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Industrial Legacies and Germany's Specialization in Customization

In 2009, the German Ministry of Education and Research awarded an EUR 40 million research and development (R&D) grant to a group of German solar firms. Comprising twenty-nine solar manufacturers, suppliers, and nineteen research institutes in the *Länder* of Saxony, Saxony-Anhalt, and Thuringia, "Solarvalley Mitteldeutschland" hoped to benefit from the same agglomeration effects as its namesake in California. Federal research funds were intended to support collaborative R&D projects among local firms with the goal of achieving grid parity for solar power by 2013. Subsidies and tax breaks for manufacturing in structurally weak regions in eastern Germany offered additional financial support to firms in the cluster.[1]

A mere year after winning the federal R&D support, observers raised doubts about the viability of manufacturers in Solarvalley. In 2010, Sunfilm, a producer of solar panels with two plants in the region, filed for bankruptcy. Operating losses mounted among other manufacturers.[2] Q-Cells, once Germany's largest producer of solar cells, followed Sunfilm into insolvency during a devastating financial performance in 2012. The German weekly *Der Spiegel* proclaimed that the "bankruptcy of Q-Cells [. . .] shows that the days of German solar cell production are numbered."[3] Meanwhile, the Berlin daily *Der Tagesspiegel* wistfully remembered the days when Solarvalley was "a piece of California in central Germany," referring not to the weather, of course, but to the enviable economic performance of tech firms in Silicon Valley.[4]

Solarvalley's dramatic failure to live up to its Californian namesake distracted observers from another story quietly unfolding during the same period: the striking success of small and medium-sized wind and solar suppliers and their role in the maturation of global renewable energy industries. Hidden in faceless industrial parks, these sectors sprang up around the development and manufacturing of components and production equipment for solar modules and wind

[1] Aulich and Frey 2009; Bundesministerium für Bildung und Forschung 2017; Thüringer Allgemeine 2012.
[2] Stafford 2010.
[3] Schultz 2012.
[4] Hoffmann 2012.

turbines. In 2011, the German Engineering Federation (VDMA), the industry association for the German mechanical engineering sector, listed more than 170 member firms active in the wind industry. Only ten were manufacturers of wind turbines. The majority of firms instead developed and produced towers, blades, mechanical components, hydraulics systems, and production equipment for wind turbine manufacturers.[5] By 2019, the number of VDMA member firms supplying parts for wind turbines had increased to 200.[6] Similarly, in the solar photovoltaic (PV) sector, more than seventy firms offered production lines, automation equipment, coatings, and laser processing machines. With roughly 41,000 employees in 2014, employment in solar PV equipment and component firms far surpassed the 12,000 jobs that had once existed in Germany's solar module manufacturers.[7] As of 2019, overall employment in German renewable energy industries reached 290,000, compared to roughly 800,000 workers in the German auto industry.[8]

Germany's wind and solar firms were small, often family-owned, and frequently far from large urban centers, tucked away in small towns ranging from the Baltic Sea to the Black Forest. The transition of firms from Germany's industrial core into the emerging renewable energy sector was therefore far less visible than the highly publicized bankruptcies of prominent solar manufacturers or the ubiquitous wind turbine installations that signaled energy sector change, yet their capabilities in managing complex production processes with high degrees of customization were becoming central to the maturation of global renewable energy sectors. Already in the 1990s, before global renewable energy markets had fully matured, German renewable energy firms began to collaborate with an increasingly international customer base, particularly in China. Firms reached export quotas of more than 50 percent in the solar sector and up to 80 percent in the wind industry over the course of the 2000s.

This chapter chronicles the development of Germany's networks of small and medium-sized enterprises (SMEs) focused on R&D capabilities in *customization*. I use "customization" to refer to R&D skills required for the development of production equipment and components that are not part of the process of invention but are necessary inputs into the commercialization of new technologies. Examples of customization include automated production lines for new technologies and novel components that cannot be readily purchased as standardized equipment.

As I discussed in Chapter 2, renewable energy policies pursued the goal of creating domestic renewable energy sectors capable of inventing, commercializing,

[5] Arbeitsgemeinschaft Windenergie-Zulieferindustrie 2012; Germany Trade & Invest 2010.
[6] Arbeitsgemeinschaft Windenergie 2019, 17.
[7] O'Sullivan, Lehr, and Edler 2015.
[8] IRENA 2018, 30; VDA 2019.

and manufacturing technological breakthroughs flowing out of Germany's R&D institutes—precisely the types of firms that had failed so spectacularly in Solarvalley. I show here that collaboration with global partners—and the resulting opportunities for specialization—actually allowed suppliers of components and production equipment to repurpose local institutions, so that Germany's legacy manufacturing economy could focus on developing complex components and manufacturing equipment for renewable energy sectors. Many SMEs from the traditional core of the German economy, the *Mittelstand*, played a central role in structuring the country's entry into wind and solar sector and the energy transition more broadly. This view is often missed in accounts depicting Germany's framework either as a top-down vision implemented by policymakers over private sector interests or as the result of citizen activism fueled by the environmental catastrophes of the 1980s.[9]

This chapter shows empirically that globalization led to a set of benefits for German wind and solar firms that I refer to as *collaborative advantage*. In particular, when German firms collaborated with Chinese firms, they identified new possibilities for specialization in global supply chains—and began crafting new pathways into the global wind and solar sectors. Relationships with China's manufacturing firms relieved smaller German firms of the burden of mastering all the activities typically required to develop and commercialize new energy technologies, especially those capital-intensive mass manufacturing competencies that proved difficult to finance in Germany. Through partnerships with Chinese firms, German suppliers from a range of existing industrial sectors learned to diversify, entering the renewable energy sectors with niche capabilities in customization and small-batch production.

In the process, Germany's wind and solar suppliers appropriated and repurposed a number of familiar public resources and institutions, many of which were originally established for legacy industries. I chronicle how the existence of this particular set of legacy institutions shaped the impact of collaborative advantage on the Germany economy and supported domestic wind and solar firms focused on customization. Political economists have long expressed concerns that the institutions underlying the German manufacturing economy—including strict labor market regulations, firm ownership patterns, corporate governance structures, and domestic financial markets—stifle industrial change.[10] In fact, these institutions presented a set of tools that were used to support the R&D required to enter the renewable energy industries. Collaborative advantage enabled wind and solar suppliers to sustain the legacy

9 For a detailed analysis of the politics of Germany's energy transition, see Hager and Stefes 2016.
10 See Hassel 2014; Thelen 2014.

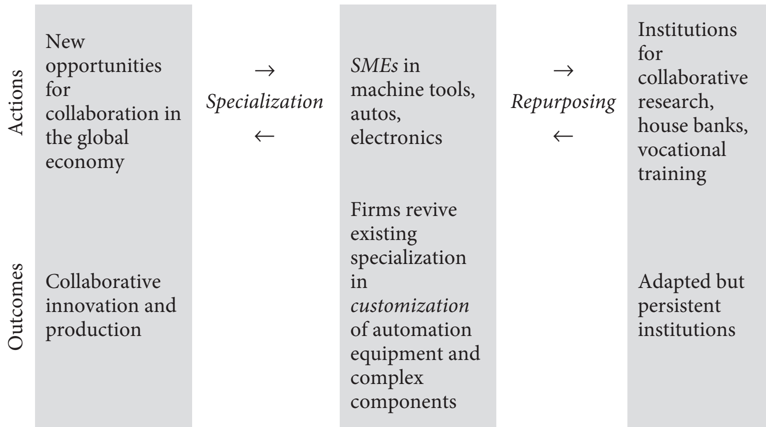

Figure 4.1 Industrial Specialization in Germany

institutions of the manufacturing economy; they became critical resources in support of the development of new industries (Figure 4.1).

This chapter begins with a discussion of industrial origins of Germany's wind and solar firms, focusing in particular on machine tools, automation, and automotive sectors. It then outlines the learning process that firms navigated in pivoting from their existing industries into new industrial sectors. The second half of the chapter focuses on the two key resources that enabled these developments: new opportunities for specialization as a result of collaboration, in particular with China, and the repurposing of institutional legacies. It concludes by highlighting the political implications of this particular industrial composition within Germany's renewable energy sectors, as firms used their membership in established industry associations to defend policy support for wind and solar sectors over time.

Building on Industrial Legacies

In 1990, when the German parliament began to debate the passage of the first Feed-in Law (*Stromeinspeisungsgesetz*) to subsidize power from renewable sources, wind and turbines and solar panels remained niche technologies. Large multinationals, in Germany and elsewhere, had largely closed or sold their wind and solar divisions. In the shadow of federal government R&D programs that had targeted large industrial conglomerates for many years, the renewable energy sectors continued to be the modest domain of passionate environmentalists, who tinkered with new technologies in a makeshift fashion without much

Table 4.1 Select Industrial Policies for German Wind and Solar Sectors

	Germany
Technology Push	Since 1954 Industrial Collaborative Research (ICR) funding Since 1974 Federal Energy Research Programs, renewed six times
Market Pull	1990 Electricity Feed-in Law 1998 Renewable Energy Sources Act (EEG) 2004 EEG Renewed 2009, 2012, 2014 EEG Modifications 2016 EEG reform, switch to auctions, "deployment corridors"

government support. Policymakers only gradually discovered the economic potential of the wind and solar industries; and at least initially, they vastly underestimated the effects of renewable energy legislation. Their lack of adequate information proved to be a blessing in disguise: the inability of lawmakers to predict the rapid development of renewable energy installations—and the concomitant growth of powerful industrial sectors—ushered the ambitious renewable energy law past parliamentary scrutiny. The implementation of the Feed-in Law on January 1, 1991, marked a critical transition from government-supported renewable energy research to long-term demand stimulation through the regulatory framework (Table 4.1).

Initially, the growing domestic markets created as a result of demand-side subsidies saved existing renewable energy manufacturers from bankruptcy. In the wind industry, the Feed-in Law helped a number of small German wind turbine manufacturers find stable financial footing after decades without reliable sources of demand. Experimental wind turbine start-ups founded in the 1980s now found themselves empowered to increase sales and invest in upgraded production facilities after years of makeshift operations.[11] With the exception of the industrial conglomerate MAN, these firms had in common their small size, an experimental approach, and roots in the agricultural machinery sector.

As wind power generation capacity in Germany expanded in the decades after the introduction of the Feed-In Law—increasing between 30 and 50 percent annually through the 1990s and slowing to annual growth rates between 6 and 20 percent in the early 2000s—a few additional manufacturers entered the sector.[12] Jacobs Energie and DeWind emerged in the 1990s in response to new

[11] Among the twelve firms with the most turbine installations in 1992, seven were from Germany, four from Denmark (Vestas, AN Bonus, Nordtank, and Micon), and one from the Netherlands (Lagervey). Company websites; Keuper, Molly, and Stückemann 1992, 21; Ohlhorst 2009; Schlegel 2005, 33; Tacke 2003.

[12] Earth Policy Institute 2020.

market opportunities. Vensys and Bard joined the industry in 2000 and 2003, bringing gearless turbines and offshore wind technologies to the market. On balance, however, the assembly of wind turbines was dominated by firms with origins prior to the Feed-In Law; more than half of wind turbine manufacturers operating in Germany in 2010, for instance, were founded during the 1980s or earlier.[13]

Once the 2000 Renewable Energy Sources Act (EEG) increased electricity rates for solar energy to compensate for the high cost of solar technologies, solar firms, too, could rely on rapidly increasing domestic demand. As in the wind industry, these changes initially benefited existing solar firms. It also encouraged larger manufacturing firms such as Schott Solar and Schüco, founded as glass and window producers during the 1950s, to enter the solar business. After decades of challenging technological trajectories and uncertain market environments—factors that had prompted large conglomerates to divest their solar divisions—the subsidies included in EEG once again made the PV industry desirable for large multinational firms. Firms like Bosch and Siemens, for example, entered the solar sector simply by taking over existing businesses.[14]

Although the wind industry in Germany had been on the upswing since the 1991 Feed-in-Law, standardized production equipment had not been developed; and no supplier industry existed to support small domestic manufacturers. Companies bought components from related industrial sectors and repurposed them for wind turbines as best as they could. Since government R&D projects on large-scale turbines in Germany and the United States had not yielded results, firms relied on an entrepreneurial, do-it-yourself approach as they applied engineering principles to turbines of increasing size. Sönke Siegfriedsen, head of the German wind turbine engineering firm Aerodyn, describes testing new turbines in the absence of standardized measurement equipment as a process of placing increasing numbers of sandbags on the blades; he remembers worrying that the new blade designs would be unable to withstand the required force.[15] In an interview, the head engineer for another German turbine manufacturer explained that he "didn't like coming to the office on Mondays during [the 1990s], because there would always be a message about a failed turbine somewhere. After every storm you would get a call about a failed turbine. We learned a lot from these problems, and it really taught us how to properly adjust specifications and improve turbine designs."[16]

[13] For a compilation of wind turbine manufacturers operating in 2010, see Germany Trade & Invest 2010. Founding dates according to company websites.
[14] Germany Trade & Invest 2011c.
[15] Siegfriedsen 2008, 58.
[16] Author interview, CEO of German engineering firm, May 20, 2011.

Growing markets required firms to restructure their manufacturing operations and made such experimental approaches increasingly untenable. As sales volumes increased, firms had to replace the components they had previously borrowed from other industries and repurposed in a makeshift fashion; to do so, they turned to designated, professional solutions. Wind turbine manufacturers began searching for external expertise in the production and design of components such as gearboxes, generators, blades, towers, and control software. In the solar industry, the growing market demand for solar panels necessitated the development of specialized manufacturing equipment for wafer, cell, and module production.

During the early 1990s, small-batch production and the prototyping of new cell technologies had occurred in the absence of specialized equipment suppliers, forcing manufacturers to modify production equipment from other sectors—particularly the microelectronics industry—and to perform many production steps manually.[17] While the production requirements for solar cells were less demanding than integrated circuits when it came to particulate contamination—solar production guidelines permitted the use of scrap silicon from the microelectronics industry—using equipment from other sectors still presented enormous challenges. Wafers twice as thin as those used in semiconductors, for instance, required a redesign of all handling aspects of the production line to prevent breakage; and changing material purity requirements necessitated new production and testing processes to isolate impurities. With the rapidly growing demand for solar modules, repurposed equipment at best presented a stopgap measure. Ultimately, such repurposing could not support the manufacturing volume and the cost reductions that Germany needed to establish solar energy as a competitive source of electricity.[18]

Despite concerns that Germany's high-wage manufacturing economy would be unable to compete in the long run against fierce competition in increasingly globalized industries, it was precisely SMEs from Germany's core manufacturing sectors that stepped forward to take advantage of opportunities in global renewable energy sectors.[19] Germany's *Mittelstand* possessed a rich fabric of firms with an array of expertise—these firms proved well-suited to support wind and solar manufacturers. They offered skills both in the production of components required in the wind sector and in the manufacture of production lines and automation equipment necessary in the solar industry.

Initially, the small size and ownership structure of German manufacturing firms left many of them reluctant to place bets on emerging renewable energy

[17] Author interview, CTO, German solar PV manufacturer, May 17, 2011.
[18] See Crane, Verlinden, and Swanson 1996; Green 2001.
[19] Berghoff 2006; Seliger 2000.

industries. For some firms, limited R&D resources precluded complicated development projects unless commercial prospects were relatively certain; for others, a history of custom orders had established a practice of developing new products only after a customer had been identified. By establishing long-term demand-side subsidies through the regulatory system, the 1990 Feed-in Law and the 2000 EEG provided the necessary investment stability and customer base to attract small and medium-sized firms.[20]

The managing partner of a family-owned supplier of automation equipment explained the reasoning behind the decision of many SMEs to enter the solar sector. His firm was heavily exposed to the auto industry, with 90 percent of their business coming from domestic automotive manufacturers. "We thought this kind of exposure to one sector in one market was very dangerous, so our team started thinking about sectors that we could diversify into," he said.[21] The firm hoped to find an industry where its core capabilities could be supplemented with additional skills to develop an innovative, competitive product. In early 2004, thanks to stable government policies and rapidly growing markets, the solar PV sector promised a significant demand for industrialization and low levels of automation. "Only a few firms were offering automated production solutions, and their processes were slow. We looked at what they were doing and thought we could do a lot better."[22]

Germany retained a large manufacturing sector of similar SMEs, particularly compared to other advanced industrialized economies, where the relative importance of manufacturing was rapidly declining. Between 1995 and 2005, the share of manufacturing value-added increased slightly in Germany, from 22.6 percent to 22.7 percent; in the United States, it dropped from 16.8 percent to 13.6 percent over the same period.[23] A significant share of German manufacturing remained concentrated in the production of machine tools, automotive supplies, and automation and process equipment. In 1995, for example, the production of machinery and equipment constituted 28 percent of manufacturing activity in Germany, making it the largest manufacturing subsector, ahead of fabricated metal products, chemicals, and food products. Overall, 6.3 percent of value-added in Germany came from machinery and equipment manufacturing firms, compared to 3.5 percent in the United States. Metal products, machinery, and equipment together accounted for more than half of manufactured output.[24]

[20] On policy stability and the development of German renewable energy sectors, see Grünhagen and Berg 2011; Lipp 2007; Mitchell, Bauknecht, and Connor 2006; Vasseur and Kemp 2011. For a discussion of policy stability and renewable energy sector development more broadly, see Butler and Neuhoff 2008; Couture and Gagnon 2010; Nemet 2009.

[21] Author interview, managing partner, Solar PV supplier, May 20, 2011; October 15, 2019.

[22] Author interview, managing partner, Solar PV supplier, May 20, 2011; October 15, 2019.

[23] OECD STAN Indicators, "Manufacturing Share of Value-Added 1970–2009," 2013.

[24] Author calculations based on OECD STAN database, 2020. Machinery and equipment figures calculated using ISIC code C29T33.

Small and medium-sized enterprises played a significant role in these industries. In 2002, enterprises with fewer than 500 employees made up 98.2 percent of businesses and 38.2 of revenue in machinery and equipment manufacturing. In metal fabrication, 99.6 percent of firms and 38.1 percent of turnover came from small and medium-sized firms.[25]

The vast majority of suppliers entered from these sectors that had long formed the heart of the German economy. In the wind energy arena, demand created by the 1990 Feed-in Law attracted the first wave of component suppliers to develop designated products for the wind industry, initially in collaboration with domestic manufacturers. These new suppliers included tower manufacturers, blade producers, manufacturers of mechanical components, and firms offering electrical components and control systems. Starting in 2004, after a EEG revision provided greater subsidies for offshore installations, firms began providing solutions specifically for wind turbine installations at sea.[26] Most suppliers carried decades of manufacturing experience from multiple industrial sectors. EEW Special Pipe Construction was founded in 1974 as a producer of steel pipes for refineries before it began specializing in towers and foundations for offshore wind turbines in 2003.[27] Back in 1926, SGL supplied wooden rotor blades for agricultural machines; decades later, the company began building expertise in fiber-reinforced plastics, eventually becoming a blade manufacturer for modern wind turbines.[28] Hansa-Flex, HAWE, and HYDAC were producing hydraulics and lubrication machinery for a wide range of industrial sectors before developing designated applications for the wind industry.[29] Stromag, founded in 1932 as a manufacturer of conductor rails and electric rail material, specialized in the production of clutches and breaks for textile machines before shifting to offer pitch controls, break systems, and gearbox components to the wind energy sector.[30]

After the domestic solar market expanded in the early 2000s, the solar industry, too, witnessed an influx of supplier firms from existing industries. Centrotherm, Roth & Rau, Schmid, and Singulus began producing turnkey production lines for crystalline solar cells; others targeted the manufacture of wet chemical benches, equipment for antireflective coating, and screen printers, as well as stringers and laminators for module manufacturing. Bürkle and Leybold

[25] Günterberg and Kayser 2004, 8. In Germany, SMEs (Mittelstandsunternehmen) were traditionally defined as enterprises with fewer than 500 employees and less than EUR 50 million in revenue. More recently, Germany has converted to the general EU definition, which defines SMEs as firms with fewer than 250 employees and less than EURO 50 million in revenue.

[26] Ohlhorst 2009, 196. Years of industry entry compiled from company websites.

[27] EEW 2013.

[28] SGL 2013.

[29] Flex 2013; HYDAC 2013.

[30] Stromag 2016.

started offering thin film production lines; and firms like Reis Robotics, Schmalz, and Rofin began the production of automation and laser processing equipment for solar firms.[31]

As in the wind industry, these firms had previous experience in the machinery and equipment sectors. Founded in 1948, Centrotherm initially specialized in the manufacture of production equipment for microelectronics and semiconductor firm.[32] Bürkle supplied machinery to furniture, automotive, electronics, and glass firms for more than eighty years before supplying production equipment to thin film solar firms.[33] Schmid, founded in 1864, began the production of manufacturing equipment for furniture businesses in 1926, started manufacturing printers for electronic circuit boards in 1965, and entered the solar industry in 2001. In 2008, Schmid developed the first automated production process for higher-efficiency selective emitter cells in collaboration with a Chinese solar manufacturer. In 2011, Schmid's production lines set the record for conversion efficiency for monocrystalline solar cells.[34] Schmid was representative of Germany's renewable energy suppliers not just for its rich manufacturing history across successive industrial sectors but also for its location. Headquartered in Freudenstadt, a small town of red-roofed houses dating to the sixteenth century on a high plateau above the Black Forest, the firm was far removed from both urban centers and the designated wind and solar clusters established by ambitious regional governments.

Entering Wind and Solar Sectors

Germany's wind and solar firms had direct roots in legacy manufacturing industries long at the core of the German economy. Technically, these were emerging industrial sectors that only became commercially viable as a result of regulatory policies in the 1990s and 2000s. Yet they were populated by firms with deep roots in existing industries, including the German auto sector, which policymakers had held out as an example. The profiles of Germany's wind and solar suppliers therefore broadly resembled the overall industrial specialization of Germany's manufacturing economy, which had historically prioritized customization, small-batch production, and the complex manufacturing of components and production equipment.

Although their backgrounds in traditional industrial sectors provided many of these firms with the type of tacit knowledge they needed to produce intricate

31 Timing of industry entry compiled from company websites.
32 Centrotherm 2016.
33 Bürkle 2013.
34 Schmid Group 2013.

machines and components, applying these existing skills to the emerging wind and solar industries entailed a steep learning curve. To enter the wind and solar sectors and successfully develop new generations of products required these firms to be adaptable and flexible, as they learned to substantially modify their existing product lines and technological capabilities. R&D engineers described three main modes of learning among wind and solar suppliers.

A first group of firms entered wind and solar supply chains through what I call *reengineering*, essentially a process of modifying and repurposing existing technologies for new applications. Customers played an active role in the reengineering process by encouraging industry entry, providing product specifications, and often participating in the design process through collaborative R&D. Reengineering existing technologies occurred in the wind industry, for instance, when Hedrich Vacuum Systems, a firm with decades of experience in the production of casting equipment, modified its cast resin technology for application in the manufacture of wind turbine blades from epoxy resins.[35] Similarly, SHW Werkzeugmaschinen, a firm with seventy years of experience in the manufacture of production equipment for large engines, reused its core technology, a milling head, in machines for the production of turbine housing and nacelles.[36]

Reengineering was particularly prevalent in the solar sector, where the similarity between microelectronics (semiconductors) and crystalline PV cells encouraged numerous firms to use their capacities in semiconductor manufacturing as a platform to enter the solar sector. The resulting production machines shared many technological principles with their ancestors in the semiconductor industry but applied them dynamically and creatively to new product applications.

In many cases, the initial entry of suppliers into renewable energy sectors was prompted by domestic manufacturers who had borrowed production equipment from the semiconductor industry. While these improvised production lines were adequate as long as production volumes remained low, manufacturing quality sometimes varied; and experimental lines were unsuitable for mass production—many of the steps had to be performed manually.[37] An integrated solar manufacturer originally began development and production in the facility of a previously state-owned East German semiconductor firm that had been divided and sold off in separate pieces after German unification. As the firm's chief technology officer (CTO) explained, in the late 1990s there simply was no commercial equipment available for the large-scale production of PV cells.[38]

[35] Hedrich Group 2013.
[36] de Vries 2011.
[37] Palz 2011.
[38] Author interview, CTO, German solar PV manufacturer, May 17, 2011.

In order to bring the technology from lab to mass production, the firm decided to use its local microelectronics industrial base—which already boasted a history of large-scale production—by repurposing the existing knowledge and machinery within that arena for the budding solar industry. While the production requirements for solar cells were less demanding than integrated circuits, in other ways using equipment from the microelectronics industry presented challenges. Thinner wafers required a redesign of all handling aspects of the production line to prevent breakage, and different material purity requirements necessitated the introduction of new production and testing processes to isolate impurities. After successfully experimenting with production lines retained from the semiconductor plant, the solar firm contacted some of the original equipment manufacturers and persuaded them to formally collaborate on the development of specialized solar production equipment.[39]

Although many manufacturers of production equipment initially resisted investing in product development for such young and emerging industries, the need for professional automation and manufacturing machinery in the solar industry presented a market opportunity too good to pass up. A manufacturer of wet benches for the semiconductor industry described how maintenance calls from solar firms whose teams were experimenting with semiconductor wet benches ultimately convinced the company to develop a product line specifically for the solar sector. This process not only entailed the design of a new product based on principles borrowed from the microelectronics industry but also necessitated new manufacturing strategies that would increase production speed while simultaneously allowing a greater degree of customization than was common in the semiconductor sector. The company eventually developed a modular production system that permitted higher manufacturing volumes while offering customers individual options for cell size and wafer thickness. It took the firm a year to design the first prototype to enter the solar sector, and an additional seven years to improve the product so that it could be mass produced. As the work progressed, the firm collaborated with solar cell manufacturers in Germany and, increasingly, with mass producers in China. Team members also worked closely with the Fraunhofer Institute for Solar Energy Systems (ISE) to further improve the firm's technology.[40]

A second group of firms developed wind and solar components through a process of *integration*: firms borrowed principles from different industrial sectors and applied them in an original way to new products and industries. Integration often occurred through collaboration among firms with different

[39] On the differences between microelectronics and solar PV in early mass production, see Crane, Verlinden, and Swanson 1996; Green 2001; Morris 2012, VI.

[40] Author interview, CEO, solar PV equipment manufacturer, May 10, 2011.

core skills and capabilities. Occasionally, however, it took place within the same firm, through the integration of technologies and skills internally. Although principles from the original application of technologies and processes were here repurposed, the combination of different technologies resulted in the development of new product designs.

In a fairly typical example, a small supplier of automation equipment used strategic learning and hiring to combine its core skills in the production of automation and testing machines for the auto sector with proficiencies from other industries. Trying to reduce its exposure to a single sector, the firm decided to diversify into solar module assembly, since very little automation technology for that activity was on the market; and much of the existing automation technology originally developed for the auto sector could be reapplied. While the firm reused about 70 percent of the technologies it had previously applied in the auto industry, it also integrated novel infrared and laser welding processes, as well as laser drilling technology originally used in dental offices. These dynamic additions allowed the firm to process cells contact-free, an improvement that increased speed, reliability, and production efficiency, particularly in the handling of ever-thinner wafers that were prone to breakage.[41]

In addition to hiring engineers with skills in laser welding and setting up training programs for existing R&D staff, the firm worked closely with laser and robotics suppliers during product development. The head of R&D pointed out the following:

> A lot of these suppliers are just down the road. In that sense, we benefit from being in the Silicon Valley of the machine tool industry. They send engineering teams that can come for days, weeks, or months, and work on site with our engineers until the product works. It's very different from working with global software firms, for instance, from whom we purchase testing and measuring software. If we have a problem there, we can call a call center, but those people don't really know any more than our own staff.[42]

All in all, the firm took two years to develop a prototype and another two years to start delivering the first products to customers—a lengthy process that occupied almost all of the firm's R&D sources.

A third mode of industry entry, *resizing*, pervaded the German wind power sector. Resizing occurred when the application of an existing technology to a new industry required a radically different scale not just of production but also

[41] Author interview, managing partner, solar PV equipment manufacturer, May 10, 2011; October 15, 2019.
[42] Author interview, head of R&D, solar PV equipment manufacturer, May 11, 2011.

of the product itself. Especially with mechanical parts, resizing often dictated a complete redesign of the product and the production process: structural loads and forces changed exponentially as the size of the product increased. As a consequence, computer models had difficulty developing adequate specifications for new components, and trial-and-error approaches dominated product development, as they do to this day.[43]

A manufacturer of gearboxes for wind turbines originally produced gearboxes for tunnel drilling machines in the mining sector. Although the core principles shared similarities—both types of gearboxes needed to withstand strong forces, high operating temperatures, and, unlike cars, needed to maintain almost continuous operation for years or even decades—gearboxes for large wind turbines required a completely new design. This remake needed to accommodate the structural requirements of the new size, new control software, a new logistics system to run operations, and new measuring and testing procedures; what's more, it also needed to use different materials to prevent corrosion in off-shore applications. Since gearboxes needed to meet the particular requirements of a wind turbine design, they almost always were developed in close cooperation with a future customer. Accordingly, for the firms' initial gearbox and subsequent product generations, a wind turbine manufacturer supplied specifications for interfaces, noise levels, vibration tolerances, and other parameters. The gearbox manufacturer then developed a prototype in close consultation with the customer, who was also involved in testing and ramping up to volume production. Although the firm possessed decades of experience in the gearbox industry, the development process for the first wind turbine generation lasted more than four years, with slightly shorter development times for subsequent product generations.[44]

A generator manufacturer described a similar process of bringing generator technologies from the shipbuilding and railways industries into the wind energy sector. In this case, space constraints and more stringent weight requirements inside the turbine prompted a redesign of the product and production line, a process repeated every time a larger turbine generation required exponentially larger components. The plant manager explained that for some components, the firm found ways to reuse parts from its railway and industrial engine business; but for others, the need for smaller and lighter-weight structures and the reality of different climate conditions in wind turbine applications mandated the use of alternative materials and construction methods. In adapting existing technologies to the requirements of the wind turbine industry, the firm benefited greatly

[43] Author interview, plant manager, gearbox manufacturer, May 16, 2011.
[44] Author interview, plant manager, gearbox manufacturer, May 16, 2011.

from its proximity to local suppliers, who worked closely with the firm's engineers to adapt parts and components. As the plant manager explained:

> We work with a local iron caster on making a part. Even with something as simple as iron casting we have to be careful. These firms make parts for all sorts of machines, so they don't know what's relevant and important in our business. For the first 100 parts or so we have to have an engineer work on site with them to make sure the part is optimized. For a small company like us, it's much easier if the supplier is around the corner, because we can jump in the car and meet with them to discuss tolerances and fits.[45]

Collaboration and the Mittelstand

These unlikely entrants into Germany's wind and solar industries succeeded in finding their customization niche because of collaborative advantage. Collaboration freed up options for specialization, allowing renewable energy firms in Germany to pick competitive strategies that built on their existing strengths in customization. If conventional wisdom predicted that small and medium-sized manufacturing firms in a high-wage economy would be threatened by competition with China, the reality on the ground subverted this assumption: precisely *because* of their engagement in China, these firms were able to survive. Relationships with Chinese firms allowed these companies to enter renewable energy sectors without having to set up mass manufacturing facilities, allowing highly specialized German firms to enter the marketplace.

In both the wind and solar power sectors, the development of new technologies necessitated large investments in time and capital, even if they allowed firms to draw on existing knowledge. Product development times of two to four years were standard among the majority of firms interviewed for this project, with an almost equal length of time recorded for each new product generation. For small and medium-sized suppliers, the move into wind and solar sectors commandeered the vast majority of their R&D resources, preventing firms from working on product alternatives for different industrial sectors.[46] In this context, Germany's small and medium-sized supply firms were attracted to the wind and solar sectors as much by the stability of Germany's renewable energy legislation as by growing market demand. In both sectors, suppliers entered after

[45] Author interview, plant manager, German generator manufacturer, May 17, 2011. I also visited the Chinese partner of the German firm and interviewed the lead R&D engineer, December 6, 2016.

[46] Author interview, engineer, robotics manufacturer, May 13, 2011.

government support had switched to long-term demand stimulation by passing the 1990 Feed-in Law and the 2000 EEG.

In the solar sector, the availability of off-the-shelf manufacturing equipment for solar cell production—attributable to the growing number of designated supply firms—lowered barriers for entry for manufacturers both in Germany and abroad. In previous decades, field tests had struggled to replicate laboratory results. Manufacturing difficulties often led to large variances and degradation of solar cell performance over time. Before the development of designated production equipment, assembling a solar production line comprised a makeshift combination of chemical baths, screen printers, furnaces, and other equipment borrowed from various industries.[47] Advanced manufacturing equipment now permitted manufacturers to more reliably translate their R&D efforts into mass production and made it easier to reach scale economies. The greater consistency and standardization of manufacturing output—including the development of industry norms for wafer and cell sizes—further supported firm specialization in discrete steps of the supply chain, since the interfaces between different production steps now enjoyed compatibility across producers.

In the 1980s and 1990s, wafers had to be cut from silicon ingots one at a time. In the early 2000s, the introduction of wire-saws by equipment producers allowed 4,000 wafers to be cut simultaneously, reducing cost, time, and capital expenses.[48] In the early 1990s, a single manufacturer was at best able to produce solar panels with a few kilowatts capacity annually. A mere decade later, a single production line could churn out solar panels with 66 MW of generation capacity a year. Although R&D efforts by universities, research institutes, and industry improved the conversion efficiency for multicrystalline cells by 15 percent between 1995 and 2005, advances in manufacturing technology allowed the price of solar PV systems to drop by more than 40 percent over the same period, far exceeding gains from increased conversion efficiency.[49]

In theory, the availability of off-the-shelf production equipment permitted anyone to produce solar cells with the flick of a switch. In practice, producers relied on extensive collaboration among solar firms, equipment producers, and research institutes. To embed new technologies in production equipment, research institutes and solar firms shared the results of internal R&D efforts with equipment producers. These firms had experience with automation technology and equipment manufacturing but, in return, often lacked knowledge of new solar

47 Morris 2012, vi.
48 Swanson 2011, 543.
49 Cell efficiencies over time gathered by NREL. See https://www.nrel.gov/pv/cell-efficiency.html (accessed November 12, 2020). Prices of solar PV systems over time compiled by Grau, Huo, and Neuhoff 2012, 23, figure 4.

PV technologies. Solar manufacturers and equipment suppliers generally collaborated on extensive field-testing of new equipment.

For solar firms, participating in R&D joint projects meant walking a tightrope between protecting proprietary technologies and accessing advanced automation equipment to commercialize these technologies. Investments in new production technologies made little commercial sense to equipment manufacturers if they could not be marketed to other customers, so few were willing to build equipment exclusively for a particular solar firm. Additionally, through their collaboration with equipment suppliers, solar manufacturers could access technological contributions made by competitors and research institutes, a benefit many believed outweighed the disadvantages of making proprietary technologies available to the competitors. In interviews, solar firms emphasized the risk of missing out on important technological innovations when not collaborating with equipment suppliers, a possibility that deterred them from trying to manufacture equipment in-house.[50] The CTO of a producer of thin-film solar modules summarized this point: "we often have internal debates over whether we want to be like Apple and follow a closed innovation concept, or whether we want to be more like IBM and use an open platform."[51] In the end, the firm decided to follow the IBM model in order to benefit from knowledge sharing through equipment suppliers.

Of course, once production lines had been installed in manufacturing facilities, solar firms continued to improve and alter purchased equipment in ways they did not always share with equipment suppliers. Yet at the core of technological innovation and the development of mature production technologies was a highly collaborative process in which equipment producers acted as a focal point for contributions made by a wide range of firms.

In Germany, such collaboration initially occurred domestically. As Germany's domestic wind and solar manufacturers stagnated in size and were quickly surpassed in production capacity by large-scale manufacturing facilities in China, demand for the latest wind turbine components and solar PV production equipment increasingly came from abroad. Small and medium-sized German manufacturers of production equipment possessed neither the financial support nor the technological capacities to establish large solar PV manufacturing operations. At the same time, suppliers' ability to develop manufacturing equipment required that they have access to engineering knowledge about mass production. Although German manufacturers had initially triggered the rise of domestic wind and solar suppliers, partners with complementary skills in mass

[50] Author interviews: CTO, German solar PV manufacturer, May 17, 2011; head of German operations, global equipment manufacturer, May 18, 2011; CEO, German equipment manufacturer, May 10, 2011; CTO, German solar PV manufacturer, May 23, 2011.

[51] Author interview, CTO, German solar PV manufacturer, May 23, 2011.

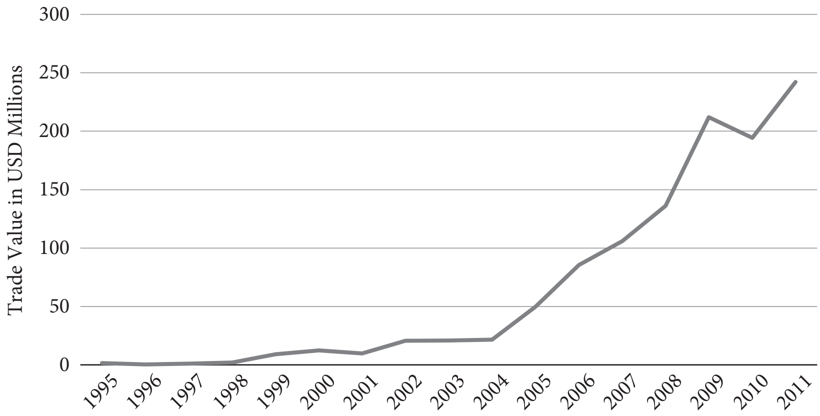

Figure 4.2 Germany's Exports of PV Equipment to China, 1995–2011
Source: UN Comtrade Database (no designated HS Code exists for PV equipment. As an approximation, I am using HS Code 854140 for "Photosensitive/photovoltaic/LED semiconductor devices" to track the growth in export value).

production—those with a need for the customization and small-batch production supplied by German SMEs—were increasingly located abroad. For German suppliers, the most important sources of such complementary skills were Chinese manufacturers (Figure 4.2).[52]

In the solar sector, the German manufacturer of solar production lines Centrotherm had already begun selling its products to Chinese customers by 2000. Similar partnerships quickly followed.[53] Between 2000 and 2007, the export quota for German PV equipment producers rose from 10 to 51 percent, most of it destined for Chinese factories.[54] In interviews, German equipment suppliers reported that the scale of production activities and access to large-scale financing for manufacturing plants afforded their Chinese partners the option of setting aside considerable resources to test new production equipment. Several Chinese firms constructed demonstration facilities with full test production lines—so-called Golden Lines—on which new technologies could be developed in collaboration with German equipment suppliers.[55] An analysis of 178 Sino-German technology collaborations between 2010 and 2012 conducted by the German Ministry for Research and Technology revealed more than a dozen such

[52] Rothgang, Peistrup, and Lageman 2011; Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010; Seemann 2012.
[53] Nussbaumer et al. 2007, 109.
[54] EuPD Research data cited in Fischedick and Bechberger 2009, 26.
[55] Author interviews: CEO, Chinese solar manufacturer, August 10, 2011; CEO, Chinese solar manufacturer, August 26, 2011; chief engineer, Chinese solar manufacturer, March 31, 2015; head of research and development, Chinese solar manufacturer, January 7, 2019.

interactions between German machine builders and Chinese renewable energy firms.[56]

More than mere customers, Chinese manufacturers became long-term partners in the development of production equipment for new solar PV technologies. In bringing new solar technologies from lab to market, China's producers willingly assumed considerable risks in the development and application of new production technologies and materials. The rapidly growing demand for new production lines often allowed equipment manufacturers to apply new production technologies first in China, relying on mass-manufacturing skills of Chinese solar firms throughout the commercialization process. Centrotherm and Schmid, the two German equipment suppliers, experimented with the development of production equipment for selective emitter cells but were unable to find German producers willing to partner on the commercialization of this new technology. In 2009, it was Chinese cell manufacturers who proved willing to collaborate with German suppliers on developing production equipment for elective emitter cells, adjusting their own production processes to test and optimize the new equipment with German engineers.[57] In 2010, Roth & Rau, another German equipment supplier, entered a similar agreement with a Chinese solar manufacturer to develop production equipment for a new thin-film technology.[58] Although Chinese manufacturers sourced basic production equipment from domestic suppliers, production lines for the latest PV technologies continued to be developed in Sino-German collaborations.[59]

China differed from other markets both in its aggregate demand for production equipment and because the scale of manufacturing activities in individual solar firms far exceeded those elsewhere. In 2010, Suntech, a single Chinese manufacturer, produced more solar modules than the top five German manufacturers combined.[60] Finding new ways to manufacture cheaper, faster, and at greater scale dominated the value proposition of China's solar firms. Working with equipment producers to achieve cost reductions on new production equipment constituted standard practice. In the words of the CEO of one of China's major solar cell manufacturers, "Solar PV is not so much a technology as it is a manufacturing business."[61] As China's solar firms took the lead in fully automating the production of wafers, cells, and modules, they continuously demanded new

[56] Grune and Heilmann 2012.

[57] Neuhoff 2012, 156.

[58] Roth & Rau 2010.

[59] Author interviews: managing partner, German solar PV equipment manufacturer, May 10, 2011; head of R&D, German solar PV equipment manufacturer, May 11, 2011; CEO of German solar equipment manufacturer, May 20, 2011.

[60] Germany Trade & Invest 2012, 26; Christopher Martin, 2010, "Suntech Boosts 2010 Solar Panel Shipments, Production Capacity on Demand," *Bloomberg*, August 18.

[61] Author interview, CEO, Chinese solar manufacturer, August 10, 2011.

production equipment and retrofits to existing manufacturing lines. Over time, Chinese solar producers thus became important partners to German equipment suppliers in the commercialization of new production technologies.[62]

In the wind industry, global turbine producers also partnered with German supplies in the commercialization of new technologies. As I mentioned earlier, entrants to the wind sector came from a variety of industries and included manufacturers of control systems and software, producers of manufacturing equipment and machine tools, and steel and composite materials firms. Many of the new supplier firms possessed technical expertise and production experience that could be applied to the manufacture of wind turbine components. For example, a firm that for decades had supplied gearboxes for large tunnel-drilling machines in the mining sector wanted to reduce its exposure to a declining mining industry in Germany. In 1992, the firm decided to develop the capabilities to produce gearboxes for wind turbines. In 1996, after four years of R&D, it was ready to enter mass production.[63] Similarly, a generator supplier for trains and industrial motors decided to diversify its product portfolio, and in 1998 began the development of a generator for the wind market.[64]

The growing wind industry supply chain permitted firms to restructure their manufacturing operations and to devote attention to core strengths. With the exception of Enercon, which to this day manufactures major components in-house in order to protect proprietary technologies, wind turbine manufacturers began to rely on the expertise of outside firms for the production and design of components such as gearboxes, generators, blades, towers, and control software. Turbine design and component specification remained with the turbine manufacturer. The production experience that supply firms had gathered in other industries contrasted sharply with that of younger, smaller, and less experienced wind turbine manufacturers. The introduction of new production technologies by supplier firms—including lean production practices borrowed from the automotive sector—reduced cost, permitted increased production scale, and enabled the fabrication of ever larger turbine designs without the technical failures that had plagued large-scale turbines in previous decades. In interviews, suppliers—particularly in the generator and gearbox sector—frequently pointed to lean production concepts such as just-in-time-production, continuous improvement (Kaizen), six sigma, and the Toyota production model in explaining their contribution to the wind energy sector.[65]

[62] Author interviews: CEO, Chinese solar manufacturer, August 10, 2011, CEO, Chinese solar manufacturer, August 26, 2011.

[63] Author interview, plant manager of German gearbox manufacturer, May 16, 2011.

[64] Author interview, plant manager of German generator manufacturer, May 17, 2011.

[65] Author interviews: plant manager of German gearbox manufacturer, May 16, 2011; plant manager of German generator manufacturer, May 17, 2011; head of European operations of global turbine manufacturer, May 19, 2011.

Over the course of the 1980s, the majority of debates within the wind industry on wind turbine design had been settled; and almost all manufacturers had converted to the Danish model: they built turbines with three blades positioned upwind that could be rotated along their own axis to adjust for variable wind speeds.[66] Aside from improving aerodynamics, the main remaining challenge was scale. Increasing the size of turbines meant exponentially larger loads and stresses on components, many of which could not be simulated well on computers. By combining the results of ongoing R&D efforts with new production methods and technical expertise contributed by third-party suppliers, turbine manufacturers successfully increased the average rotor diameter from 30 meters to 70 meters over the course of the 1990s, enlarging the area swept by the rotor blades by a factor of five and improving average generating capacity from 250 kW to 1500 kW by the year 2000.[67]

German suppliers became a resource for an expanding global network of wind turbine manufacturers, increasingly seeking collaboration with foreign partners and competing with supply firms elsewhere. Aside from Denmark, which had long played a pioneering role in wind energy development, and Spain, which began subsidizing the large-scale installation of wind turbines in the late 1990s, the most important foreign partners of German supply firms heralded from the United States and China.

In October 1997, Enron Corporation, an American electricity and natural gas company, purchased Tacke Windtechnik of Salzbergen. Enron had previously bought Zond, one of the few American wind turbine manufacturers remaining from the California wind boom in the 1980s, but experienced technical problems with the Zond turbine technology. The purchase of Tacke, which kept operating under its own name until GE took over Enron's wind business in the wake of Enron's accounting fraud scandal in 2001, gave Enron access to Tacke's turbine technology and supplier network. Enron retired the Zond turbine technology, and Tacke's 1.5 MW turbine became Enron's workhorse wind energy product.[68] GE retained its relationships with German suppliers, in particular with Eickhoff, which had manufactured the gearboxes for the 1.5 MW Tacke turbine, but also with Winergy and Bosch Rexroth, the other large German gearbox suppliers, and VEM Sachsenwerke, a generator firm. It remained an active member of the VDMA's wind chapter, participating in collaborative research activities to advance wind turbine designs.[69] Over time, GE began sourcing components from

[66] Musgrove 2010, chapter 6.

[67] Data from Bundesverband Windenergie. See http://www.wind-energie.de/infocenter/Technik. (accessed March 25, 2019.)

[68] Lewis 2013, 95; Windpower Monthly 1997. For additional details on GE's path into the wind energy sector, see Chapter 6.

[69] VDMA website, http://wind.vdma.org/en/article/-/articleview/599526 (accessed March 15, 2019).

other locations, adding suppliers from China (gearboxes and metal castings) and Brazil (blades).

The early model of collaborative relationships that originated in the German wind sector during the 1990s was now being applied globally and maintained through successive product generations. At the core, it brought together specialized expertise residing in companies around the world to develop and manufacture ever-larger turbine designs. According to GE's chief wind engineer at the time, Vincent Schelling, GE has to "put the knowledge in the gearbox manufacturers' hands. It would be better if we designed the gearbox and they built it, but we don't have all the knowledge." Likewise, Thomas Narath of Eickhoff stated, "Gearbox design is always a close cooperation between the turbine OEM (original equipment manufacturer) and the gearbox suppliers. OEMs usually deliver the main product specifications and a conceptual design which our engineering team further develops into a final product design." Narath added, it "also happens that gearbox development advancement points to a need for main chassis [i.e., wind turbine] design changes. This underlines the great value attached to regular exchange of ideas."[70] Cross-border collaboration of the kind described here between GE and Eickhoff was singularly important to the maturation of wind energy technologies starting in the late 1990s.

Around the time that the United States became an important market for German wind turbine suppliers, Chinese firms also made their first foray into the wind energy industry. From the beginning, Chinese producers relied on a global supply chain for wind turbine components and entered collaborative relationships with specialized suppliers. Just as German gearbox manufacturers worked with GE to improve gearbox and turbine designs without co-locating production, so Chinese firms also drew on expertise from abroad.[71] Global sourcing lowered the level of local content for China-assembled wind turbines to as low as 12 percent in 2002, though this percentage increased significantly as foreign suppliers set up manufacturing facilities in China and as domestic firms entered the industry over the course of the decade.[72]

Much as in the United States and Europe, these relationships with supply firms, joint venture partners, and license grantors were not a case of one-directional technology transfer. Although market access considerations and the complex regulatory environment in China certainly contributed to the willingness of foreign firms to enter joint development agreements, such relationships frequently resulted in multidirectional learning that benefited the foreign partner. According to an engineer working for a German wind turbine design

[70] de Vri es 2013; Windpower Monthly 2005a.
[71] Wang Z. 2010, 197–203.
[72] Wang Z. 2010, 68.

firm, the ability to learn from Chinese engineering teams as they reconfigured a product design for mass manufacturing constituted a key motivator for the German firm to jointly develop and commercialize a wind turbine, rather than simply selling a license.[73] Even under licensing agreements, however, foreign firms found avenues to learn from Chinese wind turbine manufacturers. In the case of one generator licensed from a German supplier, for instance, the Chinese firm improved the original design through reconfiguration of the product architecture, so much so that it licensed the improved generator design back to the German firm.[74] In other cases, foreign firms tried to replicate capabilities in scale-up and mass manufacturing outside of formal relationships with Chinese partners, setting up their own manufacturing facilities in China and poaching engineers from their Chinese competitors.[75]

For Chinese wind turbine manufacturers, an expanding Chinese domestic supply chain frequently complemented relationships with suppliers from Germany and elsewhere. While Chinese suppliers developed capabilities focused on cost, scale, and ease of manufacturability, German suppliers retained expertise in producing components for prototyping, small-batch production, and commercialization. Engineers for wind turbine manufacturers indicated that they were relying on German suppliers in early stages of product development. For large scale production, however, they switched to local partners, as innovation in the scale-up to mass production does not center around technological improvement, but rather on changing product designs to accommodate lower-cost manufacturing processes and materials.[76]

A long-term collaborative relationship between the German turbine firm Vensys and the Chinese wind manufacturer Goldwind illustrates this dovetailing of skills. Lacking capabilities in mass production, Vensys entered into a partnership with Goldwind to commercialize a novel direct-drive technology that Vensys had developed. Direct-drive technology eliminates the need for a gearbox, which is one of the costliest turbine components and notoriously prone to technical problems. Vensys first licensed its technology to Goldwind in 2003, having previously only manufactured a small number of prototypes. From that point on, commercialization and the preparation for mass manufacturing took place in China. This was the case for a first 1.5 MW model as well as

[73] Author interview, CEO of German engineering firm, May 20, 2011.
[74] Author interview, plant manager of German generator manufacturer, May 17, 2011.
[75] Author interview, head of China operations, European wind turbine manufacturer, September 22, 2011.
[76] Author interviews: plant manager of German generator manufacturer, May 17, 2011; head of China operations, global wind turbine manufacturer, January 21, 2011; head of China operations, European turbine manufacturer, October 28, 2010; head of China, German wind turbine design firm; March 27, 2017; head of R&D, Chinese generator manufacturer, January 4, 2016.

subsequent product generations.[77] By 2008, the relationship between German and Chinese engineers had become so central to the development of the technology that Vensys sold a 70 percent stake to Goldwind over a number of other bidders. According to Vensys, Goldwind was chosen as a partner precisely for its capabilities in commercialization and large-scale production. Upstream R&D for Vensys's new turbine generations has remained in Germany, but the design changes to improve cost and manufacturability take place at the Goldwind facilities in China.[78] The two firms have maintained this division of labor nearly fifteen years after first establishing a relationship.[79]

Manufacturing Institutions and Green Energy Innovation

If collaboration allowed firms from Germany's Mittelstand to apply their existing skills in customization, it also allowed them to repurpose existing institutions of the domestic economy. These legacy institutions of the German manufacturing economy retained value in wind and solar industries precisely because they no longer had to support the full range of activities required to invent and commercialize new technologies domestically. It is important to note here that these domestic institutions formed a particularly good fit for the strategies of those small and medium-sized German firms that had found ways to collaborate with Chinese manufacturers. In the solar industry, German manufacturers that tried to compete with China directly struggled like their American counterparts to raise the financial capital to build manufacturing plants that could reach the necessary scale economies. Collaboration with Chinese firms was also difficult for German manufacturers of wind turbines such as Nordex, which established relationships with local partners but were, over time, largely driven out of the Chinese market. Local competitors both underbid German firms on price, but local procurement rules also created additional obstacles for foreign manufacturers of wind turbines in China. Domestic institutions of the German economy offered little protection against these broader obstacles to competing in the Chinese wind power market.

Despite the eventual success of small and medium-sized firms, Germany's renewable energy legislation contained few provisions specifically targeting the development of dense supplier networks for wind and solar sectors. Initial renewable energy laws were not expected to lead to the development of large domestic industrial sectors. Subsequent changes to the Feed-in Law and its successor, the

[77] Vensys sold similar licenses to manufacturers in other markets but was not as closely involved in production and scale-up with its other licensees.
[78] See Peters 2009; Vensys 2012.
[79] Vensys 2017. Author interview, Beijing, March 23, 2015.

EEG, adjusted tariffs for different sources of energy to account for technology improvements. Specific provisions for small and medium-sized firms were absent from later generations of renewable energy legislation, as well. Neither the original Feed-in Law nor the EEG included local content requirements or loan programs for German wind and solar suppliers. For manufacturers of solar panels and wind turbines, grants of up to 50 percent of investment costs for capital-intensive manufacturing plants were available as part of special development policies for eastern Germany. Most solar PV manufacturers subsequently chose to locate in Berlin, Brandenburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt, and Thuringia.[80] Such programs were of little use to existing small and medium-sized producers of components and production equipment—they remained deeply anchored in local supplier networks and needed to retool extant production facilities.

Just as demand-side legislation provided little concrete assistance for firms seeking to enter renewable energy sectors, federal R&D funding for energy technologies also bypassed small and medium-sized firms. A series of federally funded energy research programs (*Energieforschungs-programme*), each of which offered a specific substantive theme within the field of energy technologies, and which ran between three and ten years' duration, dispensed EUR 1.81 billion for renewable energy research between 1990 and 2005.[81] Though they promoted advanced wind and solar research in Germany, these programs primarily targeted large firms and research institutes such as the Fraunhofer centers. An evaluation of research funded through the third Federal Energy Research Program, for example, which ran from 1990 until 1996, included projects conducted by industrial laboratories at Siemens, Bayer, Wacker Chemical, and Deutsche Aerospace, but revealed little participation from smaller firms.[82]

The situation improved by the time the 2000 EEG created large-scale demand for solar energy products. The firms carrying out these research activities now began to reflect the diversity of suppliers in wind and solar sectors. Among manufacturing firms that received federal R&D funding for renewable energy research, machine tool producers and manufacturers of electrical equipment (*Elektrotechnik*) constituted the two largest groups; they made up 13 percent and 11 percent of firms, respectively.[83] Despite the shift in federal research programs

[80] Grants comprised incentives available through two separate programs: the Joint Task Program for the Promotion of Industry and Trade (*Gemeinschaftsaufgabe*), available in all of Germany depending on local economic conditions, and the Investment Allowance (*Investitionszulage*), designed specifically as part of the economic recovery program for Eastern Germany. See Germany Trade & Invest 2013.

[81] Bundesministerium für Wirtschaft und Arbeit 2005, 22; Prognos AG et al. 2007, 14; Sandtner, Geipel, and Lawitzka 1997, 260.

[82] Forschungszentrum Jülich 1993.

[83] Prognos AG et al. 2007, 204–6.

to include small and medium-sized suppliers, federal R&D funds played only a small role in helping firms enter and compete in wind and solar industries. More than 70 percent of firms receiving federal funds for renewable energy R&D stated that they were already active in renewable energy sectors prior to participating in the programs. Forty percent of firms indicated that federal R&D funds were used to bolster existing R&D activities or had no influence on firm strategy at all. Fewer than 30 percent of firms used federal funds to enter new industries and markets.[84] For the majority of firms, federal R&D support thus at best supplemented existing R&D infrastructures and resources.

Instead, supply firms made extensive use of resources, networks, and industrial practices familiar to them from prior activities. Broad macroeconomic institutions, established long before the emergence of wind and solar industries, shaped firms' strategies as they entered global renewable energy supply chains. The development of wind and solar supply chains contrasts with expectations that economic competition in highly globalized sectors would threaten the survival of such institutions.[85] The ability of firms to insert themselves into global chains depended on their reliance on, and repurposing of, legacy institutions. This self-insertion also made firms in emerging industries part of broader political coalitions in support of such institutions. Firms participated in these existing institutional arrangements not because they lacked alternatives, but because these institutions provided resources for the specialized learning strategies they chose to pursue. Three sets of institutions in particular were repurposed by renewable energy firms.

First, wind and solar suppliers highlighted the importance of collaboration between their R&D engineers and their manufacturing workforce in developing technologies for wind and solar industries. For many products, such collaboration and bidirectional exchanges were not just critical to improving the manufacturability of new designs, but they also formed the core of trial-and-error based development processes that could not easily be modeled using computer-aided design (CAD) technologies. To foster collaboration between R&D and manufacturing staff, firms located their R&D teams inside or in close proximity to manufacturing operations. Almost all German wind and solar supply firms retained production activities close to their headquarters.[86]

In the opinion of executives, the skills and training of their employees—R&D engineers as well as manufacturing staff—was as important to product development as the co-location of such activities (if not more so). The recruitment of highly skilled production workers and their continuous professional

[84] Prognos AG et al. 2007, 262.
[85] Hassel 2014; Thelen 2014.
[86] Germany Trade & Invest 2010, 2011c.

development remained essential to the overall success of the operation. Without the appropriate skills and training opportunities, workers would be unable to identify problems within the product development process, suggest appropriate technical solutions, and implement these solutions together with R&D engineers. The production and research activities in many small firms were so closely linked that some did not formally differentiate between R&D teams and their manufacturing staff. According to the director of R&D for one solar equipment supplier, all production staff had gone through industry-specific training in Germany's vocational training system, and most engineers had also completed an apprenticeship before entering university. Despite such rigorous practical training for production workers and R&D engineers, tacit knowledge acquired on the job was also considered critically important. "CAD and similar programs are unable to simulate the conditions that we find in our machines," the R&D director said. "So what we do instead is to build the machine and then test it, tweak the parameters, and then test it again. A lot of this process is tacit knowledge. Our capital is the experience of our staff, and they didn't gain this [experience] in university, they learned it on the job."[87]

In finding, training, and retaining skilled workers, firms reaped the benefits of broader labor market institutions. Firms collaborated through interfirm networks and industry associations, maintaining programs for highly industry-specific vocational training in the form of apprenticeships and, increasingly, dual degree programs (*duales Studium*). The latter offered joint practical training and a university education at vocational universities (*Berufsakademie*). Together, firms ensured that individual companies continued to contribute to such programs by offering traineeships and extracted financial support from Länder and federal governments.[88] These skills and training institutions did face challenges: firm participation in collaborative efforts declined over time, leading to calls for an "apprenticeship tax" (*Ausbildungsplatzabgabe*) for firms unwilling to contribute; and growing numbers of high-school graduates were shut out of the vocational training system altogether as demand for apprenticeships continued to outstrip supply. From the perspective of manufacturing firms, however, the vocational training system continued to work well.[89] In a 2012 survey of more than 14,000 firms conducted by the Association of German Chambers of Commerce and Industry (DIHK), manufacturers in machinery and equipment sectors planned to offer permanent positions to 80 percent of their apprentices;

[87] Author interview, head of R&D, solar PV equipment manufacturer, May 11, 2011.

[88] Culpepper 1999; Ebner, Graf, and Nikolai 2013; Minks, Netz, and Völk 2011, iii–v. On dual degree programs, see Ebner, Graf, and Nikolai 2013; Graf 2013; Streeck 1989, 37–38. For a history of the vocational training system with examples specifically from the metal-working industry, see OECD 1994.

[89] On changes in collaborative institutions, see Streeck 2009, esp. chapter 4.

84 percent of firms indicated that ensuring access to skilled labor was their principal motivation for contributing to the vocational training system.[90]

At the same time, strong worker representation and employment protection legislation slowed employment turnover, even as a series of labor market reforms permitted more flexible employment contracts.[91] Barred from organizational restructuring through large-scale hiring and firing, German manufacturers instead invested in training their existing workforce, taking the onus on themselves to meet the skill requirements of new R&D and production activities.[92] To retain experienced production staff during recessions and seasonal downturns, federal short-time labor policies (*Kurzarbeit*) subsidized wages through policies akin to part-time unemployment support.[93] During the 2008–2009 economic crisis, a survey conducted by the VDMA showed that despite a 25 percent drop in orders, employment among VDMA member firms only shrank 5 percent, in large part due to short-time labor subsidies.[94] In 2009 alone, the federal government spent EUR 5 billion on short-time wage subsidies for more than one million employees.[95] In short: by offering resources for sector-specific training and by ensuring long employment tenures, labor market institutions established well before the rise of large-scale renewable energy industries had a lasting impact on the type of R&D activities that firms entering the wind and solar sectors could—and did—pursue.

Second, existing *financial institutions and legacy firm ownership patterns* allowed firms to compete in the wind and solar industries. Germany's bank-based financial system offered few opportunities to fund the commercialization of new technologies through venture capital. Government attempts to create a venture capital sector had failed repeatedly, as funds suffered losses and financiers shied away from investing in new firms and technologies.[96] Of venture capital invested in Germany in 1996, for instance, only 7 percent supported seed and start-up funding; more than 60 percent went to investments in large, established firms.[97] Even though the federal government injected nearly EUR 1.5 billion in venture capital funds between 2005 and 2006, overall venture capital activity remained at 0.06 percent of GDP, compared to 0.8 percent in the United States.[98] In 2011, a little more than one-third of venture capital financing came from (mostly

[90] Deutscher Industrie- und Handelskammertag 2012, 29–30. For similar results reported in a broader survey across industries, see Wenzelmann, Schönfeld, and Dionisius 2009.
[91] OECD 2012, 43.
[92] Culpepper 2001; Estevez-Abe, Iversen, and Soskice 2001.
[93] Bosch 2011; Eichhorst and Marx 2009; OECD 2012, 47.
[94] Author interview, VDMA Stuttgart, May 31, 2012.
[95] "Kurzarbeit rettet mehr als 300 000 Arbeitsplätze," *Handelsblatt*, October 1, 2010.
[96] Becker and Hellmann 2003; Mayer, Schoors, and Yafeh 2005.
[97] Giesecke 2000, 215.
[98] Röhl 2010.

government-funded) organizations headquartered in Germany.[99] Not surprisingly, a number of studies identified the financial system as the main obstacle to R&D activities of young, innovative firms in high-technology industries.[100]

The scarcity of venture capital funding presented fewer barriers to existing firms seeking to diversify into wind and solar supply chains. Because, for most firms, developing wind and solar components amounted to a variation of their existing R&D practices, many could rely on funding sources they had used in the past. In doing so, some firms benefited from long-term relationships with local credit unions, which agreed to provide loans after demand-side subsidies had created stable market conditions for renewable energy sectors. Other firms reported either supplementing such loans with retained earnings or completely relying on internal funds for R&D activities. Among the firms interviewed for this project, only one CEO mentioned floating a bond to finance the construction of a new production facility, adding that "financing has never been an issue for us."[101] Wind and solar suppliers reflected broader trends among small and medium-sized businesses: a 2010 survey among German firms that had received federal R&D assistance found that nearly 69 percent of R&D activities were funded through earned income or retained earnings. Only 6 percent of R&D funds came from bank loans, with the rest coming through grants and subsidies.[102]

Although loans and retained income provided relatively modest sums for R&D projects, particularly when compared to the venture capital financing available to high-technology firms in the United States and Israel, these funds had few constraints attached. They allowed firms to pursue long-term development strategies, and this mattered greatly. Taking up to four years to develop a complex equipment or component prototype was not uncommon, and many firms could not generate revenue from investments in renewable energy R&D until years after they made the initial decision to enter the wind and solar supply chains. Local credit unions, familiar with firms' R&D practices, thus provided essential bridge funding. As credit unions stepped forward to finance long-term development projects with firms that they knew, the income that these firms generated from activities in other sectors could be used to cross-subsidize projects in ways that were simply not possible for newly established firms.

The high share of family-controlled firms in Germany, particularly among small and medium-sized businesses, further assisted firms seeking to diversify into new sectors through complex, long-term R&D projects. Over the past

[99] Zademach and Baumeister 2013. For 2011, the Zademach and Baumeister report even lower venture capital activity in Germany than Röhl, at 0.028 percent of GDP.

[100] See, for instance, Kreditanstalt für Wiederaufbau 2006; Zimmermann and Hofmann 2007.

[101] Author interview, CEO of solar equipment manufacturer, May 20, 2011.

[102] Belitz, Eickelpasch, and Lejpras 2012, 102.

twenty-five years, the share of family-controlled businesses among Germany's 100 largest firms remained relatively stable at around 20 percent, with significantly more family control among smaller businesses.[103] In 2002, more than two-thirds of firms with fewer than 500 employees were sole proprietorships.[104] In interviews, the managers of wind and solar suppliers repeatedly emphasized how their owners' commitment to preserving the businesses for future generations served to motivate diversification into emerging industrial sectors. That same commitment also made it strategically possible for these firms to reinvest profits in R&D projects. The plant manager at a German generator supplier explained that the family owners had not withdrawn funds from the business since the early 1990s, instead allowing the firm to reinvest its profits into the firm's diversification from ship building into the wind turbine sector.[105] The CEO of an automation equipment manufacturer discussed entering the solar business to reduce overexposure to the automobile industry by investing retained earnings when he took over the family business from his father.[106] Long-term planning horizons created a willingness to forgo immediate profits in favor of future returns, an outlook that sharply differed from short-term strategies driven by the need to maximize shareholder profits.[107]

A third set of legacy institutional tools *helped firms access capabilities and resources outside the firm*. The development of new technologies, components, and production equipment for wind turbine and solar PV industries posed challenges particularly to small and medium-sized firms. Limited R&D resources, which had long prevented smaller firms from absorbing the new technologies generated by publicly funded R&D programs, constrained these smaller firms' ability to develop new technologies, components, and equipment for emerging industrial sectors.[108] For all the skills such firms had historically acquired—proficiencies in the application of core technologies, as well as competencies in managing long-term, complex, and trial-and-error-intensive R&D processes—the development of products for wind turbine and solar PV supply chains required that they adopt new materials, components, production processes, and industry standards. Particularly among smaller, more specialized firms, the capabilities required to master such product development processes could not all be found or maintained within the four walls of the firm.

[103] Lubinski 2011, 705.
[104] Günterberg and Kayser 2004, 12.
[105] Author interview, plant manager, generator supply firm, May 17, 2011.
[106] Author interview, CEO, solar equipment manufacturer, May 10, 2011.
[107] For an analysis of the impact of financial markets and shareholder value considerations on American manufacturing firms, see Davis 2009. For a discussion of the long-term planning horizons of German family-owned manufacturing firms, see Berger 2013b, chapter 5.
[108] Belitz, Eickelpasch, and Lejpras 2012, 51; Bruns et al. 2011, 55–56.

The role played by external capabilities is perhaps best observed in the process of integration, in which firms strategically chose new technologies and associated capabilities to complement their existing skills. At the same time, albeit less visibly, other modes of industry entry and subsequent product development processes also required competencies that firms did not possess in-house. Their solution? In order to master specifications for new components, find materials capable of withstanding the stresses of new applications, and use novel production processes, firms turned to external partners. For small and medium-sized suppliers, such partners in many cases were larger wind turbine and solar PV manufacturers, initially domestically and subsequently in global supply chains. Other firms turned to universities, research institutes, and contract researchers for help. In a situation somewhat unique to Germany, however, many small and medium-sized firms also collaborated with one another other, pooling resources and sharing capabilities across sectoral boundaries to meet product development challenges.

In their reliance on external capabilities, small and medium-sized German firms in the wind and solar sectors built on a long tradition of collaborative R&D in German industry. Starting in the late nineteenth century, German manufacturing firms organized themselves in research networks to find suitable partners for joint R&D projects. By 1939, just prior to World War II, nineteen such research networks had been created. By 2011, 101 industrial research associations were facilitating collaborative research activities among member firms.[109] Of the 101 associations active in 2011, 91 focused on a single industry, including machinery and equipment manufacturing; chemicals, plastics, and rubber sectors; and the production of energy generation equipment. Ten research associations had an interdisciplinary focus. By 2011, a total of 50,000 firms had organized themselves into such associations.[110]

Although research associations relied on industry associations to find members, set up collaborative projects, and at least partially fund research through member dues, the state played a critical role in encouraging these joint efforts. In 1954, a Federation of Industrial Research Associations (*Arbeitsgemeinschaft industrieller Forschungsvereinigungen*) was established to facilitate interdisciplinary projects across sectoral boundaries and to represent the interests of research associations to the government. In the same year, the Federal Ministry of Economic Affairs began supporting collaborative research projects through subsidies and research grants.[111] Initially, the main justification for federal support

[109] Rothgang, Peistrup, and Lageman 2011, 398.
[110] Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 79; Rothgang, Peistrup, and Lageman 2011, 400–401.
[111] A number of Länder governments later began to also fund collaborative industrial research, complementing federal policies. Rothgang, Peistrup, and Lageman 2011, 398.

for industrial collaborative research (*Industrielle Gemeinschaftsforschung*) was to level the playing field for SMEs, which were assumed to suffer from competitive disadvantage in an economy increasingly populated by large diversified companies. Over the years, however, as SMEs ceased to be regarded as structurally disadvantaged legacies and came to be understood as integral parts of Germany's innovation economy, the reasoning behind continued support for collaborative research shifted to the creation of spillovers for the broader economy from encouraging R&D in SMEs.[112]

Despite these shifting motivations for state involvement in collaborative research, the policies and institutional resources provided to foster such collaboration remained relatively stable over time. At the core, state support for industrial collaborative research (ICR) meant R&D funding for research projects that included partnerships among several firms and research institutes.[113] Participating research institutes included universities, industry research institutes funded by industry associations, and nonuniversity institutions such as Germany's large number of Fraunhofer and Max Planck Institutes. Funded projects were by definition precompetitive: to qualify for funding, projects needed to focus on technologies and materials with multiple potential applications in a range of future products, rather than targeting the development of commercializable products. The results of ICR projects were shared among all members of participating research associations, although direct involvement in the project was often necessary for firms to be able to use these research findings.[114]

In contrast to other federal R&D funding schemes, firms designed these ICR projects without thematic requirements.[115] As members of research associations, firms could suggest ideas for new projects at association meetings, find partners, and identify research institutes with expertise in solving the particular problem at stake. In finding partners for R&D collaboration, firms explicitly targeted colleagues with different technical capabilities, R&D resources, and priorities in product development.[116] Each project formed a planning group of participating firms, and that group defined the exact scope of the R&D undertaking, jointly submitting

[112] For a full discussion of the motivation behind such programs and changes in the justification of subsidies for collaborative research over time, see Eckl and Engel 2009; Karmann-Proppert 2017; Rothgang et al. 2011.

[113] In addition to the programs for industrial collaborative research, other government R&D programs provided bonus funding for projects involving several partners. For instance, ZIM (Zentrales Innovationsprogramm Mittelstand), which provided R&D funding targeted specifically at SMEs, dispensed R&D grants to individual firms but increased funding for projects that involved multiple partners or entire clusters of firms. Author interview, department head, Federal Ministry of Economics and Technology, May 24, 2016.

[114] Author interview, director of research association in the machinery and equipment sector, May 25, 2016.

[115] Eckl and Engel 2009, 4.

[116] For detailed results of a survey of R&D intensive firms engaged in collaborative projects, see Windolph 2010, 7. For results specifically for the PV industry, see Seemann 2012, 353.

applications for federal funding under one of the ICR programs. In addition to government grants, these associations funded projects through membership fees; and individual firms were expected to contribute funds, R&D staff, and equipment. In some cases, donations by larger firms made more costly R&D projects possible.[117] Industry contributions allowed relatively modest sums of federal government support to initiate much larger R&D efforts. In 2008, for instance, EUR 123 million in federal subsidies went to ICR funding; and a total of EUR 2.6 billion has been dispensed since the inception of ICR programs in 1954. Estimates suggest that as little as 15 percent of funds spent on ICR projects came from government coffers.[118]

As firms from Germany's traditional manufacturing sectors began to create products and components for the rapidly growing wind and solar industries, they relied on ICR programs to solve concrete technical challenges; and they benefited from relationships with other firms and research institutes established through previous participation in collaborative projects. Even in the absence of research associations established specifically for the renewable energy sectors, firms accessed federal ICR funding and entered interdisciplinary research networks through participation in one of the many associations set up for existing industrial sectors. Within this open, bottom-up structure for research collaboration, shaped largely through the input of individual member firms, partnerships in the wind and solar sectors manifested in a wide range of forms.[119]

For some firms, collaboration simply meant working closely with end-customers for products and components.[120] Such relationships initially focused on wind and solar manufacturers in Germany, but increasingly they began to draw in international partners, as sizable renewable energy industries emerged in China and elsewhere. Other firms used ICR networks to fund collaboration with research institutes or used contacts from past joint projects to independently facilitate collaboration with external research centers. The CEO of a manufacturer for production equipment for solar modules, for instance, recalled using such ties to establish a cooperation with the Fraunhofer ISE in Freiburg.[121]

In some cases, firms participated in projects set up by associations from other sectors. For example, the director of a research association for the machinery and equipment sector established by the VDMA described how

[117] Author interviews: director of research association in the machinery and equipment sector, May 25, 2016; department heads, Federal Ministry of Economics and Technology, May 24 and June 4, 2016. See also Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, chapter 3.

[118] Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 399.

[119] Bouncken 2004; Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 75; Seemann 2012.

[120] Braun 2001.

[121] Author interview, CEO, solar module equipment manufacturer, May 10, 2011.

small suppliers and a multinational wind turbine manufacturer participated in interdisciplinary projects to develop new alloys that none of the partners could have created on their own.[122] In other cases, firms formed still larger clusters, seeking funding both through regional development programs for high-tech clusters (set up by the Federal Ministry of Education and Research) and through traditional ICR programs for individual projects conducted within the group. In Solarvalley Mitteldeutschland, the cluster that included a number of ill-fated solar PV manufacturers, some ninety-eight collaborative projects conducted by members along the entire solar PV supply chain received state research support.[123]

In a survey of 60 firms in the solar PV industry, 72 percent of firms that had received public support for collaborative research stated that they would not have participated in the absence of government subsidies. Seventy-four percent of all respondents reported participating in collaborative R&D efforts.[124] Active research associations for a wide range of industrial sectors and government subsidies for collaborative R&D both encouraged and maintained collaborative practices in Germany's manufacturing industries—practices retained by small and medium-sized firms as they entered the emerging wind and solar sectors.

Small and medium-sized firms from Germany's legacy industries responded to policies for renewable energy industries by building on existing capabilities and by using institutions established in support of sectors that had long lain at the core of the German economy. Rather than abandon such institutions when entering new economic sectors, firms repurposed and applied these institutions to the global wind and solar sectors. In doing so, they used Germany's distinct institutional infrastructure to compete in highly globalized sectors and expanded the political coalitions behind such institutions beyond the areas that had originally backed them. Globalization did not threaten the existing fabric of the German manufacturing economy. Instead, specialization and repurposing explain why globalization enabled Germany's specialization in customization to over time.

Conclusion

In the shadow of the high-profile bankruptcies of a number of German solar manufacturers—precisely the type of firms that government policy had

[122] Author interview, director of research association in the machinery and equipment sector, May 25, 2016.
[123] Author interview, CEO, solar PV supplier, May 18, 2011. For information on individual projects conducted within the cluster, see http://www.bmbf.de/en/20870.php (accessed September 10, 2019).
[124] Seemann 2012, 355–59.

supported when it prioritized invention in early R&D funding programs—suppliers of automation equipment and complex components created dense networks of firms focused on customization. The ability to repurpose core strengths for new applications within an environment of collaborative advantage lent specialized suppliers remarkable flexibility.[125] Collaborative advantage in global renewable energy sectors allowed these suppliers to contribute skills to a wide range of product development processes with partners from around the world, making them increasingly independent from the fate of local assemblers.

I have argued in this chapter that collaboration with manufacturers from China enabled firms to pursue competitive strategies that aligned with legacy institutions of Germany's domestic economy. Labor market and training institutions, the German financial system, and state support for collaborative research supported SMEs as they pivoted to new industrial sectors. The trajectory of industrial development I have described points toward an interactive evolution of both firm specialization and institutional change. Firms entered new sectors in response to new opportunities for collaboration in global supply chains and found their competitive niche by repurposing domestic institutions and existing skills for application in new sectors. The fact that their turn to customization mirrored the historic strengths of the German economy obscures the central role of learning and industrial change in this narrative. Firms were not simply borrowing from existing knowledge. They were actively learning and reinventing themselves.

The strong response of Mittelstand firms to state industrial policies shaped the trajectory of renewable energy policy. It underlined the divergent interests of firms that could exploit collaborative advantage and firms seeking to compete with China head-on. Highly dependent on an open economy, wind and solar suppliers used their political connections to maintain support for domestic renewable energy markets while preventing trade barriers and other obstacles to collaboration. Between 2005 and 2009, installed solar capacity doubled every two years. Despite its perpetually gray skies, Germany now accounted for nearly half of the world's installed solar PV modules, most of which they imported from China. This breakneck development speed raised concerns about the increasing cost and long-term sustainability of domestic renewable energy markets.[126]

These networks of wind and solar suppliers, organized in politically well connected industry associations such as the VDMA, were vocal in their support

[125] Suppliers were, of course, also not immune to industry crises and suffered during broader downturns in global renewable energy industries, including during the 2009 financial crisis and other periods of overcapacity and stagnation in wind and solar sectors.

[126] Earth Policy Institute 2020.

of continuing policies that favored domestic renewable energy markets. In addition to industry associations and environmental groups, Länder governments in regions with renewable energy manufacturing and deployment now lobbied on behalf of local industries.[127] The decentralized nature of these renewable energy supply chains helped broaden the coalition of subnational governments opposed to drastic subsidy cuts and willing to block such legislation in the Bundesrat, Germany's second chamber.

Because of this widespread policy support, successive government administrations at the federal level struggled to change the legislation. After the 2005 federal election, the Conservative/Social Democratic coalition government left the tariff schedule unchanged. In 2009, when a new Conservative/Liberal coalition attempted to cut subsidies for solar energy in a revision to the EEG, several Länder governments blocked the amendment in the Bundesrat to protect the local economy.[128] The federal government again tried to reduce subsidies in 2012, provoking protests by subnational governments and widespread demonstrations in front of government offices in Berlin.[129] Both instances resulted in a compromise between Länder governments seeking to protect local firms and the federal administration. Feed-in tariff rates were reduced, but not by nearly as much as requested by the federal government.[130] The core principle of the feed-in tariff remained unchallenged until 2014, however, and electricity generated from wind turbines and roof-top solar installations continued to receive above-market compensation.[131]

Despite their successful campaign to protect the feed-in tariff legislation, the interests of original equipment manufacturers and the domestic supply industry increasingly diverged. The Mittelstand had long been instrumental to maintaining and shaping industrial policy for the wind and solar sectors in Germany. Firms' geographical spread and their powerful industry organizations added significant political weight to the broad coalition of renewable energy supporters. As the production of solar panels and wind turbines stagnated in Germany and suppliers increasingly depended on global markets, they used their political clout to defend positions that no longer aligned with domestic OEMs. In 2012, German manufacturers of solar panels called for trade barriers to prevent import competition from Chinese competitors, filing antidumping cases domestically and with the European Union.[132] Protests by Germany's component suppliers and manufacturers of production equipment, who vehemently

127 Grewe 2009.
128 For a detailed account of the negotiations leading up to the 2009 revision of the Renewable Energy Sources Act, see Dagger 2009.
129 Ismar 2012; Theile 2012.
130 Gawel and Klassert 2013.
131 Schwenn, Rossbach, and Heeg 2012.
132 Bullis 2012.

and ultimately successfully opposed plans to enact antidumping measures, stemmed from the recognition that their contributions to solar technology development now relied on collaboration with global partners.[133] Not only did wind and solar suppliers from Germany's Mittelstand use their political clout to maintain policy support for domestic renewable energy markets, but they were also instrumental in ensuring that these markets remained open to their Chinese partners.[134]

[133] Wessendorf 2013.
[134] Meckling and Hughes 2017.