2

Varieties of Innovation in Wind and Solar Industries

On October 23, 2009, in a speech celebrating the 150th anniversary of the Massachusetts Institute of Technology (MIT), United States President Barack Obama warned that the United States risked falling behind in the "global clean energy race." "From China to India, from Japan to Germany," he argued, "nations everywhere are racing to develop new ways to produce and use energy. The nation that wins this competition will be the nation that leads the global economy."[1]

A few days after Obama's speech, the *Financial Times* and *Wall Street Journal* both ran articles about the disappointing US competitive position in global renewable energy sectors. Their articles relied in part on a policy report published by an Oakland-based energy think tank, The Breakthrough Institute, which cautioned that in clean energy industries, China was "poised to replicate many of the same successful strategies that Japanese and South Korean governments used to establish a technological lead in electronics and automobiles. Those governments supported nascent companies with low-interest loans, industry-wide R&D, government procurement, and subsidies for private purchase of advanced technologies."[2] President Obama and the *Wall Street Journal* rarely agreed on much, but they were in lockstep on the notion of a global clean energy race. They also drew surprising parallels between the era of rapid economic development in postwar East Asia and the current period of investments in wind and solar power.

Their statements exemplified a view of national competitiveness and technological innovation that was widely held in media and policy circles, both in the United States and internationally. This view sees the world's large economies as engaged in a race to dominate clean energy sectors; in this paradigm, winning such a race would require large government investments to build domestic industry. Nations would have to be proficient both in innovation and production to achieve and maintain their lead. These expectations were neither new nor unique to clean energy sectors. They built on the experiences of the postwar global economy, when large conglomerate firms, capable of inventing,

1 The White House 2009.
2 Harvey 2009; Johnson 2009.

commercializing, and producing goods, formed the engines of technological innovation and national competitiveness.

As I argued in the previous chapter, the reorganization of the international economy since the 1970s demands a new understanding of how technological innovation is organized across firms and a recasting of state-business relations in the process of creating innovative industries. The growth of global clean energy industries, which I detail in this chapter, provides the empirical context for this argument. The chapter rules out two common explanations for the persistence of distinct national profiles in the global economy: that governments pursued different industrial policy goals, and that they did so using different industrial policy tools.

In the pages that follow I make two central points. First, I show that a common political logic led governments in China, Germany, and the United States to converge on similar policy goals and industrial policy tools. Public investments in renewable energy began as state initiatives to support scientific discovery; the scientific rationale behind such early support for renewable energy technologies was not immediately connected to expectations of economic results. That changed when improvements in wind and solar technologies opened up new prospects of economic growth and industrial development. As policymakers discovered the economic potential of renewable energy sectors, public investments in R&D and subsidies for the deployment of clean energy technologies became easier to justify politically—these investments now promised local economic returns, particularly in the form of manufacturing jobs. Governments subsequently combined policies to support R&D with demand subsidies, often explicitly tied to local content regulations and other means to attract local industrial activity. The need to provide political justification for public investments in renewable energy sectors yielded similar growth and employment-focused industrial policies across the three countries, irrespective of the underlying political system.

Second, I chronicle the central outcome I explain in this book: the persistent and consequential divergence of national industrial specializations in spite of these policy similarities. Even as governments pursued comparable industrial policy goals, their efforts yielded distinct national profiles in global industries. In the early 2000s, just after China's World Trade Organization (WTO) accession accelerated changes in the organization of many global industries, firms in China, Germany, and the United States chose different technological specializations and competitive strategies for participation in emerging wind and solar industries. The ascent of global clean energy was not, in fact, a race: these national profiles in global renewable energy sectors proved, on the whole, to be complementary, as different types of firms entered wind and solar sectors in each location and pursued distinct competitive strategies.

Scholars of globalization and comparative capitalisms have long been concerned with the ability of states to protect distinct political economies from the forces of liberalization in the international political economy. I show here that such concerns are overstated. The persistence of national industrial profiles challenges the notion that government policies alone are the protectors of national differences and shows that global economic pressures do not, in all cases, chip away at the ability to organize distinct domestic industrial practices and competitive strategies. This is especially true when we recognize that cross-national differences in wind and solar sectors endured even as governments hoped to converge on similar industrial profiles in global renewable energy industries.[3]

Renewable Energy Policies in the Postwar Decades

In making the case that renewable energy policy transitioned from a scientific to a growth and employment rationale, I distinguish between policies aimed at scientific exploration and green industrial policies that explicitly targeted growth and structural economic change. I use the phrase "industrial policy" here to refer to state initiatives whose primary goal is to increase economic output through changes to the composition of domestic economic activity. Industrial policies use the strategic allocation of resources to accelerate economic growth and facilitate structural change in the economy.[4] As such, they differ from science and technology policy that prioritizes scientific discovery without short-term economic objectives, as well as from energy policies that focus primarily on the domestic energy mix and do not emphasize the creation of industries engaged in the development and production of new energy technologies.[5]

Before wind and solar technologies reached sufficient maturity for commercial application, public investments in wind and solar technologies primarily pursued scientific discovery. If science and technology funding had an economic objective, it was simply to prevent broader market failures in R&D.[6] In the United

[3] Scholars of globalization have long been concerned with the ability of states to protect distinct political economies from the forces of liberalization in the international economy. They have disagreed over whether such competitive pressures lead to the convergence of domestic political economies or yield varieties of economic liberalization. Yet the literature on comparative capitalisms nonetheless pits global economic forces against the ability of states to craft distinct pathways into highly globalized industries. See, for instance, Höpner and Krempel 2004; Hsueh, 2012; Streeck 2009; Streeck and Mertens 2010; Thelen 2014.

[4] Definitions of "industrial policy" have ranged from any policy governing industrial activity to specific forms of public–private collaboration. See, for instance, Dobbin 1994, 1–2; Schneider 2015, 2.

[5] Aklin and Urpelainen, 2018; Ornston 2013.

[6] Government approaches to R&D in the postwar period embodied the common notion of a linear relationship between scientific advances and the broader economy. Basic research was

States, the main engine of scientific discovery in the postwar decades was the federal government, which spent more than any other nation on wind and solar energy research.[7] Many of the technological advances underlying silicon-based solar cells and thin-film photovoltaic (PV) applications emerged from federally funded R&D institutes and enterprise laboratories starting in the 1950s. Publicly funded research conducted in American universities enabled the spread of solar technologies from their initial application in the space industry to the grid-connected solar PV models that are widely available today. In the wind industry, research consortia led by US corporations made early efforts to apply aerospace technologies to the design of large wind turbines. These costly investments were almost entirely funded through federal government programs.[8]

The first solar cell was developed in AT&T's Bell Labs in 1954, the same year that scientists at RCA Laboratories in Princeton, New Jersey, and at the US Air Force Aerospace Research Laboratory in Dayton, Ohio, published evidence showing that semiconductor devices could convert light into electricity.[9] By 1955, solar cells had reached 8 percent conversion efficiency under laboratory conditions, prompting a flood of speculative media reports about possible future uses of "limitless" solar energy.[10] In reality, applications were few and far between. In 1956, Bell Lab scientists calculated that the number of solar cells needed to power a single-family home would cost more than USD 1.4 million, preventing any use of solar energy in large-scale electricity generation.[11]

The high cost of solar cells was less of a concern in the space sector, where solar PV technologies found an early application as a power supply for satellites. In 1955, President Eisenhower announced plans to launch US satellites into space, only to be defeated at the finish line by the Soviet Union, which launched two Sputnik satellites in 1957. In a scramble to find a reliable and lightweight power source for the American satellite—batteries were bulky, heavy, and capable of holding only limited amounts of electricity—Bell Lab's solar cells offered a promising solution. The first US satellite partially powered by solar cells, Vanguard 1, was launched into orbit in 1958 and outlasted the Soviet satellites by several years. Vanguard's battery failed after twenty days, yet the solar cells provided power until 1964.[12] Despite such early successes, the market for solar cells remained

expected to spark applied research, lead to development and commercialization, and eventually give rise to mass production and industrial development. Leyden and Menter 2018, 228. Stokes 1997, 10.

[7] International Energy Agency (IEA) 2008, 31.
[8] On the contributions of European research, see Heymann 1998. The role of US conglomerates is discussed in Righter 1996, 149–69.
[9] Loferski 1993, 67.
[10] Deudney and Flavin 1983, 89.
[11] Perlin 1999, 36.
[12] Bailey, Raffaelle, and Emery 2002, 400.

limited to satellites and other small, highly specialized applications such as solar-powered radios and calculators.[13]

If the 1950s heralded the modest beginnings of the modern solar PV industry, they marked the end of an era in the wind sector. In 1956, Jacobs Electric Wind Company went out of business; and Wincharger, a second large American producer of wind turbines, all but ceased production.[14] Jacobs had manufactured some 30,000 2–3 kilowatt (kW) wind turbines since its founding in 1927; Wincharger, founded in 1935, had sold more than 400,000 small and affordable wind generators that could charge batteries used for lighting and radios.[15] Both companies supplied agricultural communities before electrification, building on a century-long history of small US firms producing wind turbines for rural America. Overall, six million small wind generators are estimated to have operated in the United States between the mid-nineteenth and mid-twentieth century.[16] Their market rapidly eroded when the Rural Electrification Administration started subsidizing the construction of electric grids in agricultural communities in 1935; by 1956, nearly all American communities were electrified, leaving only a niche market for wind energy.[17]

By the time of the first oil embargo in 1973, neither wind nor solar energy technologies had been established as viable options for large-scale electricity generation. The two oil crises of the 1970s added international urgency to the search for alternative energy sources and prompted widespread strengthening of research efforts. In the United States, as in many other large economies, the government responded by swiftly expanding domestic research efforts (Table 2.1). Supported by bipartisan agreement on the need to diversify the US energy supply, federal investment in renewable energy R&D enjoyed a resurgence, peaking in 1980—two years after the second oil shock—at USD 1.3 billion.[18]

In 1974, immediately following the first oil crisis, the federal government established a Solar Energy Research Institute (SERI) within the Energy Research and the Development Administration (ERDA), the predecessor to the Department of Energy (DOE).[19] The federal government also coordinated

[13] Perlin 1999, 35–40. The main solar firm at the time, Hoffman Electronics, which produced solar cells for the Vanguard satellite based on a license to Bell Lab's original solar technology, had four competitors in the United States: Heliotek (which also supplied solar power devices for space applications and eventually merged with Hoffman when both were acquired by Textron in 1960), RCA, International Rectifier, and Texas Instruments. In contrast to Hoffman and Heliotek, RCA, International Rectifier, and Texas Instruments were large corporations that had diversified into the solar sector from the radio and semiconductor industries. All three left the sector by the end of the 1960s, discouraged by the limited commercial market for solar PV. See Colatat, Vidican, and Lester 2009.

[14] Righter 1996, 102.

[15] Righter 1996, chapter 4.

[16] Bereny 1977, 167.

[17] Wolman 2007.

[18] Martinot, Wiser, and Hamrin 2005, 3.

[19] Loferski 1993, 74; Strum and Strum 1983, 134–47.

Table 2.1 Select Industrial Policies for Wind and Solar Sectors

	United States	Germany	China
Technology Push	**1973–1988** US Wind Research Program **1991–2000** PVMaT R&D Program **Since 1990s** NREL R&D Grants **2008** American Recovery & Reinvestment Act: Loans **Since 2009** ARPE-E Program	**Since 1954** Industrial Collaborative Research (ICR) funding **Since 1974** Federal Energy Research Programs, renewed six times	**Since 1986** R&D funding for applied research through "863 Program" **2008** "Indigenous Innovation" Initiative **2010** "New Energy" included under Strategic Emerging Industries
Market Pull	**1978** Public Utility Regulatory Policies Act (PURPA) **1992** Production Tax Credits (since then renewed seven times) **Since 1997** Renewable Portfolio Standards (thirty states by 2012)	**1990** Electricity Feed-In Law **1998** Renewable Energy Sources Act (EEG) **2004** EEG Renewed (+ 2009, 2012, and 2014)	**2003** Wind Power Concession Program **2006** Renewable Energy Law **2007** Feed-In Tariff: Wind **2009** Feed-In Tariff: Solar **2009** Golden Roofs Initiative **2009** Golden Sun Program

a national wind power research program, which allocated USD 380 million for the development of commercial wind turbines between 1973 and 1988.[20] As part of the program, conglomerates from aerospace, energy, and defense industries were paid to design turbine technologies that could reach generation capacities of up to 7 megawatts (MW), larger than any of the turbines in commercial use today.[21] Ultimately, however, the programs failed to yield a single viable turbine design. The original conglomerates closed their wind turbine divisions over the course of the 1980s.[22]

In Germany, as in the United States, the upheaval in global energy markets spurred by the oil crises of the 1970s made securing access to reliable and domestic sources of energy a central government concern. Germany's scarcity of domestic energy resources, together with its reliance on natural gas from the Soviet Union, fueled a particular sense of vulnerability.[23] The state responded

[20] Righter 1996, 158.
[21] Gipe 1995, 77; Righter 1996, 158.
[22] Ackermann and Söder 2002.
[23] Bahnsen 2013.

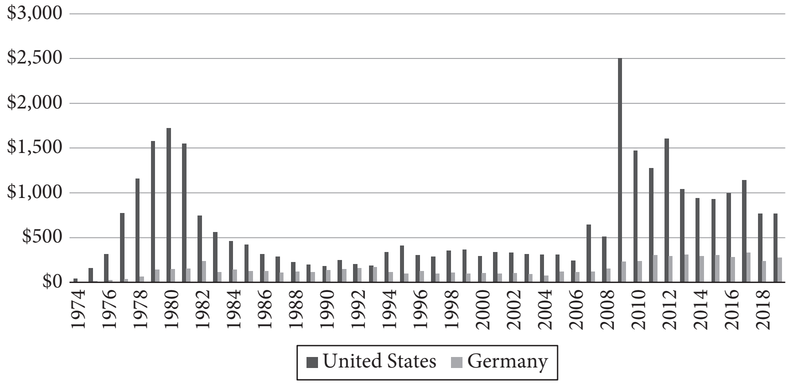

Figure 2.1 Selected Countries' R&D Budgets for Renewable Energy (in Million USD).
Source: IEA Energy Technology RD&D Statistics, 2020

by ramping up R&D efforts, albeit at a smaller scale than the United States had undertaken (Figure 2.1).[24] Starting in 1977, a series of Federal Energy Research Programs (*Energieforschungsprogramme*) supported R&D for specific energy technologies, including wind turbines and solar PV.[25] Despite a focus on manufacturability, these programs failed to yield wind and solar technologies that were ready for mass production. Solar panels produced by participating German firms continued to perform poorly, and many large firms exited the sector in spite of government research funding.[26]

As in the United States, German research funding in the wind industry prioritized the development of large-scale wind turbines and suffered a similar fate. A 3 MW turbine prototype commissioned by the German federal government in 1977 took six years to develop, consuming more than two-thirds of federal funding for wind energy research in the 1970s and 1980s.[27] The turbine encountered a range of technical difficulties before being dismantled in 1987. All in all, the turbine operated for just 320 hours over the course of three years, making it one of the most prominent failures of German science and technology policy to this day.[28] In spite of the research efforts spurred by the 1970s oil crises, commercially viable renewable energy technologies remained elusive.

[24] IEA 2020.
[25] Bundesministerium für Wirtschaft und Technologie 2011.
[26] Lang 2003.
[27] Ohlhorst 2009, 97.
[28] Ohlhorst 2009, 96.

The postwar decades demonstrated that wind turbines and solar panels could be used to generate electricity, not just in remote locations, but also in connection to commercial electricity grids. High production cost and reliability issues, however, confined both industries to a niche existence, leaving them unable to gain traction among commercial players and increasingly cut off from government support.

The Making of Industrial Policies

During the 1980s and 1990s, R&D support for wind and solar technologies was paired with public funding for demonstration projects and deployment. Although production costs declined and some of the technical challenges of early wind turbines and solar panels found solutions, these newer offerings remained uncompetitive with conventional sources of energy. Beginning in the 1980s, governments employed regulatory measures and subsidies to offset some of the cost disadvantages, enabling the first commercial wind and solar installations as demonstration projects for technologies resulting from publicly funded research programs. The combination of ongoing public investments in the development of new technologies and subsidies for their commercial application shifted the goals of government engagement from scientific discovery to economic growth and national competitiveness.[29] By the mid-2000s, China, Germany, and the United States had arrived at remarkably similar industrial policy portfolios to support the creation of new renewable energy technologies and their deployment in domestic markets (Table 2.1).

United States

The transition from R&D as scientific endeavor to R&D as strategic support for industrial development was perhaps the most complicated in the United States, where the federal government had traditionally avoided the impression of economic intervention in favor of particular industries. More generally, plans to support domestic renewable energy industries consistently caused heated debates along partisan lines. Even with these challenges, however, policies that supported the creation of domestic markets gradually took shape, complementing federal investments in renewable energy R&D.

In the wake of the oil crises, the 1978 Public Utilities Regulatory Policy Act (PURPA) required electric utilities to purchase power from third-party generators and to pay for such power at the rate of avoided cost. PURPA was unable to make renewable energy cost-competitive unless state-level policies accompanied it. Wide variation in implementation meant that in some states PURPA

[29] Nemet 2009; Nemet 2019, chapters 4 and 6. A similar shift toward growth-driven climate and environmental policy also occurred in international organizations. See Meckling and Allan, 2020.

initially had no effect.[30] When the first Gulf War shone a spotlight on alternative energy sources as a matter of national security, the Bush administration again raised R&D budgets. It also passed a production tax credit (PTC), the first federal attempt to close the cost gap between renewable and conventional sources of electricity through an incentive that rewarded the generation of wind power.[31]

Political conflict between Democrats and Republicans over renewable energy policy continued throughout the 1990s and 2000s, leading to volatility in both federal R&D funding and the availability of tax benefits.[32] Between 1992 and 2006 alone, the PTC for wind energy was renewed in five separate instances, often only for one or two years. On three separate occasions, the PTC expired before it could be renewed, leading to periods of up to nine months during which no federal support was available at all.[33]

The volatility of federal policy prompted state governments to step forward. States became a central force behind the creation of domestic renewable energy sectors and the prioritization of economic benefits in particular. Starting in the 1990s, states began to require electricity retailers to source a percentage of electricity from renewable sources by enacting Renewable Portfolio Standards (RPS). The Massachusetts legislature passed the first RPS in 1997; by 2012, the number of states with RPS had grown to thirty.[34] A second policy measure to encourage renewable energy demand, often used in conjunction with RPS, involved so-called Public Benefit Funds (PBFs). By 2005, 23 states had passed legislation to establish PBFs for renewable energy, collecting some USD 300 million annually to provide low-interest loans, equity investments, and funding for test centers, demonstration projects, and technical support.[35] In addition, a number of states passed so-called net-metering laws. These permitted commercial and individual owners of renewable energy installations to deduct any electricity supplied to the grid from their electric bills. By 2005, 38 states had passed such net-metering laws, and an additional three states passed net-metering legislation between 2005 and 2016.[36]

In contrast to earlier programs aimed at scientific discovery, these state-level demand-side programs prioritized industrial policy objectives that were not hard

[30] Martinot, Wiser, and Hamrin 2005, 3–4; Redlinger, Anderson, and Morthorst 1988, 182–85. An early outlier was California, where PURPA, in combination with a production tax credit, led to lucrative long-term contracts for wind power generation in the early 1980s. More than 15,000 turbines were installed between 1980 and 1986. The elimination of a host of additional tax incentives in 1986 left PURPA as the only remaining support mechanism in California, and new installations came to a halt. See Harborne and Hendry 2009, 3583.

[31] Laird and Stefes 2009, 2625; Martinot, Wiser, and Hamrin 2005, 3–4; Wiser, Bolinger, and Barbose 2007, 78.

[32] Laird and Stefes 2009, 2625.

[33] Karapin 2016, chapter 9; Wiser, Bolinger, and Barbose 2007, 79.

[34] Shrimali et al. 2012, 33.

[35] Bolinger et al. 2001, 84–85; Martinot, Wiser, and Hamrin 2005, 10.

[36] Inskeep et al. 2016; Martinot, Wiser, and Hamrin 2005, 10; Menz 2005, 2404. These regulations were not uncontested, and utility companies in particular mobilized to revert support for renewable energy legislation that they saw threatening to their business model. See Stokes, 2020.

to identify. To build the political coalitions necessary to pass renewable energy legislation, many programs included local content regulations that directly aimed to attract economic activity. Particularly when regulatory measures were insufficient and public funds were required to stimulate the creation of demand, government programs often paired their renewable offerings with the promise of local jobs and economic activity.[37] Measures included, for instance, preferential loans for renewable energy projects that required wind and solar equipment to be manufactured locally. Other states enacted RPS that required a percentage of renewable energy to be generated in-state. In some cases, to meet RPS requirements, utilities had to use locally manufactured solar panels and wind turbines.[38] A 2015 survey found at least forty-four renewable energy programs in twenty-three states that contained local content requirements, often in violation of international trade rules.[39]

Germany

In Germany, the transformation of renewable energy policy into industrial policy took place by accident. Lawmakers fundamentally underestimated the potential of their signature legislation, the 1990 Feed-in Law, in the absence of existing renewable energy industries. Over time, economic justifications for renewable energy policy took center stage as domestic industries grew in response to Germany's initial feed-in tariff. Policymakers took seriously the growth potential of the wind and solar sectors as export industries. The resulting program was more centralized than in the United States. The German federal government controlled all energy sector regulation, thereby avoiding the patchwork of state-level policies seen in the United States.

The 1990 Feed-in Law extended long-term subsidies to producers of renewable energy, combining previous technology-push policies with an attempt to create markets for renewable energy technologies. It required utilities to connect renewable energy generators to the grid, and it mandated the purchase of their electricity at rates between 75 and 90 percent above average end-user tariffs. The federal government estimated that the legislation would at most double renewable energy generation capacity on the grid.[40] Between 1989 and 1995, installed wind generation capacity increased from 20 MW to 1100 MW, more than tripling overall renewable energy generation capacity on the German grid in defiance of original predictions.[41] Yet precisely because the government initially depicted

[37] Stokes and Warshaw 2017, 3.
[38] Mack et al. 2011, 11–17.
[39] Meyer 2015, 1959–60.
[40] Deutscher Bundestag 1990, 4.
[41] Advocate General Jacobs 2000; Lauber and Mez 2004, 602. Prior to the Feed-In Law, Germany's renewable energy generation capacity consisted of some 4,000 hydropower plants with a total generation capacity of 470 MW. Deutscher Bundestag 1990, 3.

the Feed-in Law as a small and inconsequential change to electricity sector regulation, an unlikely alliance of environmental progressives and Christian conservatives seeking to support small hydropower plants in their home districts had convinced a majority of the Bundestag to support the legislation.[42]

The German utility sector, which had also missed the initial significance of the legislative changes, came to regard the Feed-in Law as a threat to its business model. Forced to integrate a rapidly growing share of wind energy, utility companies launched a series of legal challenges in parliament and in the courts.[43] These attempts to stop the creation of domestic renewable energy markets were defeated in the courts, and lobbying efforts also failed politically. After sixteen years of conservative government rule, the 1998 federal election awarded victory to a coalition of Social Democrats and the German Green Party, a long-term champion of renewable energy. The new government set ambitious goals to increase the share of renewables on the German electric grid. Acknowledging the development of domestic green energy sectors over the previous decade, government leaders now justified such goals in both environmental *and* economic terms.[44]

The coalition agreement between the two parties listed two key priorities: the creation of jobs through investment in sustainable growth and the "ecological modernization" (*ökologische Modernisierung*) of the domestic economy to marry environmental and economic goals.[45] In late 1999, the new government introduced a new demand-side legislation for renewable energy markets.[46] Replacing the Feed-in Law, the Renewable Energy Sources Act (*Erneuerbare Energien Gesetz*) determined specific rates for each energy source, rather than setting prices as a percentage of end-user tariffs.[47] The introduction of differentiated demand-side subsidies created rapidly growing market demand for solar PV technologies. Particularly after a 2004 amendment that further increased the rates for solar power, the German PV market expanded exponentially, turning Germany into the largest solar market in the world.[48] Cumulative installations of solar panels grew from 370 MW in 2003 to 17,000 MW by 2010. Germany now accounted for nearly half the world's total installed solar energy generation capacity.[49]

[42] Berchem 2006. Jacobsson and Lauber 2005; Laird and Stefes 2009. For a history of the German Green Party, see Mair 2001. On environmental politics in Germany more generally, see Hager 1995.

[43] Advocate General Jacobs 2000; Lauber and Mez 2004, 106–8.

[44] Sozialdemokratische Partei Deutschlands and Bündnis 90/Die Grünen, 17–19.

[45] Sozialdemokratische Partei Deutschlands and Bündnis 90/Die Grünen, 2.

[46] Bechberger 2000, 20–26.

[47] For 2000, for instance, the legislation set a price of Euro 0.091/kWh for wind power and 0.506/kWh for solar power. Bechberger, 46–50; Dagger, 73–76; Deutscher Bundestag 2000; Lauber and Mez, 610.

[48] Bruns et al., 208.

[49] Wind and solar data compiled by Earth Policy Institute 2020.

China

The link between state support for renewable energy and economic growth objectives proved strongest in China, which identified wind and solar sectors from the beginning as potential vehicles for industrialization and development. Encouraging the development of an indigenous wind industry, the Chinese government pursued a three-pronged strategy: creating domestic markets, supporting R&D efforts by local enterprises and research institutes, and providing incentives for foreign firms to localize manufacturing and transfer technology to local partners. Throughout the 1990s, Chinese energy policy prioritized the establishment of a domestic wind industry over other emerging renewable energy technologies. Wind turbines had already been tested in large-scale installations in California during the 1980s and remained far more affordable than solar power during this period.[50] In 1994, the Ministry for Electric Power mandated the purchase of wind-generated power from turbines installed on demonstration sites. Under the Ninth Five-Year Plan (1996–2000), part of China's policy practice of setting comprehensive economic goals in five-year increments, government leaders added designated funds for wind turbine R&D to China's 863 Program for applied research, introduced a 40 percent local content requirement for new wind power projects, and created a loan program for wind farm development through the State Development Planning Commission and the Ministry of Science and Technology (MOST).[51] In the early 2000s, the centrally funded 863 Program for applied research dispensed RMB 20 billion (roughly USD 3 billion) to research institutes and enterprises, including to startups such as Suntech and Goldwind, which would become some of China's largest producers of wind turbines and solar PV technologies over time.[52] Overall funding for the 863 Program rose nearly fifty-fold between 1991 and 2005.[53]

The creation of large-scale markets for wind turbines subsequently improved China's domestic capabilities. Starting in 2003, through the Wind Power Concession Program, the government provided subsidies for large-scale wind turbine installations through a tender-based bidding system. A clear sign of industrial policy ambitions, the government-run program contained stringent domestic content regulations of up to 70 percent, as well as tax incentives to attract foreign turbine manufacturers and their suppliers to China.[54] More than 3,350 MW of turbines—many produced by foreign turbine manufactures in

[50] China had extensive installations in hydropower, which had been used for rural electrification during the Mao years. In 1984, more than half of China's counties had small-scale hydro dams for local power generation. Technically, wind was China's second renewable energy industry. China Yeh and Lewis 2004, 443.

[51] For a detailed timeline of wind power policy, see Lewis 2012, 68–74; 2013. For an in-depth analysis of China's 863 program, see Zhi and Pearson, 2017.

[52] Campbell 2011, 3; Karplus 2007, 23–24.

[53] Osnos 2009.

[54] Ru et al. 2012, 65; Wang Q. 2010, 705–6.

China—were installed between 2003 and 2007. The Wind Power Concession Program rapidly transformed China into one of the largest wind markets in the world.[55]

In 2006, the central government declared "indigenous innovation" (*zizhu chuangxin*) a central goal of the Eleventh Five-Year Plan (2006–2010), after technology was primarily imported throughout the 1990s.[56] In the renewable energy sector, indigenous innovation guidelines triggered the aggressive expansion of renewable energy markets and strengthened support for domestic R&D activities. The central government passed China's first renewable energy law, which provided a framework for introducing feed-in laws similar to those in effect in Germany. The new law also set up the legislative basis for cost-sharing mechanisms to retrieve the cost of renewable energy subsidies through ratepayer surcharges.[57]

In 2009, the central government eliminated individual feed-in laws that had arisen in various provinces in the wake of the renewable energy law, and it instead established China's first national, unified feed-in tariff for wind energy. China was now the world's largest market for wind turbines, having doubled its cumulative wind power capacity from the previous year.[58] At the same time, the first nationwide feed-in tariff for solar energy created a small but growing domestic market for solar PV technologies, with additional subsidy programs available to support both residential customers and developers of utility-scale solar PV installations.[59] These subsidies for a domestic solar PV market went into effect after the global financial crisis had led many European governments to drastically reduce support for local solar installations—a decision that had slowed global market development and caused overcapacity among China's solar producers.[60] After decades of wind turbines dominating the local renewable energy market, solar PV technologies were finally having their moment: cost reductions made these technologies more attractive for domestic use.[61]

By the mid-2000s, China, Germany, and the United States had arrived at remarkably similar industrial policy tools to support the creation of domestic renewable energy industries. In all three economies, governments combined support for renewable energy markets with public funding for R&D activities with the goal of creating domestic wind and solar sectors. As I lay out in the remainder of this chapter, however, firms maintained divergent industrial profiles

55 Ru et al. 2012, 65.
56 State Council 2006.
57 Lewis 2013, 53.
58 Data compiled by Earth Policy Institute, 2020.
59 Campbell 2011, 8.
60 For an overview of the effects of the global financial crisis on the solar PV industry, see Bartlett, Margolis, and Jennings 2009.
61 Goodrich et al. 2013, figure 1.

in global renewable energy sectors in spite of similar policy environments. The development and persistence of distinct national industrial profiles in wind and solar technologies is surprising, particularly if we consider the similarities in renewable energy industrial policy that these countries shared.

The Political Logic of Green Industrial Policy

By 2009, when President Obama invoked the notion of a clean energy race during his speech at MIT, renewable energy sectors had mushroomed into sizable industries. More than 159 gigawatts (GW) of wind power and 21 GW of solar PV had been installed—equivalent to the generation capacity of roughly 180 nuclear power plants. Such a feat was beyond imagination as recently as the late 1990s, when the high cost of wind turbines and solar panels limited their use to niche applications. Over the early 2000s, however, annual investment in renewable energy installations had steadily climbed, reaching USD 150 billion in 2009. Germany, China, and the United States constituted the world's largest investors at the time. Public subsidies and regulatory incentives made much of this investment possible, helping offset some of the competitive disadvantages of new energy technologies.[62] As governments eagerly eyed the growth trajectory of renewable energy markets and the size of public investments, they began to shift their strategies. They were no longer content to be mere consumers of these resources, nor were they satisfied with attracting individual segments of global renewable energy supply chains. Instead, policymakers hoped to lead the way into a new future: by providing R&D funds and supporting market demand, firms would invest in technological innovation and ultimately co-locate activities to commercialize and produce wind and solar technologies domestically.

The link between renewable energy policy and the promise of material benefits in the form of industrial development (and domestic manufacturing activities) followed a broader political logic. Among state initiatives promoting the reduction of greenhouse gas emissions, policies that pledged to support growth and employment attracted policymakers in part because they allowed for the creation of political coalitions organized around renewable energy by reaching beyond the usual suspects, or core groups of environmental advocates. Mobilizing this broader political support remained particularly important for policies that entailed large public expenditures. The formation of these coalitions also helped justify the additional financial burdens imposed on consumers of electricity, who were being asked to help offset the cost differential between traditional energy sources and higher-priced wind and solar technologies. Simply put, green

62 REN21 2010, 13.

industrial policies that achieved emissions reductions while simultaneously creating new sources of growth were easier to implement politically. They also provided an opportunity to create new interest groups in support of energy sector transformation.[63] Public investments in the creation of industries that could invent, manufacture, and possibly export wind and solar products also followed the goal of strategically positioning domestic economies in sectors with future growth potential.[64]

In his speech at MIT, President Obama gave voice to this ambitious outlook. He delivered his remarks against the backdrop of the global financial crisis of 2009, which had prompted the US government to use stimulus spending to support domestic renewable energy firms in unprecedented ways. The American Recovery and Reinvestment Act (ARRA) included a specific tax credit for clean energy manufacturing, as well as loan guarantees for wind and solar manufacturers and training programs for workers in clean energy sectors.[65] Little about these programs could not be interpreted as targeted industrial policy: government resources were to be deployed with the explicit goal of accelerating growth and facilitating structural change in the economy through the support of select industrial sectors. These national green industrial policy initiatives implemented during the Obama administration followed on the heels of more widespread support for wind and solar industries at the state level. By the time Obama delivered his remarks at MIT, the majority of states had already implemented some form of renewable energy mandates, often directly tied to the promise of employment and growth.[66]

In Germany, the goal to utilize the clean energy transition as a path to broader industrial transformation became apparent in widespread comparisons to the German car industry. Automobiles had historically been developed and assembled by three domestic manufacturers—BMW, Mercedes-Benz, and Volkswagen. Up to three-quarters of domestic vehicle production was destined for export.[67] In the mid-2000s, policymakers argued that wind and solar PV technologies—like cars before them—could create domestic industries with

[63] Breetz, Mildenberger, and Stokes 2018, 500; Meckling et al. 2015, 1170; Nahm 2017a, 711–13.

[64] Additional considerations have led policymakers to consider manufacturing a sector of the economy worthy of political support. In addition to the role of manufacturing businesses in creating (unionized) employment and investing in R&D, policymakers and academics alike have questioned whether, in the long run, domestic strengths in innovation can be sustained without proximity to production capabilities. Particularly in the early stages of technology development, such views have assumed that geographical proximity between R&D and production activities helps commercialization and offers opportunities for learning that fuel further innovation. See, for instance, Ezell and Atkinson 2011a; Helper, Krueger, and Wial 2012; Pisano and Shih 2012; President's Council of Advisors on Science and Technology 2012; Ramaswarmy et al. 2018; Sivaram et. al, 2020; Tassey 2010.

[65] Mundaca and Richter 2015, 1177.

[66] Stokes and Warshaw 2017, 1–2.

[67] Ulrich 2017, 1.

substantial export potential, justifying large public investments in domestic renewable energy markets. A 2005 cabinet decision on Germany's sustainability strategy openly justified continued support for wind and solar sectors by appealing to the "tremendous export market that will permanently secure growth and employment."[68] In 2008, the Federal Ministry for the Environment predicted that green industries—renewable energy but also recycling and energy efficiency technologies—would surpass the German auto sector in their contribution to GDP by 2020. The notion of green industrial policy (*ökologische Industriepolitik*) became an established concept in Berlin policymaking circles.[69]

Industrial development objectives behind public support for wind and solar were perhaps most obvious in China, where renewable energy sectors were treated as potential export industries in the broader context of the nation's economic development strategy. In 2010, renewable energy sectors were included on a list of designated "Strategic Emerging Industries" (SEIs). The SEI initiative aimed to use a range of preferential policy treatments—including low-interest loans, tax breaks, and R&D support—to forge the development of industrial sectors critical to future national competitiveness. The central government in Beijing encouraged firms to reduce dependence on international technology transfers and to fill remaining gaps in domestic supply chains, including in the production of advanced manufacturing equipment for renewable energy technologies.[70] The Twelfth Five-Year Plan for the solar PV industry called for 80 percent of solar production equipment to be manufactured domestically by 2015.[71] Up until then, the domestic deployment of these technologies had been secondary, particularly in the solar industry, as the vast majority of solar production was destined for export. The central government in Beijing hoped to use the window of opportunity provided by the emergence of new clean energy technologies to establish a strategic foothold in the industries of the future.

Innovation in Global Networks

Burgeoning global markets in China, Germany, and the United States—created as a result of government policies outlined earlier—provided incentives for firms to enter renewable energy sectors, leading the modern wind and solar sectors to emerge virtually simultaneously in all three economies. At the time, a recognition of the links between innovation and national competitiveness—and the related material benefits of growth and employment—prompted governments

[68] Bundesregierung 2005, 19.
[69] Bundesministerium für Umwelt 2008, 6.
[70] State Council 2010; US-China Business Council 2013.
[71] Ministry of Industry and Information Technology 2012; National Energy Administration 2011.

to advocate for the domestic establishment of virtually all economic activities related to wind and solar innovation. China, Germany, and the United States, the three largest investors in renewable energy in the early 2000s, were locked in a tight race for leadership in renewable energy. The image of the three nations going head-to-head to attract and build domestic renewable industries dovetailed with a broader narrative, one that described nations in the global economy as locked into a zero-sum competition for global market share and technological leadership. This latter view made a resurgence beginning in 2015 as the US–China economic relationship deteriorated amid mercantilist sentiments and widespread calls for economic decoupling.[72] The idea that national systems competed for leadership in innovative industries also pervaded business school literatures, which portrayed innovative firms as the result of unique conditions attributable to states. From this perspective, the pursuit of innovative firms, the ultimate source of national competitiveness, placed states in direct competition with one another.[73]

Historically, however, the development of global clean energy sectors does not conform to such views. Despite similar government goals and industrial policy tools—firms in each geographical location established distinct industry structures and national patterns of industrial specialization. These national profiles in global renewable energy industries differed in the kinds of innovation and technological challenges they addressed, the type and size of firms that made up the majority of industrial activities, and the relationship between technological innovation and manufacturing (Table 2.2). I distinguish in this book between these three types of R&D capabilities in the transition of new technologies from inception to market application. Underlying this categorization is a definition of innovation as consisting of both invention and deployment. Innovation encompasses *both* the development of new technologies *and* the subsequent changes and modifications required to bring such new developments to market. From this perspective, all three national specializations can be seen as constituent elements of innovation, yet no single specialization can single-handedly complete the innovation process without reliance on external capabilities.

I use the term "invention" to refer to the development of new technologies and the early stages between the laboratory and prototyping before commercial

[72] Nahm, 2020.

[73] See, for instance, Porter 1990. Scholarship on innovation has shared the notion that nations remained capable of undertaking technological innovation fully within the domestic economy, even if they have differed in the types of innovation they were able to engage. Scholars of national innovation systems, for instance, have long emphasized the influence of different constellations of domestic actors on the types of innovation that domestic firms can undertake. Institutional scholars, including in the tradition of research on the varieties of capitalism, instead proposed that domestic institutions lock economies into different types of innovation, sharply limiting the kinds of industries that can thrive in different institutional settings governing the domestic economy. Fagerberg and Sapprasert 2011; Hall and Soskice 2001, 41; Vernon 1966.

Table 2.2 Varieties of Innovation

	Germany	China	United States
Type of Innovation	*Customization*	*Innovative Manufacturing*	*Invention*
Challenge addressed	Automation, production equipment, complex components	Commercialization, scale-up of new technologies	Development of new technology
Firm Type	Suppliers	Manufacturers	Start-ups
Predominant Firm Size	< 2000 Employees	> 2000 Employees	< 500 Employees
Production Scale	Medium/Low	High	Low/None

application. In fact, many inventions, including new types of printable solar cell technologies and novel wind turbine designs, never make it beyond the prototyping stage because they lack commercial application. "Customization" describes the R&D skills required for the development of production equipment and components that are not part of the process of invention, but instead constitute necessary inputs into the commercialization of these novel technologies. Automated production equipment and early-stage components for novel technologies share at least two common traits: they are generally not mass-produced, and they require substantial customization and iterative adjustments. Examples of customization include automated production lines for new technologies or novel components that cannot be readily purchased as standardized equipment. "Innovative manufacturing" refers to the engineering skills required to scale and design these technologies for mass production, operating at the intersection of traditional R&D and manufacturing. Such innovation includes, for instance, the substitution of materials, redesign of particular components, and the reorganization of internal product architecture.[74]

Literatures on technological innovation have treated this third set of capabilities residing in the manufacturing process as primarily related to process innovation, describing changes and improvements in the manufacturing process and the method of product delivery.[75] Scholars of product innovation, in contrast,

[74] For a detailed discussion of innovative manufacturing and its relationship to broader theories of innovation, see Nahm and Steinfeld 2014.

[75] OECD 2005, para. 163.

have focused on differences between radical and incremental innovation, the former introducing new concepts and technologies that depart significantly from past practice, and the latter improving gradually on existing designs.[76] More recent work has added the concept of architectural innovation, referring to changes in the overall architecture of a product that do not alter its underlying components.[77] Yet the commercialization and production of new products in high-technology industries often face challenges in the scale-up to mass manufacturing. These challenges cannot be met through process innovation alone—they require changes to product design. When it comes to new technologies that lack standardized manufacturing processes, innovative manufacturing serves as an integral part of the innovation process.

Although China, Germany, and the United States each incorporated a mixture of firms with a range of industrial specializations, renewable energy sectors in each economy predominately focused on one of the three constituent elements of innovation noted previously. As Chapters 4–6 discuss in detail, a number of large multinational firms operated in multiple locations, often entering wind and solar industries through acquisitions of smaller start-ups as new energy technologies became promising fields of economic activity. Some manufacturers continued to exist in both Germany and the United States; China, too, was home to select firms focused on invention and customization. But the majority of industrial activity in the United States, Germany, and China revolved around invention, customization, and innovative manufacturing, respectively. Far from the notion of a clean energy race, firms in the three economies settled into complementary evolutionary niches in global wind and solar industries, despite their governments' similar industrial policy goals and broadly comparable policy tools.

In the United States, start-up firms with capabilities in the *invention* of new technologies dominated wind and solar industries in the early 2000s. A number of multinational energy and defense firms had maintained wind and solar divisions in the 1970s and 1980s, but lack of market demand had prompted most to shut their renewable energy divisions.[78] The majority of new firms entering US wind and solar sectors in the late 1990s and early 2000s were start-ups seeking to lower the cost of renewable energy through the invention of new technologies. Many amounted to spin-offs from universities and research institutes, often founded by university faculty or research affiliates seeking to commercialize technological breakthroughs. Patent counts reflect this focus on invention: US firms and research institutes account for approximately 25 percent of cumulative wind and solar energy patents until 2009, roughly twice the number of patents

[76] Abernathy and Clark 1985; Abernathy and Utterback 1978.
[77] Henderson and Clark 1990. For an application of these concepts to the case of China, see Ernst and Naughton 2008.
[78] Colatat, Vidican, and Lester 2009; Heymann 1995, 349–54.

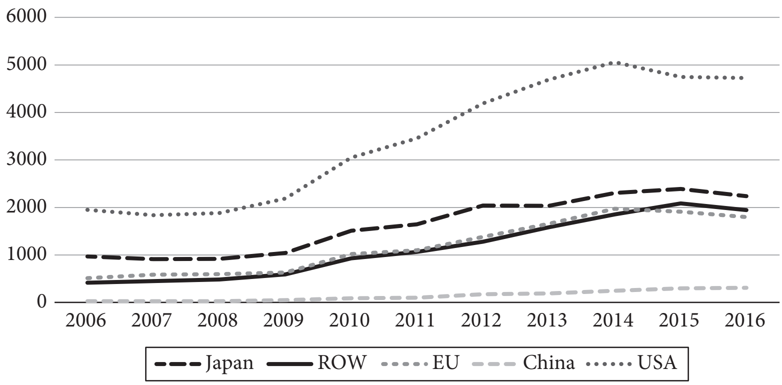

Figure 2.2 Annual USPTO Patents in Clean Energy Technologies
Source: US National Science Foundation Science and Engineering Indicators

filed by China or the European Union.[79] Clean energy patenting in the United States continually outpaced other large economies (Figure 2.2).

In the solar sector, many of the new US firms focused on the development of thin film technologies, which promised to lower prices by replacing silicon, an expensive raw material, with cheaper alternatives.[80] Other firms experimented with new manufacturing processes and new types of solar technologies, including cells that could be printed on paper and plastic.[81] The Massachusetts-based company Evergreen had its beginnings in a radically new production technology developed at MIT that would allow wafers to be produced in one continuous piece, eliminating the silicon waste incurred in traditional production methods that used a silicon block to saw off wafers.[82] By 2009, out of 100 solar companies operating in the United States, at least 73 were start-ups.[83] Although fewer in number than in the solar sector, US wind start-ups also sought to decrease the cost of wind energy with radically different designs. For example, Clipper Windpower proposed replacing a single turbine generator with several smaller generators to increase efficiency.[84] Boulder Wind attempted to make obsolete gearboxes in turbine designs, and firms like Ogin borrowed principles

[79] Bettencourt, Trancik, and Kaur 2013, 3.
[80] A particular concern among US scholars of China's rise in renewable energy manufacturing has been the possibility of technology lock-in. Declining prices for solar technologies as a result of China's investments in manufacturing have made it increasingly difficult for new technologies to break into the market, even if they in principle offer better performance potential in the long run. See Hart, 2020.
[81] Morton 2006.
[82] Renewable Energy World 2000.
[83] Knight 2011, 176.
[84] Goudarzi and Zhu 2013, 199.

from jet engines to develop alternatives to the traditional three-blade design.[85] Others, such as a start-up named Vortex, tried to eliminate blades altogether.[86] If these companies thought about manufacturing at all, they did so to demonstrate the commercial feasibility of their designs through proof-of-concepts and prototyping. They did not focus on the production of mass manufacturing facilities dedicated to cost efficiency and scale (see Table 2.3).

In Germany, large numbers of small and medium-sized suppliers from existing industrial sectors diversified into renewable energy sectors by zeroing in on *customization*, the development of complex componentry and production equipment. Interview data reveal that the absence of specialized suppliers in renewable energy industries had previously required wind and solar firms to resort to improvisation, repurposing equipment and modifying components from other industrial sectors for application in wind turbines and solar PV modules.[87] Germany's existing manufacturing firms possessed a rich fabric of capabilities applicable to the development of wind turbine components and production lines for the solar industry that could address these needs. German firms subsequently responded to this opportunity by applying their niche capabilities to global renewable energy sectors. Firms entered from a variety of industries, including machine building, automation and laser processing equipment, metal fabrication, and shipbuilding.

In one of my interviews, for example, I met the second-generation head of a German machine tool manufacturer who wanted to diversify the business beyond the automobile sector. He explained that he was actively looking for an industry where the firm could use 70 percent of what it already knew and complement it with 30 percent newly acquired skills to produce innovative technologies. Realizing that little automation equipment existed for the production and assembly of solar modules, where demand was rapidly growing, the tool manufacturing company entered the solar industry by building on its experience in the auto sector with new technologies in infrared and laser welding.[88] The majority of renewable energy producers in Germany were much like this man. They represented firms from adjacent industrial sectors, and they were looking for new applications of the core skills and capabilities that they already possessed.

By 2011, VDMA, the German Engineering Federation, had listed more than 170 member firms active in the wind industry, only 10 of which were manufacturers of wind turbines. The vast majority of firms developed towers,

[85] Boulder Wind Power 1999; Gertner 2013.
[86] McKenna 2015.
[87] 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; plant manager of German gearbox manufacturer, May 16, 2011; plant manager of German generator manufacturer, May 17, 2011.
[88] Berger 2013b, 135. Author interview, October 15, 2019.

Table 2.3 R&D Activities, Select Wind and Solar Firms

Firm	Background	R&D Focus
USA		
Innovalight (Solar)	Silicon Valley start-up, founded 2003.	- R&D on *silicon ink nanomaterial* to increase cell efficiency, funded by DOE and NREL. Research with JA Solar (China), acquired by DuPont (2011).
MiaSolé (Solar)	Silicon Valley start-up, founded 2004.	- VC-funded ($550 million) development of *flexible thin-film cell* on stainless steel substrate. Experimental production line. Acquired by Hanergy, China (2012).
Ogin (Wind)	Aerospace spin-off, founded 2008.	- VC and ARPA-E funding to develop *jet-engine-based high-efficiency wind turbines.* Some R&D and component development in China.
Makani (Wind)	California-based start-up, founded 2006.	- Google-backed R&D on *kite-based flying wind turbines* to increase generation efficiency. Acquired by Google X in 2013 while still prototyping.
Germany		
Schmid Group (Solar)	Family-owned. Founded as foundry in 1864.	- Background in circuit board printers, develops turnkey solar production lines (2001). R&D on *selective emitter cell lines* with Chinese partner (2009).
RENA (Solar)	Private, founded in 1993.	- Applies R&D on semiconductor equipment to wet bench chemical *processing equipment* for solar. Currently work on passivated emitter and PERC cells.
Eickhoff (Wind)	Founded 1864, equipment for mining sector.	- Uses in-house foundry and background in gearboxes for mining to develop *wind turbine gearboxes*. Small-batch production of ultra-large, offshore gearboxes.
VEM Sachsenw. (Wind)	Family-owned machine builder, founded 1903.	- Background in generators, engines for streetcars. R&D on *wind turbine generators* beginning in 1998. Small-batch production of ultra-large, off-shore generators.
China		
JA Solar (Solar)	PV producer, founded 2005.	- Founded by returning overseas Chinese scientists, focus on commercialization of *high efficiency multi-SI cells*. First to apply silicon ink technology (with Innovalight)
CSUN (Solar)	PV producer, founded 2004.	- Founded by returning overseas Chinese scientists, focus on commercialization of *high efficiency mono- and poly-SI cells*. First to commercialize selective emitter cells.

Continued

Table 2.3 *Continued*

Firm	Background	R&D Focus
Goldwind (Wind)	1998 Spin-off from state-owned firm.	- R&D on commercialization of *gearless wind turbines* to avoid maintenance associated with traditional gearbox designs. Collaboration with Vensys (Germany).
Mingyang (Wind)	2006 spin-off from electrical equipment firm.	- R&D on commercialization of *super compact drive turbines* to lower maintenance cost, especially offshore. Collaboration with Aerodyn (Germany).

Source: Information compiled from company websites and public financial filings.

blades, mechanical components, hydraulics systems, and production equipment for the wind industry.[89] Similarly, in the PV sector, more than seventy firms offered production lines, automation equipment, coatings, and laser processing machines. With roughly 41,000 employees in 2010, employment in solar PV equipment and component firms far surpassed the 12,000 jobs in Germany's solar module manufacturers in the same year.[90] Of the four vertically-integrated solar manufacturers operating in Germany in 2011, only two remained in existence by 2014. Their combined annual production capacity amounted to less than a single Chinese PV manufacturing plant.[91] The small number of domestic wind turbine and solar PV manufacturers made Germany's renewable energy suppliers highly dependent on global markets. Export quotas of more than 50 percent in the solar sector and up to 80 percent in the wind industry underscore the tight integration of Germany's wind and solar firms into global renewable energy supply chains.[92]

Chinese wind and solar firms, by contrast, focused on technical capabilities in commercialization and scale-up—what I call skills in *innovative manufacturing*—that neither US start-ups nor German suppliers had established in-house.[93] The majority of wind turbine producers spun off from state-owned or formerly state-owned manufacturing firms. In the solar industry, firms were frequently founded by Chinese scientists educated in solar PV research laboratories abroad.[94] When these firms entered wind and solar PV sectors in the late 1990s and early 2000s, few manufacturers of wind turbines and solar panels were

89 Germany Trade & Invest 2010; Arbeitsgemeinschaft Windenergie-Zulieferindustrie 2012.
90 Germany Trade & Invest 2011b, c.
91 Germany Trade & Invest 2011a, 2014.
92 Fischedick and Bechberger 2009, 26.
93 Nahm and Steinfeld, 2014.
94 See Alexander 2013.

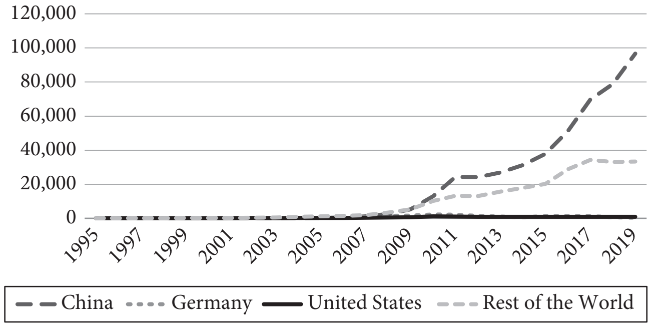

Figure 2.3 Annual Solar Photovoltaics Cell Production by Country, 1995–2019 (in Megawatts).
Source: Earth Policy Institute 2020, Jäger-Waldau 2020.

producing at scale. While technology could be accessed in global networks, mass manufacturing knowledge was simply not available. According to Wu Gang, the founder of Goldwind, one of China's first wind turbine firms: "Whole blades dropped off. The main shafts broke. It was really very dangerous."[95] Chinese firms subsequently concentrated their efforts on building R&D skills around the commercialization and rapid scale-up of complex wind and solar technologies.

By 2012, China's renewable energy firms accounted for over 60 percent of the global production of solar PV modules and nearly half of the world's wind turbines (Figure 2.3).[96] Seven of the ten largest solar manufacturers and four of the ten largest wind turbine producers in the world were Chinese firms.[97] The majority of these producers continued to license technology and source components and production equipment abroad.[98] Site visits revealed designated engineering teams with advanced capacity to rapidly translate complex technologies into mass-manufacturable products.[99] Such tasks required improvements to process designs long associated with manufacturing innovation, but they also entailed changes to product designs—to accommodate manufacturing

[95] Osnos 2009.
[96] Earth Policy Institute 2020.
[97] Bebon 2013; IHS Solar 2013.
[98] Lewis 2013, 136–37.
[99] Author interviews: Senior VP global supply chains, Chinese solar manufacturer, March 13, 2011; CTO and director of R&D at Chinese solar manufacturer, August 26, 2011; head of China operations, European wind turbine engineering firm, January 13, 2011; CEO, European wind turbine engineering firm, May 20, 2011; CTO, Chinese wind turbine manufacturer, August 29, 2011; CEO, Chinese solar cell manufacturer, August 10, 2011; president, Chinese wafer manufacturer, August 26, 2011. CEO, Chinese cell and module manufacturer, interviewed June 28, 2013. Nahm and Steinfeld 2014.

requirements, to incorporate new materials and components, and to meet cost targets for final products.

The engineering teams devoted to innovative manufacturing frequently operated in a separate R&D division that looked solely at the challenges posed by scale-up and mass production. At the wind turbine manufacturer Mingyang, for instance, out of 300 R&D staff in 2010, approximately one-third of the engineers focused on developing new technologies, while two-thirds worked on bringing existing technologies to mass production.[100] Similarly, Trina Solar reported that out of 425 employees working in its R&D division in 2012, just 79 focused on technology development; the remaining 346 engineers devised solutions to the challenges of commercialization in a designated test facility with production lines solely dedicated to R&D.[101] Even as the wage gap widened between urban workers in coastal and interior provinces, wind and solar firms maintained such knowledge-intensive innovative manufacturing strategies in high-wage coastal locations.[102] For instance, Chinese solar PV manufacturers were among the first firms to employ fully automated production lines in response to such changes.[103] Such feats, of course, would be hard to conceive without the makers of production equipment, predominately from Germany, who provided the basic machinery on which such innovative manufacturing capabilities could be applied.

Collaboration *and* Competition

While wind and solar sectors in China, Germany, and the United States developed rapidly and simultaneously throughout the early 2000s, the majority of firms in each location did not compete directly. Firms established distinct—and often complementary—technological skills to carve out unique competitive niches in global renewable energy sectors. In contrast to the notion of a clean energy race, these distinct national industrial specializations remained interdependent: none of the states examined in this book established all the technological capabilities required to invent, commercialize, and produce new energy technologies domestically. The capabilities required to bring new technologies from lab to market spanned the organizational boundaries of the firm, and the resources required to establish such capabilities cut across

[100] China Ming Yang Wind Power Group Limited 2011, 54.
[101] Trina Solar 2012, 64–65.
[102] Li et al. 2012, 62.
[103] Author interviews: CTO and director of R&D at Chinese solar manufacturer, August 26, 2011; CEO, Chinese cell and module manufacturer, interviewed June 28, 2013. See also Nahm and Steinfeld 2014.

national borders. Wind and solar industries were not nationally self-sufficient in a particular type of innovation, nor did they distinguish themselves according to each nation's tier in the global economy. Rather, firms specialized in different activities that at one point might have all occurred under the roof of one enterprise, but now required collaboration across firms. In doing so, firms circumvented the traditional division of labor between industrialized and developing economies and transcended the national innovation systems expected to support them.

Before the reorganization of the global economy began in the 1980s, firms tended to have the capacity to translate between complex designs and manufacturing requirements within the four walls of their own company. In the postwar decades, this all-in-one-approach had favored large enterprises as the primary drivers of economic growth and competitiveness. The core competitive advantage of large enterprises had been precisely the ability to establish a broad range of engineering capabilities required for technological innovation and the commercialization of new technologies. Such skills were either established within the four walls of the firm or, at the minimum, located in local clusters of third-party suppliers that could provide such capabilities in close proximity. Moreover, large enterprises could make the capital, human, and financial investments required to establish this broad range of engineering capabilities in ways that smaller firms could not. By organizing manufacturing and R&D in close proximity to one another, these firms coordinated and established critical linkages between innovation and production capabilities in the early stages of product development, more efficiently transitioning new products from lab to mass production.[104] Only after products were reliable, manufacturing processes standardized, and price premiums from technological advantage depleted did production activities shift to developing economies—countries with fewer technical capabilities, lower degrees of vertical integration, and less sophisticated market demand.[105]

In many cases, the relocation of manufacturing activity to developing economies through outsourcing and offshoring has removed the demand or need for such skills in advanced economies. It has created opportunities for manufacturing firms in developing economies to specialize in precisely the type of engineering capabilities that are required to prepare advanced products for mass manufacturing. Throughout the 1970s, US car manufacturers, competing with challengers from Japan and Germany, made more than 70 percent of their

[104] Where scholars of East Asian economic development saw a need for the state to encourage the creation of such business in late-developing economies, Chandler, in a study of the origins of large business in the United States, argued that the dominance of conglomerates in the US economy was a result of their competitive success. See Chandler 1977, chapters 3 and 9.

[105] Vernon 1966. For dynamic versions of product cycle theory, see Antràs 2003; Grossman and Helpman 1991; Krugman 1979.

components in-house, tightly integrating the development of new car models and the supply chains required to produce them. Reliance on external suppliers for the remaining parts was primarily an exercise in benchmarking internal production costs and provided a means to respond to rapid fluctuations of demand that could not be met internally. Even as shifts in the global economy prompted outsourcing and offshoring, the lead firms in global auto supply chains firmly controlled the invention and commercialization of new technologies and the growing number of suppliers involved in producing them.[106] In contrast to modern renewable energy sectors, national automobile industries remained firmly anchored in domestic political economies. They competed with firms from other countries that possessed a similar capacity to invent, commercialize, and produce new cars domestically.

Compare the integrated US auto sector of the 1970s to contemporary electronics firms such as Apple. Not only has Apple entrusted virtually all of its production to third-party suppliers in Asia, but it also relies on these suppliers, most importantly Foxconn, to help prepare its novel product designs for mass production. While Apple stands out among its competitors for its ability to conduct product design activities in the United States, its ability to do so largely stems from its active involvement in the commercialization process in Asia. This involvement includes industrial design, the selection of components, changes to product design to meet manufacturing needs, and the ability to translate between the design and manufacturing process and a customer base in the United States.[107] Like Apple, innovators in advanced economies not only rely on manufacturers for the production of their products but also, increasingly, depend on their R&D capabilities to prepare product designs for mass production.

The idea of a clean energy race that I referenced at the beginning of this chapter is also based on such a template of technological innovation and national competitiveness that Apple and others like it have revealed to be inaccurate. This template assumes the need for co-location of activities related to the invention, commercialization, and manufacturing for novel technologies. In contrast to the system of collaboration and specialization in wind and solar industries, governments often presumed that success in any particular sector required the full range of economic activities related to that particular sector to be located within national borders. The varieties of innovation that exist today in the wind and solar industries are therefore not novel in and of themselves, but relate to engineering skills that have long been required to invent new technologies and prepare them for commercialization and deployment. What *is* new in the empirical cases that I describe is the

[106] Sabel and Herrigel 2018, 235–36.
[107] Pisano and Shih 2009, 119.

fact that such skills are no longer all located in the same firm or region. What once occurred in a single enterprise or a domestic cluster of firms has now manifested in distinct national specializations in global industries that depend on one another to develop new technologies.[108]

Conclusion

This chapter rules out two common explanations for the persistence of distinct national profiles in the global economy: that governments pursued different industrial policy goals, and that they did so using different policy tools. Instead, a common political logic led governments in China, Germany, and the United States to converge on similar policy goals and industrial tools: after policymakers discovered the economic potential of renewable energy sectors, they justified public investments in R&D and subsidies for renewable energy markets with the promise of economic growth and employment. This led governments to combine long-standing policies to support R&D with subsidies to create renewable energy markets, often explicitly tied to local content regulations and other means to attract local industrial activity and manufacturing jobs in particular. State efforts nonetheless yielded distinct national profiles in global industries. In the early 2000s, just after China's WTO accession accelerated changes in the organization of the global economy, firms in China, Germany, and the United States chose different technological specializations and competitive strategies to enter emerging wind and solar industries.

Three broader implications follow from this phenomenon. First, as I have chronicled in this chapter, the national specializations in different types of R&D show that innovation no longer occurs entirely within national borders. Invention, customization, and innovative manufacturing, the three specializations highlighted in this book, constitute different elements of a single innovation process from lab to market that now spans national borders and the boundaries of the firm. Second, the complementarity of these national specializations in renewable energy industries belies the very notion of a clean energy race and the mercantilist approaches to green industrial policy that spring from such reasoning. Since firms in large part competed with other firms within the same economy but had competitive strategies that complemented those of firms in other countries, collaboration, not competition, lay at the heart

[108] A growing literature on global innovation systems has examined the expanding spatial complexity of technological innovation, including in renewable energy sectors. See, for instance, Binz and Truffer 2017, 1286; Markard and Truffer 2008; Wieczorek, Raven, and Berkhout 2015.

of the development of global renewable energy sectors. Third and most important, the phenomenon I describe in this chapter raises a central question to be examined in the chapters that follow: what mechanism explains the distinct national specializations of renewable energy industries in China, Germany, and the United States?