as the Chinese firm Suntech, closed their thin-film divisions as Applied Materials shuttered its thin-film division in China.[100]

Yet smaller wind and solar start-ups *also* benefited from global supply chains to find complementary capabilities, even if their limited institutional and financial resources precluded the type of global supply chain management common to multinational corporations. Since venture capital funds were rarely willing to fund investments in capital-intensive manufacturing facilities, and since start-up firms frequently lacked production experience, these start-ups frequently sought knowledge in scale-up and mass production, not access to technology, from global partners. Innovalight had received funding from the DOE and had collaborated with the NREL to apply its technology to the solar sector. Neither the federal research infrastructure nor the American solar industry could supply the type of production skills required to apply the silicon ink to large-scale manufacturing. Before SolarWorld, a German solar manufacturer, constructed a manufacturing plant for silicon-based solar PV technologies in 2008, almost all US solar plants were producing thin-film solar PV technologies, which were incompatible with Innovalight's product. A plan to build its own production facility faltered when venture capital funders refused to invest the sums required for a manufacturing plant.

[97] "Advisory: Applied Materials Reports Innovations in Solar Cell Manufacturing at SCNEC," *Reuters*, February 21, 2011.

[98] Jennifer Kho, 2010, "Applied Materials and the $1.5 Billion Sunfab Flameout," *Fast Company Magazine*, December.

[99] Gallaher, Link, and O'Connor 2012, 31–34.

[100] Michael Kanellos, 2010, "Suntech Abandons Thin Film, Wafer Experiments," *Greentech Media*, August 6, http://www.greentechmedia.com/articles/read/suntech-abandons-thin-film-experiments-revenue-up-for-2q (accessed April 14, 2014).

Ultimately, Innovalight, like many of its peers, looked to China for a partner to commercialize its technology.[101] It joined forces with JA Solar, which had a production line designated to manufacturing research and the production capabilities necessary to integrate Innovalight's silicon ink. With few engineers and depleted finances, it is unlikely that Innovalight was able to conduct a systematic search for potential partners. Rather, JA Solar's close connections to Silicon Valley facilitated the match. JA Solar's CEO at the time, Peng Fang, had completed his PhD at the University of Minnesota, conducted research as a postdoctoral student at the University of California, Berkeley, and had worked for Applied Materials and the semiconductor firm AMD in Silicon Valley before returning to China.[102] Innovalight's CEO, Conrad Burke, was also a Silicon Valley veteran, suggesting that the two firms were able to broker a collaboration through the networks of Northern California's start-up clusters.[103] The partnership between the two firms resulted in the successful commercialization of Innovalight's silicon ink technology, eventually leading to Innovalight's acquisition by Dupont.

Other start-ups followed a similar strategy, building personal ties to China in search of complementary skills—albeit in componentry. Ogin, the Massachusetts wind turbine company that developed the jet-engine turbine design, hired Lars Anderson in 2010; Anderson had previously managed the China business of Denmark's multinational turbine manufacturer Vestas.[104] Unable to find customized components for the novel turbine design in the US wind power supply chain, Ogin hoped its new CEO's familiarity with the Chinese supply chain would help identify suitable suppliers.[105] Ogin subsequently opened an R&D and component sourcing facility in Beijing to facilitate collaboration with Chinese partners.[106]

The CEO of a Silicon Valley solar start-up that had opened a production facility within China with local partners explained that Northern California gave the firm access to trained engineers, test facilities, and the technological expertise of universities and research laboratories. In China, however, the firm found manufacturing engineers with experience in the rapid scaling of new technologies. The density of solar manufacturers in China had also created a local market for used manufacturing equipment, which the firm could buy cheaply and subsequently repurpose to test and produce its thin-film technology. An abundance of local suppliers permitted the solar start-up's production engineers to easily try new materials and work with partners to improve the manufacturing process.

[101] Nahm and Steinfeld 2014, 297.
[102] "Peng Fang: Executive Profile," 2014b.
[103] "Conrad Burke: Executive Profile," 2014a.
[104] Gertner 2013.
[105] Author interview, Ogin engineer, November 30, 2010.
[106] US–China Energy Cooperation Program 2014.

Although the CEO insisted that basic research should stay in Silicon Valley for the time being, he expected more and more research staff to move to the Chinese facilities, as cost reductions through improvements to the manufacturing process were becoming more important over time.[107]

Although start-ups were able to find partners in global supply chains, managing R&D activities through such relationships posed considerable difficulties for smaller firms. Evergreen, an MIT spinoff that began the development of string-ribbon manufacturing technologies for solar wafers in the early 1990s, was unable to find US partners willing to adjust their production practices to Evergreen's nonstandard wafer size. Evergreen's string-ribbon technology lacked the maturity to produce wafers in the standard formats expected by cell manufacturers, a disadvantage that prevented Evergreen from becoming a regular wafer supplier on the global component markets. In 2005, the firm partnered with Norwegian silicon producer REC and German cell manufacturer Q-Cells to set up a manufacturing facility in Germany, where large solar markets existed at the time.[108] For the R&D engineers at the small Massachusetts-based start-up, however, such collaboration required countless trips to Germany, as incremental improvements to the technology had to be tested and implemented in its manufacturing facility. Any changes to wafer production and size necessitated subsequent adjustments of the entire production line, including cell and module manufacturing. R&D engineers involved in the commercialization of the string ribbon technology maintained that the geographical distance between the partners proved challenging for a small firm like Evergreen, slowing technological progress and preventing rapid—albeit incremental— improvements.[109]

Despite more than USD 43 million in grants from the state of Massachusetts, Evergreen's attempts a few years later to localize production in the United States failed, due to the continued high cost of the firm's technology. Evergreen gradually moved its facilities to China in 2009, where it conducted R&D and production in close proximity to a local partner, a manufacturer of cells and modules. Local suppliers of production equipment contributed to cost reductions for Evergreen's proprietary production lines; a greater number of local firms offered opportunities for more rapid incremental improvements for the firm's technology. Even with this change and a wide range of partners, however, Evergreen was unable to stay in business. In 2011, a Chinese investor bought Evergreen for USD 6 million in cash and 7.6 million in stock, a mere fraction of the state R&D funds and production subsidies that the firm had received in the United States.[110]

107 Author interview, CEO of Silicon Valley solar start-up, August 24, 2011; January 6, 2015.
108 QCells 2005.
109 Author interviews: former Evergreen engineers, May 16 and October 13, 2011.
110 Bradsher 2011.

Many start-up firms depended on global partners to commercialize their technologies, yet global relationships were not the only reason US-funded technologies were brought to market abroad. For the wind and solar industries, where the skills and expertise required to bring new technologies from lab to market often resided across multiple firms in far-flung locations, attempts to single-handedly manage the commercialization process could also result in failure. MiaSole, a Silicon Valley manufacturer of high-efficiency thin-film solar modules, had long struggled to scale the manufacturing of its technology. The start-up had received more than USD 500 million in venture financing since its founding in 2004 but was unable to increase its production from 50 MW to 150 MW annually. In 2011, it hired manufacturing experts from INTEL to improve its manufacturing operations. Falling silicon prices, overcapacity in global markets, and difficulties raising further funds to expand its facilities compounded its production problems. In 2012, the Chinese industrial manufacturer Hanergy bought MiaSole for USD 30 million, a fraction of the original VC investment. Although its facilities in California have remained in place for the time being, Hanergy has since begun to scale MiaSole's technology in larger manufacturing plants in China.[111]

As is the case with most disruptive technologies, not all innovations were destined for success, whether firms managed to find global partners or not. Ultimately, changes in the global market environment, technology failures, lack of sufficient financing at critical development junctures, and high production costs prevented many innovations born of US research institutions from finding a home in consumer markets. Start-up firms incurred risks in developing new technologies and bringing them to large-scale production and deployment; many struggled to manufacture their products at a competitive price, even with the help of global suppliers. Prices for conventional wind and solar technologies were falling rapidly, as multinational firms with large manufacturing facilities entered the US market, raising longer-term questions about problems of technology lock-in and the ability of next-generation energy technologies to compete against the products now mass-produced in China.[112] The global financial crisis led many European governments to cut their renewable energy subsidies, causing renewable energy markets to decline in other parts of the world. The discovery of large natural gas reserves in the United States lowered the price of fossil fuels there, increasing the price gap between renewable energy and conventional sources of electricity and offsetting the cost reductions in renewable energy technologies from previous decades.[113] As a result, a wave of bankruptcies shut US

[111] Bradsher 2013a.
[112] Bourzac 2009; Hart 2020.
[113] Koch 2014.

high-technology solar firms, and wind turbine producers struggled to stay afloat. Evergreen Solar ceased operations.[114] Solyndra, which had benefited not only from R&D subsidies but also from a sizable loan guarantee to build a large manufacturing facility, declared bankruptcy after the decline in global silicon prices eroded the competitiveness of its products and its venture capital investors withdrew their support.[115] SunPower and First Solar closed manufacturing facilities in the United States and abroad.[116] Out of the 200 solar start-ups that had received venture capital funding by 2008, less than half were still operating as independent businesses by 2013.[117] Where technologies did succeed in traveling the full trajectory from lab to market, they relied on federal support for R&D as much as on the contributions of firms in global supply chains. Gaps in domestic supply chains forced innovators to look outside the United States for engineering capabilities in scale-up and mass production.

Institutions for Invention

The United States has long been the single largest funder of energy research in the world. In 2017 alone, the federal government committed USD 7 billion to energy technology research, development, and demonstration.[118] As I have chronicled in this chapter, such public investments in research did not yield the same domestic industrial development that innovation yielded in the postwar decades. Collaborative advantage allowed firms to focus on capabilities on invention, as they repurposed existing public institutions for research and development to enter renewable energy supply chains. These institutions were originally established to funnel federal R&D funds into the development of new technologies that were assumed to attract complementary capabilities in commercialization and mass production into the US economy. Changes in the organization of the global economy severed those ties and allowed firms to enter renewable energy sectors without building the full range of skills required to take new technologies from lab to market. Institutions that were really intended to support much broader sets of industrial activities—those that promoted the visits of worldwide government groups to Silicon Valley referenced in the introduction to this book—were instead used by firms to support specialization in invention without these the development of such complementary skills.

114 Turner 2011.
115 Mazzucato 2013, 129–32.
116 Leone 2012.
117 Wesoff 2013.
118 IEA 2019, 108.

The federal R&D infrastructure influenced the development of American renewable energy sectors in two central ways. First, American wind and solar firms—start-ups as well as the multinational companies that in many cases acquired the smaller tech firms—utilized the federal innovation infrastructure to access core technologies by deploying institutions for technology transfer dating back to the 1980s. As part of a series of legislative changes that eased the flow of technologies from universities to the private sector, the Bayh-Dole Act of 1980 permitted universities and research institutes to patent discoveries that resulted from federally funded research and to offer exclusive licenses to third parties. The Bayh-Dole Act was just one of series of legislative changes that spurred increased university patenting and licensing over following decade.[119] In 1965, fewer than 200 patents were granted to American universities; by 1988, more than 1,000 patents were granted to universities annually, as universities enjoyed permission to commercially exploit the results of their research through patents and licensing. By 1993, many US universities and research institutes had established designated technology transfer and licensing offices and jointly held more than 4,000 active license agreements with firms, together generating USD 375 million in royalties.[120]

In Germany, a network of publicly funded applied research centers, the Fraunhofer Institutes, offered consulting services to private sector firms. The content of research collaborations was determined by the consulting clients, whose fees covered part of the cost. In renewable energy industries, such clients were manufacturers of equipment and components.[121] In the United States, by contrast, the legislative framework to encourage technology transfer allowed wind and solar firms to access technologies created with the help of vast federal investments in renewable energy research. It also provided incentives for researchers to follow innovative technologies to private sector firms. The private sector did not set research priorities, however—universities and federal research programs held that authority. Consequently, much research targeted the invention of new technologies, including the next-generation solar PV technologies and novel turbine designs discussed at the beginning of this chapter.

These firms retained close links to research institutes and universities and were often physically located near the institutions that had hosted the original research. First Solar (then named Solar Cells Inc.) was founded in 1990 in Toledo, Ohio, as the first commercial manufacturer of thin-film solar cells, a technology that reduced the use of silicon by depositing a thin layer of PV

[119] Patents could be licensed, but private sector firms could not purchase the patents. Mowery et al. 2001, 102. For a discussion of the extensive legislative changes that transformed university–private sector knowledge transfer during the early 1980s, see Mowery et al. 2004.
[120] Henderson, Jaffe, and Trajtenberg 1998, 120–21.
[121] Fraunhofer ISE 2017, 24.

material on alternate substrates. Its initial facilities were located on the campus of the University of Toledo, where collaboration between First Solar and university laboratories was funded by federal and state-level research grants.[122] Similarly, SunPower was founded in 1991 by a Stanford University engineering professor named Richard Swanson. SunPower's core technology offered a new approach to creating high-efficiency solar cells that used all-back contacts to increase energy output. The research for the all-back contacts at Stanford had been funded by DOE and NREL. SunPower financed its first facility with grants from DOE, the Electric Power Research Institute, and venture capital financing.[123] In 1994, MIT professor Emanuel Sachs spun off Evergreen Solar to commercialize a new manufacturing technology for solar wafers. Evergreen employed a so-called string-ribbon technology to manufacture thin solar wafers without cutting them from large silicon blocks, thereby preventing material loss from wire-sawing prevalent in traditional wafer manufacturing.[124]

In addition to providing core technologies, the US research and development infrastructure offered a financial lifeline for start-ups that had already spun off from universities and research institutes but struggled to access funding. Throughout the 1990s, the absence of subsidies for the large-scale deployment of renewable energy technologies in the United States made it difficult for start-up firms to generate revenue from their products. Financial institutions, in particular venture capital funds, resisted funding long-term R&D without a clear prospect of market demand—without government subsidies, even advanced wind and solar technologies were not cost-competitive with fossil fuels.[125] To stay afloat, the majority of start-up firms continued to rely on government research grants for funding and, as a consequence, few were able to invest in capital-intensive mass production facilities as a result of their limited budgets. In the 1990s, SunPower collaborated with NASA to develop a solar-powered airplane.[126] Others, such as the wind turbine manufacturer Zond, worked with utilities to build small demonstration facilities.[127] US research and development programs thereby became a lifeline for firms whose research had advanced beyond initial-stage R&D but was not yet ready for mass production. Between 1991 and 2008, the DOE invested USD 289 million in manufacturing R&D for new solar technologies as part of the PVMaT program. The program supported several solar PV start-ups, including Evergreen, throughout the 1990s when

[122] American Energy & Manufacturing Partnership 2013, 12.
[123] Swanson 2011, 537–38.
[124] For an explanation of how Evergreen's string-ribbon technology differs from conventional solar cell manufacturing practices, see Wallace et al. 1997.
[125] Moore and Wüstenhagen 2004, 243.
[126] Swanson 2011, 539–45.
[127] Department of Energy 2003.

commercial markets were small.[128] A separate program existed for thin-film cell technologies. In the wind sector, too, federal funds remained critical to keeping firms afloat.[129] For instance, Zond, one of two wind turbine manufacturers that had survived the end of California's wind power subsidies in the mid-1980s, received DOE funding for research on large wind turbines in 1995.[130]

Unlike German family-owned businesses, US start-ups did not have long-standing relationships with local banks. The United States also lacked the public infrastructure and policy banks that funded manufacturing expansion in China. Few US financial institutions were willing to invest in emerging, high-risk renewable energy sectors. This changed in the early 2000s, when prospects for global renewable energy markets rose—the result of government policies in the United States and elsewhere. This rosier outlook, in turn, encouraged venture capital funders to support renewable energy start-ups, especially in the solar sector. The percentage of government R&D funding as a share of overall investment in solar energy technologies dropped from 90 percent in 2001 to less than 10 percent in 2007 as private investment increased exponentially.[131] Global venture capital investment in clean energy technologies multiplied from USD 200 million in 2000 to USD 2.5 billion by 2007; US-based venture capital funds investing in US start-ups accounted for 82 percent of overall VC investment in renewable energy. Some 150 renewable energy start-ups received venture capital funding in Silicon Valley alone.[132] By 2011, US venture capital firms invested USD 11 billion in American clean technology businesses, compared to USD 9 billion globally.[133] The combination of global markets and domestic capital prompted a new wave of industry entry, particularly in the solar sector, where cumulative federal R&D funding had continually surpassed investments in wind turbine research and new technologies were ready for commercialization.[134] New entrants clustered close to major research institutions and venture capital firms, with California and Massachusetts emerging as two centers of start-up activity.

But venture capital funding for the renewable energy industry remained insufficient to meet capital needs. After peaking in 2008, venture capital investment decreased, dropping to USD 2 billion by 2013. The number of renewable energy start-ups that successfully vied for funding dropped from 75 in 2007 to 24 in 2013. Increasingly, venture capital funds focused on later-stage technologies and avoided early-stage projects with long development horizons and uncertain

128 O'Connor, Loomis, and Braun 2010, 3–11.
129 O'Connor, Loomis, and Braun 2010, 3–14.
130 Department of Energy 2003.
131 Jennings, Margolis, and Bartlett 2008, 8.
132 Gaddy, Sivaram, and O'Sullivan 2016, 2; Jennings, Margolis, and Bartlett 2008, 9.
133 Mazzucato 2013, 127.
134 Jennings, Margolis, and Bartlett 2008, 8.

future payoffs.[135] Against a backdrop of waning enthusiasm—coupled with widespread doubt about the ability of energy start-ups to produce the returns common in the software industry—wind and solar start-ups continued to experiment with federal R&D programs and other federal subsidies to stay afloat. ARPA-E, a federal program to support the commercialization of high-risk energy technologies, provided USD 130 million to 66 start-up firms and university labs in its first round of funding, including the MIT spinoff 1366 Technologies and the wind turbine manufacturers Ogin.[136] Other firms received grants and technical assistance from NREL and the DOE, which supported, for instance, Clipper's work to develop a turbine for low wind speeds between 2002 and 2006, covering half of the USD 19 million in R&D expenses to develop a prototype.[137] Similarly, DOE's Thin-Film Partnership program, first established in the 1990s, funded the pilot production of thin-film modules through 2008.[138] The American Recovery and Reinvestment Act provided USD 1.3 billion in loan guarantees to four solar start-ups—Solyndra, 1366 Technologies, Abound Solar, and SoloPower—to help fund investments in production facilities.[139]

Although venture capital funds played a critical role by allowing start-up firms to test and improve their early-stage products after they had left their home universities and research institutes, the basic technologies of most start-up firms sprang from federally funded research. Not only did federal R&D support encourage the development of new renewable energy technologies but federal research grants provided an important source of revenue for start-ups that had not yet found markets for their technologies. For further testing and improvements to their technologies, firms relied on resources and technical expertise provided through national laboratories. Investments in the riskiest technologies—very early research in fields with no clear market application—were thus made by the state. Venture capital funders wanted little part of this action. They shied away from investing in the highest-risk early-stage R&D, as well as the capital-intensive manufacturing facilities required for scale-up and mass production. Instead, they supported technologies that had achieved sufficient maturity to leave the university and that had an established path toward commercialization.[140] Ultimately, the large number of start-ups in the US wind and solar sectors responded to renewable energy policies by using legacy research institutions of the federal government.

[135] Gaddy, Sivaram, and O'Sullivan 2016, 2–3.
[136] ARPA-E 2009; Wald 2011.
[137] Hamilton 2011, NREL 2012.
[138] O'Connor, Loomis, and Braun 2010, 3–17.
[139] Brown 2011, 4.
[140] Mazzucato 2013, 127–29.

US strengths in innovation without capabilities in scale-up and mass production did not result from global competitive pressures and the disadvantages of a high wage environment. Strong research and development institutions did not by themselves result in broader industrial outcomes because federal policies were not complemented by policy support for the type of bottom-up industrial change that brought production capabilities to China's and Germany's renewable energy supply chains. Absent an industrial base of firms with skills applicable to the commercialization and production of wind and solar technologies and lacking the types of institutional support—including skills and training institutions, financing, and collaborative research opportunities—that could help smaller firms apply their capabilities to new industrial sectors, the US start-ups relied on collaboration in the global economy to reproduce historical strength in the invention of new technologies.

Conclusion

Just as the wind and solar sectors in Germany and China reproduced the industrial capabilities of the broader economy by employing collaborative advantage, so US R&D capabilities also benefited from policy support beyond the domain of renewable energy policy. US renewable energy firms used broad institutional support for high-technology research, including a legal framework that facilitated spinoffs (and licensing of the results of federally funded research) and a large venture capital community willing to invest in high-risk technology projects. These resources allowed for large numbers of high-technology start-ups, the majority of which focused on the development of disruptive renewable energy technologies that had originated in federally funded research programs.

Federal and state-level policies jointly created large markets for wind turbines and solar PV technologies, yet US start-up firms were not accompanied by comprehensive domestic supply chains focused on scale-up and manufacturing. A weak supplier base in adjacent industries reduced the number of firms that could enter wind and solar supply chains. Absent a vibrant industrial base and lacking the types of institutional support—including skills and training institutions, financing, and collaborative research opportunities—that could help smaller firms apply their capabilities to new industrial sectors, the United States reproduced its historical strength in the invention of new technologies without creating the vertically integrated industries that had originally motivated public spending on R&D.

The presence of collaborative advantage allowed firms to look for partners with complementary skills outside the United States. Firms in Germany and China possessed precisely the types of skills required to bring new energy technologies to market, and many American firms relied on global partners to commercialize their technologies. In practice, however, such global linkages proved easier to maintain for large, multinational corporations than for the high-tech start-ups that spun off universities and research institutes. Firms like GE and Applied Materials, which could quickly enter new industrial sectors through the acquisition of start-up firms, systematically matched their own capabilities with complementary skills in global supply chains. For smaller start-up firms, finding such partners required considerably more effort. With limited financial and human resources, such global collaborations were equally hard to maintain over time.

Governments around the world have attempted to replicate American strength in technological innovation. Despite outsized public investments in renewable energy research and development, however, the US specialization in invention has not generated vertically integrated domestic industries. In 2016, some 777,0000 Americans were employed in renewable energy sectors, making wind and solar some of the fastest growing sources of employment in the country. But less than a quarter of employment in the wind industry and a fraction of jobs in the solar sector were related to manufacturing.[141] The vast majority of jobs resided in the construction, operation, and maintenance of wind turbines and solar panels—products that in most cases contained technologies originally invented in the United States, but commercialized and produced in other parts of the world. New options for industrial specialization in the global economy allowed German and Chinese firms to maintain manufacturing-based industrial specializations. In the United States, by contrast, integration into global networks of innovators enabled firms to cut ties from the domestic manufacturing economy.

The fragmentation of domestic wind and solar sectors into firms with varying business interests and different domestic ties prevented US renewable energy industries from mounting a concerted lobbying effort in support of favorable policies against the opposition from vested interests.[142] Start-ups without capabilities in commercialization, multinational firms reliant on global markets and international suppliers, and international manufacturers without roots in the United States pursued individual political strategies. A key consequence of the American prioritization of invention over commercialization was the notably small size of the US manufacturing lobby in renewable energy sectors. In the wind industry, local content rates for US-manufactured wind turbines—even though they gradually increased over time—remained below 50 percent, even as the United States became the largest wind power market in the world.

[141] IRENA 2017, 14.
[142] Stokes 2020.

Local content rates improved after 2012, as larger turbine sizes over time made transportation more costly and motivated manufacturers to produce closer to end market. Yet they remained well below the rates of 80 or more achieved in Germany and China, and in some cases they dipped as low as 20 percent for individual turbine components.[143]

In the solar sector, where US firms and research institutes developed the foundations for virtually all of the main solar technologies in production today, US firms accounted for less than 5 percent of global manufacturing in 2010. New technologies were brought to market in other parts of the world, and key components for domestic solar PV manufacturing—including wafers, thin-film feedstock, and inverters—were imported from abroad. Although employment in renewable energy sectors has soared over the past decades, only a small share of this workforce today is employed in the development, commercialization, and production of wind and solar technologies. The DOE estimated that, in 2016, 373,807 Americans worked at least part-time in the solar industry, yet only 18.5 percent of employment was in manufacturing. The majority of solar jobs revolved around the installation of solar PV facilities, trade, and services for the solar industry.[144]

The fragmentation of industry interests appeared, among other ways, in the failure to mount an effective campaign supporting public subsidies for domestic renewable energy installations. Production tax credits for the wind industry and investment tax credits for the solar industry—the key federal incentive programs to create market demand for renewable energy technologies—had been notoriously volatile for decades. Even as the domestic markets for wind turbines and solar panels grew, they did not fully stabilize. After years of expirations and renewals, the Obama administration renewed the Production Tax Credit for three years in 2009. Again, it was not made permanent; and its renewal was as contested in 2012 as in previous years. The PTC was renewed for one year the day after it expired in 2012, yet wind turbine installations slowed dramatically in 2013.[145] The tax credit lapsed for 11 months in 2014, before a five-year extension and gradual phase-out of the wind tax credit was passed with bipartisan support in 2015.[146] But the damage was done: the uncertainty of previous years had already caused a number of turbine manufacturers, including the start-up firm Clipper, to close facilities and lay off staff.[147] In the solar sector, a 30 percent investment tax credit had been extended for eight years (starting in 2008) after

143 AWEA Manufacturing Working Group 2011; David 2009; Nahm and Steinfeld 2014, 292.

144 Department of Energy 2017a, 37–39.

145 Barradale 2010, 7699; Schwabe, Cory, and Newcomb 2009, 8. Christopher Martin, 2013, "U.S. Wind Power Slumps in 2014 after Tax Credit Drives 2012 Boom," *Bloomberg*, October 31.

146 Department of Energy 2015, 38; Mai et al. 2016.

147 Diane Cardwell, 2012, "Tax Credit in Doubt, Wind Power Industry Is Withering," *New York Times*, September 30.

several one-year-renewals.[148] In 2015, the solar investment tax credit was extended by five years. The extension stipulated a gradual phase-out in line with the policies for the wind industry.[149]

Divergent interests among start-ups seeking to find ways to commercialize their technologies, established manufacturers, and developers who relied on cheap imported products also affected trade policy. In the wind sector, a coalition of US manufacturers filed a trade complaint against wind turbine tower companies from China in 2011, leading the International Trade Commission to approve antidumping tariffs in 2013. While the move was applauded by firms with tower manufacturing capacity in the United States, developers of wind farms warned that tariffs wouldn't solve the broader problem of insufficient domestic manufacturing capacity.[150] In 2010, a coalition of solar manufacturers initially succeeded in calling for trade barriers against Chinese solar panels—making their voices heard against the opposition of solar developers and consumer advocates. A "Coalition for Affordable Solar Energy" was not able to prevent the tariffs, which were implemented in 2012. As Chinese manufacturers shifted their manufacturing locations to Malaysia and Taiwan to avoid the tariffs, US solar manufacturers appealed. In 2014, the US Department of Commerce and the International Trade Commission expanded the geographical scope and increased the tariffs in response to the request.[151] While the national industry association for the solar sector, the Solar Energy Industries Association (SEIA), had remained neutral in the initial trade cases, it now began to side with installers in opposition to domestic manufacturers. It did so, for instance, in the case of Suniva, a Georgia-based solar start-up that in April 2017 filed a petition with the US International Trade Commission to seek protection from import competition. SEIA subsequently issued a statement warning that further tariffs would threaten 88,000 jobs in the US solar industry due to price hikes for imported panels.[152]

Historically, strong links between public investments in R&D and the domestic production of at least the early versions of a new product ensured some commonality of interests among firms in a particular industry. Globalization—and the distribution of different types of innovation and manufacturing capabilities across global supply chains—severed the link between public investments in the invention of new technologies and the growth of domestic manufacturing sectors and fragmented the political strategies of domestic firms. The absence of a manufacturing coalition in support of renewable energy policy in the

[148] Solar Energy Industries Association 2014.
[149] Mai et al. 2016.
[150] Cardwell 2012; International Trade Administration 2013.
[151] Lewis 2014, 16–17.
[152] Solar Energy Industries Association 2017.

United States is of course not inevitable. In the long-run, the creation of supportive manufacturing institutions in the United States may well change the division of labor in future green industrial sectors, and indeed there is no shortage of proposals for such institutions. In the short-run, however, meeting climate policy goals in the United States will require reliance on technologies that may originate domestically but are at least in part manufactured abroad, which makes ambitious climate policy both harder to pass politically and more difficult to sustain against the opposition from vested interest.