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Introduction

It was a humid summer afternoon when I arrived at an industrial park on the outskirts of Shanghai to tour a solar photovoltaic (PV) firm. In the lobby of the main office building, glass displays advertised the latest technology breakthroughs, touting the firm's efficiency records for converting sun to electricity with different solar technologies. Across town, in one of the firm's manufacturing plants, robotic arms whizzed past in rapid succession to assemble individual solar cells into modules that would be mounted on residential rooftops in Europe. The firm I was visiting constituted part of a group of Chinese companies that had, in just a few years, multiplied global production capacity for renewable energy technologies while rapidly reducing costs. Over the course of ten years, global production of solar PV modules had increased by a factor of 40, much of it driven by Chinese factories. By 2012, barely a decade after the first solar manufacturing plants opened in China, the nation accounted for more than 60 percent of the world's solar manufacturing capacity.

Touring the Shanghai plant, I recognized that the ability to deliver ever more efficient solar panels at lower prices was emblematic of a broader phenomenon. The steady presence of research and development (R&D) teams in China suggested that the rapid rise of this nation's renewable energy industries was not simply the result of greater investments in production capacity. Something else was at play, as well. Chinese firms were succeeding because they were *innovating*, and at a level not conventionally associated with low-cost manufacturing.

In China's leading wind and solar firms, R&D teams were preoccupied with technological improvements that would enable faster and cheaper manufacturing. Solar PV manufacturers all over China had installed "Golden Lines," separate production facilities set up solely for R&D efforts, allowing engineering teams to work without interfering with manufacturing operations. Bringing mass production to emerging renewable energy industries was a feat not just of supportive government policies but also of technological innovation.

At the same time, a steady flow of foreign engineers through China's economic development zones signaled that China's rise as a center for clean energy industries also relied on technological capabilities that had originated in other parts the world. JA Solar, the firm I visited in Shanghai, had worked with Innovalight, a start-up from Silicon Valley, to commercialize a new material for solar PV production—a silicon ink. Innovalight had originally sought to become a solar

manufacturer in its own right. But the American firm lacked manufacturing skills and the type of financing and government support that would allow it to scale its technology easily. Innovalight ultimately signed a joint development agreement with JA Solar in Shanghai. After a year of collaborative research, the team successfully commercialized the technology, yielding a new generation of high-efficiency panels.[1]

The collaboration extended beyond just JA Solar and Innovalight. Like many of its peers, JA Solar sourced components and production equipment from European firms such as Schmid, a German supplier of production equipment for the solar industry. Founded in 1864, Schmid produced saws for lumber mills and manufacturing equipment for furniture before developing printers for electronic circuit boards in the 1960s. In the early 2000s, the company became one of the first producers of designated manufacturing equipment for the solar photovoltaic industry, much of it eventually destined for Chinese plants.[2]

The solar modules rolling off production lines in the industrial suburbs of Shanghai were not solely the result of Chinese innovation. Yet neither were they solely the result of innovation *outside* China, as observers in the West often made it seem.[3] The renewable energy firms dotting China's economic development zones offered a model of industrial innovation that was at once global and local. The technological capabilities and R&D efforts underpinning JA Solar's solar panels and other renewable energy firms in China relied on a global network of highly specialized firms that collaborated on technological innovation. At the same time, these firms' specialized skills remained deeply reliant on institutions, public resources, and government policies in their countries of origin. Their global partners made use of local, publicly funded institutions ranging from vocational training for small and medium-sized manufacturers in Germany's Black Forest to government research programs underpinning the tech firms of Silicon Valley. Renewable energy manufacturers in China also relied on public support, as provincial and municipal governments in China created a vast infrastructure for mass production in the nation's economic development zones. This infrastructure proved instrumental in allowing Chinese wind and solar manufacturers to focus on scale and cost in the commercialization of new technologies. The rise of this global division of labor in industrial innovation, and its links to changes in the organization of the global economy, national policies, and institutions form the subject of this book.

[1] Nahm and Steinfeld 2014, 297.
[2] Nahm 2017b, 83.
[3] Fialka 2016.

A Global Division of Labor

This is a book about the development and persistence of distinct national industrial profiles in a global division of labor. My aim is to demonstrate that new opportunities for collaboration in the global economy have reinforced national patterns of industrial specialization in technological innovation and the institutions that support them. As I show in the chapters that follow, this is the case particularly in emerging industries, such as wind and solar, where the absence of incumbent firms would lead us to expect nations to break more readily with industrial practices of the past.

In the decades before international economic integration made it easier for firms around the world to work together on tasks ranging from innovation to production, differences in national capitalisms—the institutions, actors, and relationships governing the domestic market economy—yielded equally distinct national industrial profiles for innovation, production, and competitiveness. National economies specialized in inventing and producing different types of products precisely because domestic arrangements did not lend themselves equally to all types of competitive strategies.[4] Entire industrial sectors were contained within national borders. Trade enabled the exchange of products and led to direct competition between economies that contained similar industries.

Economic globalization has changed this arrangement permanently. Many of the activities that make up the global economy now lie beyond the territorial reach of individual economies, challenging the primacy of states as organizing units for industrial sectors. These changes have been accompanied by concerns about the ability of states to preserve national differences in economic practices, industrial capabilities, and the institutions that support them.[5] A core contribution of this book is to show not only that the forces of international economic integration continue to be mediated by distinct domestic institutions but also that they actually strengthen divergent national capitalisms over time. My central argument is that globalization causes a persistent and consequential divergence of industrial specializations and national institutions.

Let's return to the example of the Shanghai solar manufacturer. JA Solar operated its manufacturing plants with a division of labor between firms from three different continents: from China, JA Solar contributed skills in manufacturing innovation; from Germany, Schmid delivered production equipment; and from the United States, Innovalight offered a novel material to increase the efficiency of solar panels. Although each firm maintained a set of skills in keeping with

[4] See, for instance, Hall and Soskice 2001.

[5] For a review of arguments about convergence as a result of competitive pressures in the international economy, see Berger 2000.

traditional industrial strengths within its country of origin, the collaboration among the three companies made each individual specialization functionally viable and economically successful in the emerging global solar industry.

The Chinese manufacturer did not replace the skills of its German and US partners with a set of capabilities established in-house, even if the Chinese government openly wished for more national autonomy in technological innovation.[6] The firm focused, instead, on a set of core skills in commercialization while relying on partnerships with others to access expertise in the development of new technologies and production equipment that were not well supported in China's domestic economy. These relationships between firms with complementary skills challenge prevailing expectations that the dynamics of our global economy undermine distinct national competitive strategies and the institutions that support them—particularly those in advanced industrialized economies. They also suggest the need for a new account of the linkages between changes in the global economy, national institutions, and firms' specialization in distinct sets of technological capabilities.

Changes in the international economy and their domestic effects have long been the subject of research in the social sciences. Throughout the 1980s and 1990s, new digital technologies, changes in global financial markets, and the evolution of international economic institutions spurred a reorganization of global production. This rise of cross-national supply chains changed industries that had previously existed within national borders. Where national industries once rivaled one another, competition now shifted to contending networks, each of which linked or connected firms from industrial backgrounds and geographical locations.[7] The present study contributes to these debates by offering a "shop floor" account of how the reorganization of the international economy made it easier for firms to enter new industries through ever-narrower specialization while relying on collaboration with others to access skills that they no longer possessed in-house or could source from their own domestic economy.

I employ the concept of *collaborative advantage* to capture the connection between these changes in the global economy, firms' competitive strategies, and their engagement in domestic political economies. Collaborative advantage describes the creative process through which firms insert themselves into globalized production systems. Two types of experimental action enable firms to reap benefits from participating in the global economy (Figure 1.1). First, thanks to new opportunities for collaboration, firms can participate in a global division of labor that allows them to specialize. This *economic* manifestation of collaborative advantage captures the creative process through which firms identify and act on

[6] Kennedy 2013.
[7] Camuffo 2004; Langlois 2002.

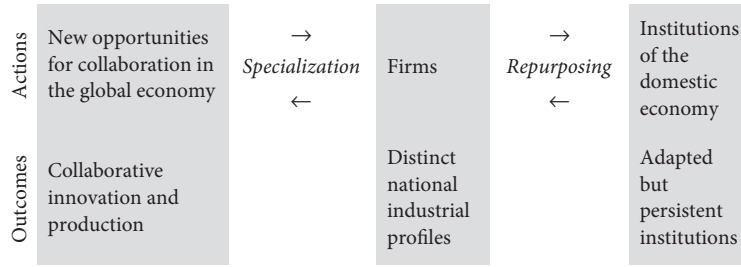

Figure 1.1 Collaborative Advantage

opportunities to compete in global industries. Second and in turn, these new possibilities for specialization allow firms to repurpose existing institutions for application in new industries. This *political* manifestation of collaborative advantage drives the persistence of legacy institutions within the domestic economy and causes their iterative reorientation toward new, global industrial sectors. As the two actions that constitute collaborative advantage, specialization and institutional repurposing together explain why distinct national industrial profiles persist in today's global economy.

Economically, collaborative advantage describes the importance of specialization in the global economy. As I show in the case of wind and solar industries in China, Germany, and the United States, globalization has created new possibilities for collaboration that relieve firms of the need to establish in-house the full range of production and innovation capabilities required to bring a new product to market. The existence of other specialized firms has made it possible for these firms to access necessary skills through collaboration in global supply chains. Globalization has made it easier to find such partners, even if they are dispersed geographically. When collaboration enables firms to specialize, the skills required for innovation—defined here as the process by which new and improved technologies are developed and brought to market—are rarely organized within a single enterprise or even a single economy. Firms and the economies in which they are located no longer have to be self-sufficient. They no longer need to be located near one another. What's more, local strengths in a particular type of industrial activity no longer necessarily lead to the attraction of related skills into the local economy. Simply put, these firms are able to compete in global industries through specialization while relying on collaboration with others.

Politically, collaborative advantage manifests in the ability of firms to repurpose existing institutions for application in new industries. Rather than establish in-house the full range of skills required to bring a new product to market, firms can pick among individual steps in the development, commercialization, and production process when strategizing how to enter new industrial sectors.

Firms use these new opportunities for specialization to make their way into new economic sectors that build on existing industrial capabilities within the firm and the domestic institutions that support them. Such institutions include the domestic financial sector, the labor market and vocational training institutions, and government programs to support R&D. Specialization allows firms to appropriate and repurpose these resources to compete in new industries sometimes far removed from their founding or original purpose.

Although industrial legacies and the presence of different types of institutions constrain what types of activities can be carried out in different economies, institutions are not incapable of change. Under the right circumstances, they can be reinvented and support firms as they respond to new opportunities in the global economy. Globalization allows firms to repurpose existing institutions for new industrial contexts, presenting a set of resources for experimentation and adaptation. These resources, in turn, ignite imagination. Globalization allows for creativity and experimentation precisely because it has opened up new possibilities for specialization. Domestic institutions no longer fully define how firms choose to enter new industries or which firms are able to do so.

The distinct national industrial profiles that I document in this book resulted from just such creativity and inventiveness. They built on domestic institutional resources while taking advantage of new opportunities for specialization. It is precisely because collaboration allowed for industrial specialization that firms in Germany were able to enter wind and solar industries that made use of traditional vocational training institutions and banking relationships. It was for the same reason that Chinese firms were able to break into global supply chains with R&D skills in commercialization: they experimented with the manufacturing infrastructure established since the beginning of economic reforms by China's subnational governments. Collaborative advantage reverses the logic that has portrayed distinct national political economies as fundamentally threatened by the competitive pressures resulting from three decades of globalization: specialization and repurposing explain why globalization leads to persistent and consequential divergence of institutions and national industrial specializations over time.

In my opening vignette, we saw a set of firms with industrial specializations that depended on one another yet remained deeply grounded in domestic institutions in their home economies. By exploring this phenomenon through the lens of collaborative advantage, this book brings together two perspectives that have often been considered separately in research on globalization, technological innovation, and industrial specialization: a focus on the policies and institutions that influence firm behavior at the national and subnational level, and the analysis of changes in the global organization of production and innovation. Collaborative advantage contests depictions of globalization as being solely

or even primarily about competition, and offers an interpretation of the nature, drivers, and consequences of international economic integration through the lens of collaboration. Using the empirical cases of global renewable energy industries, I aim to show not just that collaboration is central to shaping the international division of labor but also that it fundamentally changes how firms respond to the policies and institutions of the state.

While this book is not the first to link these debates, it offers a novel perspective on the mechanisms behind institutional endurance—and on the nature of globalization more broadly. Over the past three decades, explaining the consequences of globalization has become a central area of inquiry for scholars of political economy. One avenue of research has understood globalization primarily as a process of reaping gains from international trade based on comparative advantage. Grounded in the notion that factor endowments shape nations' relative opportunity costs for specializing in the production of some goods over others, this position has focused on the circumstances that allow and prevent nations from realizing the benefits of greater economic integration.[8] A second avenue of research, centered on increasing competition, has approached international economic integration from a domestic perspective. Without refuting potential gains from trade, such research has nonetheless focused on the constraints imposed on states by the international economy. Research in this tradition has examined what options remain for policymakers to respond to an ever more unpredictable global economic context—and how political choices shape the ability of domestic firms to engage the global economy.[9]

The analytical approach I have taken builds on these approaches and stresses both the interdependence of firms' choices about participation in the global economy and the embeddedness of these firms in domestic institutions. I unpack not only how firms in emerging industries collaborate to develop new technologies, but also how such relationships change the ways in which firms engage domestic political economies. In particular, I make the point that international economic integration and distinct domestic political economies are not locked into a zero-sum game in which states actively try to push back on global competitive pressures to maintain national differences. By showing how specialization allows firms to engage the global economy in new ways that build on and support existing domestic institutions, this book instead makes the case for a firm-based mechanism for institutional endurance.

The remainder of this chapter places governmental goals to create innovative domestic industries within the broader context of changes in the global economy. I argue that the reorganization of the international economy necessitates both a

[8] Samuelson 1938, 265.
[9] Baldwin 2016, chapters 7–8; Breznitz 2007, 4–6.

new understanding of technological innovation and a recasting of state-business relations. I then briefly introduce the core empirical outcome explained in this book—the development of distinct patterns of industrial specialization in wind and solar industries in China, Germany, and the United States—and I suggest that renewable energy sectors provide a particularly compelling analytical window into the drivers behind the global division of labor in technological innovation.

Innovation and the State in a Changing Global Context

The creation of innovative domestic industries has long captured the attention of policymakers. Government officials in China, Germany, and around the world continue to look to the United States—and Silicon Valley in particular—as a model of the powerful economic forces unleashed by technological innovation. The flow of political delegations through the district most known for its global technology giants demonstrates the importance governments worldwide have attached to technological innovation, and it reflects the status ascribed to the United States as a seedbed for innovative firms.[10] Hoping to replicate the region's success, governments have attempted to encourage similar clusters of high-technology enterprises at home.[11] Silicon Roundabout in Britain, Silicon Saxony in Germany, and Optics Valley in China all exemplify the belief that firms capable of high-technology innovation are critical to a modern economy and that governments play an important role in facilitating their creation.

In the postwar decades, governments in rapidly developing East Asian economies employed strategic intervention to encourage domestic enterprises to catch up with the innovative firms in the West. Underlying such government ambition was the notion that economic development entailed the progressive advancement from commodity production to the invention and commercialization of new technologies. To help domestic enterprises compete with incumbent firms in global industries, the state channeled support to select industrial groups. As Alice Amsden documented in the case of South Korea, a set of performance requirements made government support conditional on the continuous improvement of R&D capabilities to avoid the corruption and rent-seeking often associated with state subsidies.[12] Through a mix of public and private efforts, Korean and Japanese conglomerates rose through the ranks of global electronics

[10] Boudreau 2012; Kopytoff 2014; Traufetter 2013.

[11] Gunnar Trumbull has detailed state efforts to remake a domestic Silicon Valley in France. See Trumbull 2004.

[12] Amsden 2001, 8–12.

and auto industries, some eventually beating firms in advanced economies at their own innovative game.[13]

Governments in the West were also unwilling to leave innovation to market forces, a reluctance driven by reasons ranging from national competitiveness to national security. In the United States, the Cold War strengthened the impetus for public investments in R&D and helped lead to the eventual development of new civilian technologies—and the high-technology clusters such as Silicon Valley that sprang up around them.[14] Meanwhile, among European economies weakened by World War II, concerns about permanently falling behind the growing capabilities of the US economy drove state support for innovation. Public R&D funding for research institutes and enterprises aimed to encourage the competitiveness of domestic industries, particularly those of broader societal and economic importance. In addition to basic research and research with defense applications, governments funded innovation in sectors from automobiles and aerospace to health and energy.

In advanced and developing economies alike, public support for innovation rested on the assumption that the invention of new technologies would attract industrial activities beyond innovation itself. In the postwar decades, technological innovation often required the establishment of manufacturing facilities on site or nearby, as well as large numbers of suppliers who could successfully bring products from the laboratory to market. With their engineering teams focused on the various stages of product development and commercialization, large enterprises proved particularly capable of managing the linkages between these myriad R&D activities and local suppliers.[15] Public support for R&D was driven not by concerns about which elements of a broader division of labor to establish within national borders, but by the expectation that investments in R&D would lead entire industries to locate domestically. Public support for innovation was thus the lynchpin of broader governmental initiatives for industrial development and economic growth more generally.

Since 2000, government delegations touring Silicon Valley have retained the hope that public support for innovation will create thriving domestic industrial sectors.[16] High-technology industries, the conventional wisdom has held, create jobs not just in R&D but also in a broad range of connected activities along the trajectory from lab to market, including in manufacturing. Public investments

[13] Such accounts of the East Asian the role of industrial policy in the developmental states were not uncontested. See, for instance, Krugman 1994; Samuels, 1987; World Bank 1993.

[14] Lécuyer 2007.

[15] Chandler and Hikino 1997.

[16] There are, of course, economic benefits from high-tech sectors even without the simultaneous attraction of supplier industries and manufacturing. For a study of the benefits of attracting high-tech industries into US urban economies, see Moretti 2012.

in R&D in Germany have been expected to yield German industries that would compete, for instance, with French industries across the border.

Yet as my opening example of Shanghai's solar PV manufacturer illustrates, the organization of the international economy differed from the situation faced by firms in postwar East Asian developing economies and their European and American contemporaries. Rapid economic development had established China as the world's second-biggest economy in just a few decades. Starting in the early 1990s, a series of novel digital technologies had made it feasible to physically separate early R&D and commercialization, as blueprints and production specifications could be electronically transmitted around the world. Many firms subsequently focused on core skills in the development of new technologies while moving production activities to low-cost locations abroad.[17] In the United States in particular, financial markets began to reward such restructuring: these shifts relieved corporations of the financial burden associated with the capital-intensive construction of new manufacturing facilities.[18]

But these changes were not one-dimensional. Although the inventors of Silicon Valley were no longer geographically tethered to many commercialization and production activities that used to occur within their four walls, policymakers continued to presume tight managerial and geographical linkages between innovation and production. The emergence of truly global supply chains transformed the connections between the activities required to bring new technologies to market: economic globalization made it easier to access a broad range of technologies and skills through collaboration, while it also dispersed these same technologies and skills geographically. Rather than establish in one place the full range of R&D capabilities required to develop, commercialize, and produce new technologies, firms began to specialize and make use of new opportunities for collaboration in their global networks. The fragmentation of production and the rise of global supply chains further accelerated this process. Now capable of far narrower activities than the firms of the past, the players in this new global economy learned to access needed skills through collaboration. The United States continued to lead in the number of start-ups created domestically; in the context of economic globalization, however, these start-ups also proved far more likely to rely on technological capabilities located elsewhere to bring their products to market. Skills in commercialization and mass production, for instance, became increasingly rare domestically, as the center of global manufacturing shifted to China (Figure 1.2).

[17] Baldwin and Clark 2000; Berger 2005a, chapter 4; Sturgeon 2002.

[18] Gerald F. Davis documents how financial markets forged the restructuring of the US model of industrial organization beginning in the 1990s. See Davis 2009.

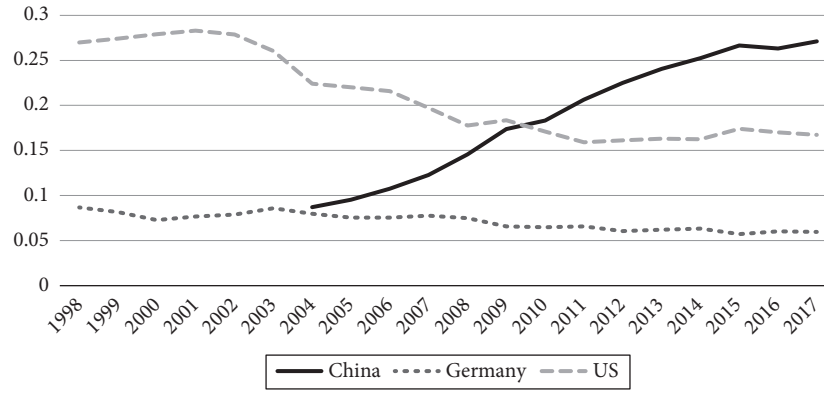

Figure 1.2 Selected Countries' Shares of Global Manufacturing Value Added.
Source: UN National Accounts Main Aggregates Database, value added by economic activity, at current prices—US dollars.

The image of Silicon Valley as the paragon of innovation-based economic success has remained prominent among policymakers around the world. Yet the global organization of production and innovation, the linkages between the activities required to bring new technologies to market, and the geography of actors involved in such activities had fundamentally changed since the postwar decades. If there was a lesson to be learned during my visit to Shanghai's solar manufacturer, it was that the payoffs from government investments in technological innovation were no longer guaranteed to manifest domestically. This book examines the division of labor in technological innovation in this new global context.

Renewable Energy Industries in the New Global Economy

What drives national patterns of industrial specialization in an era when many of the activities that make up the global economy have shifted beyond the territorial reach of individual states? What can states do to support the growth of innovative industries in their home economies within this new reality? How do firms engage their domestic economic institutions as they reach for new opportunities in global supply chains? I examine these questions through a comparative investigation of the development of wind and solar sectors in China, Germany, and the United States. Three factors make renewable energy industries a particularly compelling window onto these national patterns as they are unfolding.

First, wind and solar industries evolved *after* the reorganization of the global economy. Existing literatures have long examined the transformative effects of

globalization on innovation and industrial organization in legacy industries. Such research has attributed changes in the location of major industrial activities to the competitive forces of globalization. Some scholars have traced the impact of digital production technologies on the global organization of the computer industry.[19] Others have examined the effect of globalization—including the establishment of NAFTA, China's WTO accession, and other changes in international economic institutions—on the structure of the global auto industry.[20]

In contrast to established industries, whose origins long predate the reorganization of the international economy, firms that produced wind turbines or manufactured solar panels did not reach scale-economies until the early 2000s.[21] By focusing on postglobalization industries, this book removes from the analysis the politically contentious process of restructuring legacy industries: put another way, wind and solar sectors allow us to separate the effects of globalization on preexisting industries from the development of new industrial sectors that sprang up under globalization. My argument is that collaborative advantage has the strongest effect in industries lacking powerful incumbent firms and legacy production structures. It is here we see significant impact on the division of labor and domestic institutions.

Second, I focus on wind and solar industries because they are based on two very different underlying technologies. These technologies result in divergent production requirements, supply chain structures, and engineering challenges. Wind turbines, with many moving parts, long lists of components, and sophisticated material needs, require complex production arrangements across a large number of firms. An average wind turbine contains components assembled from more than 8,000 individual parts, which are produced by more than 1,000 different suppliers.[22] The production of solar panels, by contrast, comprises far fewer actors and thus has a much shorter supply chain. Manufacturing of crystalline silicon solar PV modules, the dominant technology in the solar industry, occurs in five major steps, sequentially arranged from the production of silicon through the cutting of wafers to the production of cells and subsequent assembly of modules. The production of solar panels based on second-generation thin film technologies is concentrated even further in a single production line.[23]

Why do these differences matter? They help demonstrate that the argument presented here applies across technologies and supply chain structures. In the wind industry, international economic integration enabled the globalization of clusters of firms. Since many component parts of wind turbines are too heavy to

[19] Baldwin and Clark 2000.
[20] Doner, Noble, and Ravenhill 2006; Thun 2006.
[21] Berger 2013b, 40–41.
[22] American Wind Energy Association 2015.
[23] Shah and Greenblatt 2010, 77–98.

be shipped economically, assembly frequently occurs in close proximity to the final site of installations. Wind manufacturing firms and their suppliers therefore established clusters in close proximity to final markets around the world, not dissimilar to the car industry. The solar sector, by contrast, presents a case of transnational supply chains, in which different production steps occur in different parts of the world, and components are easily shipped from one location to another as they progress toward the final product. Comparing cross-national patterns of technological innovation across two such different technologies and supply chain structures allows my research to isolate the influence of technology: if collaborative advantage in the global economy enables firms in a particular economy to specialize in similar technological activities across two different industrial sectors, then specialization must be the result of factors other than the technology itself.

Third and most important, renewable energy industries offer a particularly lucid empirical context for investigating the changing impact of state-business relations on national patterns of industrial specialization. Arguably more than any other set of industries, renewable energy sectors have come to exemplify the aspiration of governments to cultivate domestic high-technology industries through targeted state intervention over the past two decades. In 2014, more than seventy countries used subsidies and energy market regulation to stimulate domestic demand for renewable energy technologies. Advanced and developing economies from Algeria to Yemen set targets for the share of domestic energy to be generated from renewable sources. Globally, governments spent more than USD 5 billion on renewable energy R&D in 2014 alone.[24]

Government support for renewable energy industries has, of course, been justified by the need to switch to cleaner sources of energy for environmental reasons. Concerns about climate change have motivated citizens and governments alike to encourage energy transitions away from fossil fuels.[25] Yet few governments have supported wind and solar sectors solely on environmental grounds, despite their significance for combating the effects of climate change. Political support for renewable energy transitions and the public funds required to initiate and sustain technological change have depended on the promise of tangible benefits for the broader economy, in particular through the creation of domestic industries. These promised benefits took on added importance as clean energy industries became sizable global sectors. In 2018, the world spent more than USD 300 billion on low-carbon energy technologies (Figure 1.3).

States that have successfully supported the establishment of renewable energy firms have been able to adopt more ambitious climate policies with the help of

[24] REN21 2015, reference tables.
[25] REN21 2020.

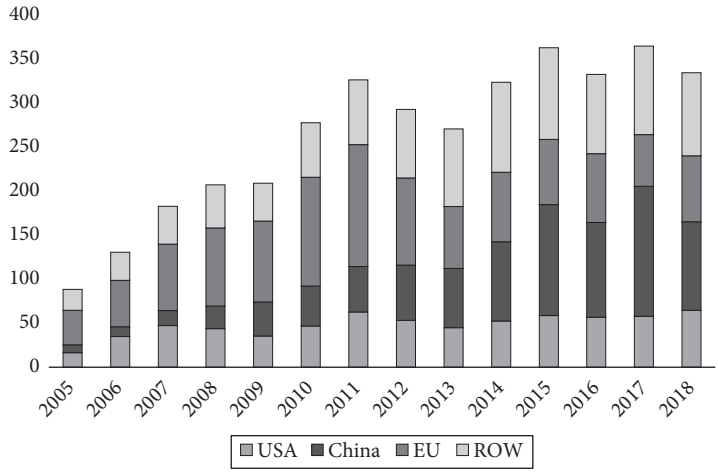

Figure 1.3 New Investment in Clean Energy Technologies (USD Billions)
Source: Bloomberg New Energy Finance

industrial coalitions and public support.[26] Other governments have seen wind and solar sectors as purely export-oriented industries, supporting them despite a lack of any ambition to use them for domestic green energy transitions in the short term.[27] As a consequence, these governments have justified the use of public funds for wind and solar industries by pointing to the potential for job creation, national competitiveness, and the need to target emerging high-technology firms in strategic industrial sectors.[28] For these states, environmental benefits alone are not enough.

Despite their differences, governments pursued remarkably similar industrial policy goals when they encouraged the development of renewable energy industries. In China, Germany, and the United States, the cases examined in this book, the state encouraged technological innovation through R&D policies, at least partly in the hope that the development of new wind and solar technologies would spur the growth of competitive domestic industries. But because electricity generated from renewable sources was not yet competitive with conventional sources of energy, governments in all three economies also employed subsidies and energy market regulation to create domestic demand for wind and solar technologies. Clearly, cross-national differences existed in the implementation of such policies, in the size and duration of subsidies, and in the conditions for

[26] Laird and Stefes 2009; Meckling et al. 2015.
[27] Zhang, Andrews-Speed, and Ji, 906–8.
[28] Zysman and Huberty 2013, xi–58.

government support. Yet by combining push-and-pull, technology-and-demand approaches to industrial policy and technological innovation, governments in China, Germany, and the United States came to share something in common: the aspiration to create firms capable of inventing, commercializing, and manufacturing renewable energy technologies domestically.[29]

The core empirical contribution of this book concerns the persistent and consequential divergence of national industrial specializations. Such divergence occurred despite similarities in state goals and industrial policies and, as mentioned previously, applied to both industries in spite of differences in underlying technologies and supply chain organization. Modern renewable energy industries emerged virtually simultaneously in China, Germany, and the United States, yet firms in each location established distinct industry profiles and distinct national patterns of technological specialization. A large literature in political economy has shown that sectoral dynamics and firms' positions in global supply chains shape firms' policy preferences, including on trade and domestic economic policy. This book, instead, explains why firms in different economies are more likely to choose different technological specializations within the same industrial sectors and, as such, achieve more prominence in some segments of the global supply chains than others.[30]

In the United States, wind and solar firms have typically taken the form of start-ups with skills in the *invention* of new technologies, but with far fewer capabilities in the commercialization and production of these inventions. In 2009, out of 100 solar PV firms operating in the United States, at least 73 were start-ups working on the development of next-generation solar technologies that lacked in-house production capabilities.[31] Few manufacturers existed in the United States with the exception of GE, a multinational producer of wind turbines that also relied on global suppliers for a large share of its components. By contrast, small and medium-sized businesses with skills in the development of componentry and complex production equipment made up the majority of German wind and solar firms. Rather than invest in novel wind and solar technologies, these firms focused on what I call *customization*: the development and small-batch production of equipment and early-stage components to produce new renewable energy technologies. In 2010, more than 70 German firms were offering manufacturing lines for the PV industry, and more than 170 firms developed and produced componentry for the wind energy sector, compared to less than a handful of manufacturers of solar panels and wind turbines.[32] In China,

[29] Nemet 2009.
[30] See, for instance, Hiscox 2002; Lake 2009.
[31] Knight 2011, 176.
[32] Arbeitsgemeinschaft Windenergie-Zulieferindustrie 2012; Germany Trade & Invest 2010, 2011b.

meanwhile, large wind and solar manufacturers focused on the R&D required for commercializing and scaling novel technologies—which I refer to as *innovative manufacturing* in this book. As a result of such investments, Chinese firms became the first to bring wind and solar technologies to mass production. Far fewer firms prioritized the production of manufacturing equipment or the invention of new technologies.[33]

As the example of the Shanghai solar PV manufacturer emphasizes, it was the collaboration among firms with such distinct technological capabilities that made each individual specialization functionally viable and economically successful. Although policymakers aspired to create broad and diversified domestic renewable energy industries, the wind and solar sectors in China, Germany, and the United States established distinct constellations of firms with starkly different technical capabilities. With American strengths in invention, German specialization in complex components and production equipment, and Chinese mastery of commercialization and mass production, we have an example of an interdependent and mutually reinforcing partnership.

Plan of the Book

The collaboration of American, German, and Chinese firms is deeply connected to broader changes in the global economy. These changes, often summed up simply as economic globalization, made it easier for goods, services, and ideas to travel between national centers of economic activity. They also restructured how new technologies are invented, commercialized, and produced. Yet any explanation for the persistence of distinct national industrial specializations during this period of international economic integration also requires an account of the domestic political economies that structured firms' attempts to build and maintain distinct capabilities. Understanding how firms in different economies have arrived at such distinct specializations in global industries requires an approach that places firms' behavior in the context of both domestic institutions and the broader forces of economic globalization. The firm-centered perspective offered here emphasizes the relationship between such changes, domestic institutions, and firm behavior. This book develops the concept of collaborative advantage to span a causal arch between new opportunities for collaboration in the global economy and the reinforcement of distinct national patterns of industrial specialization in technological innovation.

[33] For the concept of innovative manufacturing, I owe a great debt to many conversations with Edward Steinfeld, which led to the publication of a joint article on the subject. See Nahm and Steinfeld 2014.

In Chapter 2, the first of four empirical chapters, I lay out the central empirical phenomenon of this book and show how firms responded to industrial policies targeted at vertically integrated domestic industries in the context of economic globalization. This chapter highlights the similarity of industrial policy frameworks and state goals in the United States, Germany, and China. All three economies combined R&D policy with demand-side subsidies in an attempt to create vertically integrated domestic wind and solar industries. I then show that firms have responded to such similar policies with distinct and far narrower sets of industrial capabilities. I make the case that the domestic links between innovation and production—connections that prompted government policies—are no longer guaranteed in the new global economy. In the United States, the empirical case with the strongest public investments in R&D, firms responded to industrial policy efforts by creating new capabilities in technological invention without linking such skills to domestic capacity in commercialization and production. In Germany, by contrast, small and medium-sized suppliers from the nation's traditional industrial core responded to federal government industrial policy by creating new capabilities in customization. In China, despite the efforts of the central government to encourage the development of upscale R&D capabilities in high-technology sectors, firms responded by building distinct strengths at the intersection of manufacturing and R&D.

Chapter 3 expands on three elements of the central argument and places them in the context of broader literatures on globalization, technological innovation, and institutional change. I posit a theory about how opportunities for collaboration in the global economy have reinforced national patterns of industrial specialization. The chapter develops the concept of *collaborative advantage* to describe the creative process through which firms insert themselves into globalized production systems. It identifies two types of experimental action that allow firms to reap benefits from participating in the global economy. Economically, collaborative advantage captures the ability for firms to specialize as a result of new opportunities for collaboration. Politically, these new possibilities for specialization allow firms to reuprose existing domestic institutions for application in new industries. The ability to enter new industries through specialization shaped firms' responses to national industrial policies. Even where governments aimed at the creation of comprehensive national industries, firms responded with narrow competitive strategies that built on existing skills and prior experience in other industries.

The chapter documents how collaborative advantage made its impact felt through experimentation with institutional legacies across China, Germany, and the United States—a process that led to distinct industrial specializations. Firms chose specializations that were supported by existing economic

institutions, most of them established for other purposes before the emergence of renewable energy sectors. These institutions gained 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 within national borders. The chapter then outlines three structural conditions for collaborative advantage: the rise of global supply chains, nonhierarchical patterns of industrial organization, and opportunities for experimentation in response to state industrial policies.

Chapters 4–6 apply the central argument to the three empirical cases covered in this book. The chapters show that the industrial specialization of these firms relied both on the use of domestic legacy institutions and on the ability to collaborate with global partners. Chapter 4 traces how entrants from legacy industries in Germany used public resources originally intended to support technological innovation in traditional sectors, including machine tools and automobile supplies. The story of these entrants explains why even German firms in new sectors such as wind and solar have reproduced historical patterns of flexible specialization, customization, and small-batch production. Chapter 5 turns to the case of China. I argue that wind and solar firms—often in outright defiance of central government goals—relied on local support for large-scale manufacturing in the process of industrial upgrading. Contrary to the ambitions of policymakers seeking to build autonomous domestic industries, these capabilities were brought to bear on product development in collaboration with global partners. Chapter 6 makes the case that in the United States, a growing divide between an advanced R&D infrastructure and a declining manufacturing sector encouraged wind and solar firms to pursue invention largely divorced from production. Most firms lacked the production capabilities to commercialize and manufacture their innovation in-house and relied instead on the complementary strengths of global partners. In the United States, large public investments in renewable energy research have yielded the smallest industrial footprint of the three cases examined here.

Chapter 7 returns to my comparative analysis and asks what can be gleaned from these cases for our broader understanding of the role of government in industrial policy in fragmented, global sectors. I present comparative data from the automobile and electronics industries to show that even in legacy sectors, distinct national patterns of industrial specialization have shifted the nexus of innovation to global collaboration. I conclude with a reminder that global collaboration—and collaboration with China in particular—will continue to be essential to addressing the climate problem, now and in the future. Voices across the political spectrum in Washington have begun to advocate for economic

decoupling from China. Beijing, too, has amplified calls for technological self-sufficiency. Few industries have more at stake in these battles than those producing the clean energy technologies urgently needed to reduce global greenhouse gas emissions. The division of labor I outline in this book is not fixed or inevitable, yet, in the short-term, it is highly unlikely that governments will be able to alter the relationships underpinning global renewable energy industries without jeopardizing global climate goals.