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China's Specialization in Innovative Manufacturing

China has not always been an obvious location for innovation in clean energy technologies. For all the headlines generated by China's ascent in the global economy, technological innovation has—until recently—rarely featured in debates about China's role in global supply chains. Since the early 2000s, its share of global manufacturing output has more than tripled, from 6.9 percent in 2001 to over 25 percent in 2015—surpassing the United States as the world's largest manufacturer starting in 2010. Accordingly, observers focused on China's low-cost production environment to understand its contribution to the global economy.[1] Chinese firms attracted attention not with their research and development (R&D) capabilities, but with the sheer scale at which they manufactured commodities for Western markets. In 2002, Wenzhou, an industrial city in Eastern China, produced 70 percent of the world's cigarette lighters, singlehandedly causing a trade dispute with the European Union.[2] Even as Chinese firms quickly became proficient in the production of ever more complicated products—China surpassed the United States as the world's largest assembler of computer hardware in 2004, and in 2006 it became the world's largest exporter of high technology products—China's role in the global division of labor was long understood in terms of its advantages in low-cost production.[3]

China is an unexpected location for clean energy innovation for a second reason. Beginning in the mid-1990s, a combination of rapid economic growth and lax environmental enforcement triggered an air environmental crisis of unprecedented magnitude. Transportation emissions, industrial facilities, and coal power plants built to feed the energy demands of industry and a growing urban middle class spread a problem once confined to industrial centers in Northeast China to most of the coastal and interior provinces. Pollution levels in major cities at times exceeded conventional measurement scales, as official weather

[1] Levinson 2017, 3; Marsh 2011; UNIDO 2020.

[2] China Daily 2002.

[3] Meri 2009; Yang 2006. A focus on China's low-cost production environment (and inability to innovate) is prevalent both in academic and popular writing. See, for instance, Fishman 2005; Lardy 2002, 134–76; Nolan 2012; Zhang 2006. For a critical discussion of China's ability to innovate, see Economist 2012; Segal 2010.

reports continued to refer to pollution as "haze." In 2015, an online documentary about smog and its public health effects in China gathered more than 200 million views before being banned from the Chinese internet after 48 hours.[4]

Amid this environmental catastrophe, China nonetheless became the location of the world's largest clean energy industries.[5] Over the past two decades, China's renewable energy firms launched manufacturing facilities capable of producing more wind turbines and solar panels than the rest of the world combined. Between 2000 and 2010, China increased the domestic production of solar modules from 3 MW to 10,852 MW, while wind turbine manufacturing grew from 80 MW to almost 19,000 MW annually.[6] By 2016, China accounted for 81 percent of the world's manufacturing capacity for solar PV. It installed 42 percent of the world's wind turbines that same year, virtually all of them manufactured domestically.[7] The conventional narrative that China is one of the world's largest polluters is thus incomplete, if not misguided: it fails to take into account the dramatic developments in Chinese clean energy industry over the past twenty years.

This chapter chronicles the development of China's renewable energy sectors to make two central claims: First, the chapter demonstrates that China's role in global renewable energy industries was rooted in a set of R&D capabilities that I refer to as *innovative manufacturing*. Challenging views that have portrayed China's rise in the global economy as a function of factor cost advantages, I show that China's wind and solar manufacturers established R&D divisions focused on technical capabilities in commercialization and design for mass production. In the early 2000s, when Chinese wind and solar manufacturers first entered these emerging sectors, wind turbines and solar panels had never truly been mass-produced. The rapid translation of new energy technologies into mass-manufacturable products required changes to product designs to accommodate new manufacturing equipment, the incorporation of new materials and components to improve efficiency, and modifications to product architecture to lower production cost. Because Chinese firms found core technologies accessible through collaboration in global supply chains, they used central government R&D funding to build capabilities that their foreign partners could not provide: specifically, the engineering and design skills required to prepare new technologies for commercialization and to implement mass production in nascent renewable energy industries.

Second, and perhaps counterintuitively, this chapter shows that China's particular variety of innovation relied on the adaptation and repurposing of local

[4] Wong 2015.
[5] Guan et al. 2009.
[6] Earth Policy Institute 2020.
[7] Ball et al. 2017, 18; GWEC 2017, 16.

Actions	New opportunities for collaboration in the global economy	→ *Specialization* ←	Firms: Industrial legacy of mass production	→ *Repurposing* ←	Local institutions: development banks, land, and tax breaks for production, engineering schools
Outcome	Collaborative innovation and production		Firms establish skills in *innovative manufacturing:* R&D focused on scale-up to mass production		Adapted but persistent institutions

Figure 5.1 Industrial Specialization in China

government support for the manufacturing economy. China's central government in Beijing pursued a vision of industrial upgrading and economic development centered on technological independence and vertical integration in domestic industries through the support of national champions. Yet the presence of collaborative advantage allowed wind and solar manufacturers to respond to such policies with the establishment of R&D skills that took advantage of local government resources for mass production, even when they did not explicitly target such industrial upgrading. Entrepreneurial firms identified opportunities for specialization beyond the scope of central government goals and deployed the tools available in China's industrial ecosystem to advance their skills in commercialization. This ability of Chinese manufacturers to diverge from central government goals was predicated on their close relationships with firms in Germany and the United States: collaboration relieved Chinese firms of the burden of developing the full slate of industrial capabilities required to invent, commercialize, and produce green energy technologies; and it paved the way for China's particular specialization in innovative manufacturing (Figure 5.1).

Earlier I showed how, in Germany, small to medium-sized enterprises (SMEs) from the traditional industrial core that entered renewable energy industries depended on demand from and collaboration with Chinese manufacturers. This chapter discusses the flipside of this partnership. In the presence of collaborative advantage, Chinese firms strategically exploited the divergence between the central governmental goals of technological independence and the local governments that continued to support mass production and that remained wary of investing in long-term innovation strategies. Collaborative advantage allowed Chinese firms to become central nodes in technological innovation in the wind and solar industries while taking advantage of a fragmented domestic industrial policy regime.

This chapter begins with a discussion of the links between China's emerging wind and solar industries and China's broader manufacturing economy. It then uses firm-level data to explain the establishment of Chinese capabilities in innovative manufacturing—R&D skills targeting the commercialization and rapid scale-up to mass production. The second half of this chapter examines the role of collaborative advantage in enabling firms to specialize in innovative manufacturing. It then shows that collaborative advantage allowed renewable energy firms to build on and repurpose local government institutions for mass production that diverged sharply from central governmental goals. The conclusion returns to the implications of China's rise in renewable energy sectors for broader debates about industrial policy and economic development in highly globalized industries.

Scale-Up Nation

In Chapter 2, I showed that a political logic led governments to connect green industrial policies with the expectation of economic co-benefits in the form of growth and employment. These expectations soared the highest in China, which had always regarded renewable energy industries as potential sources of export-oriented development. Differences did occur in the timing of policy support for wind versus solar—the central government had emphasized creating national champions in the wind industry since the late 1990s, while the solar industry in China had initially benefited the most from subnational subsidies for manufacturing and was not included in central government plans until 2009. Nonetheless, the government's treatment of both industries mirrored the broader trajectory of economic development policy in China, which shifted from learning through the attraction of FDI to an emphasis on technological autonomy (Table 5.1).

The release of China's indigenous innovation strategy in 2006 underscored the expectation that the Chinese economy would eventually invent and commercialize homegrown technologies in key industrial sectors without foreign assistance. After technology imports had given way in the 1990s to technology transfers to Chinese firms, the central government declared the pursuit of "indigenous innovation" (*zizhu chuangxin*) a central goal of the Eleventh Five-Year Plan (2006–2010).[8] China's strategy of trading market access for technology had not achieved the desired results among domestic technology firms, and the leadership—informed by a caucus of more than 2,000 scientists, engineers,

[8] State Council 2006.

Table 5.1 Shifting Priorities for Science and Technology Funding

1988–1995 **R&D investment, technology imports**	**1996–2005** **First increase, then reduction of FDI dependence**	**2006–** **Promotion of indigenous innovation**
• Invest in R&D infrastructure • Promote university spin-offs • Promote transformation of R&D into marketable products • Promote establishment of high-technology zones in new localities • Attract research institutes to HTZs • Attract foreign investment to HTZs to increase competitiveness of local tech firms	• Establish production bases for high-tech industries in HTZs • Encourage new technology-based industrial sectors • Since 2001, encourage HTZs to return to original mission, reduce FDI dependence and promote innovation in domestic firms	• Promote "indigenous innovation" • Reduce reliance on technology imports • Preferred government procurement for domestically developed technologies • Encourage SME-based technology clusters • Encourage Chinese scientists and entrepreneurs to return to China from foreign universities and enterprises

Source: Heilmann, Shih, and Hofem 2013.

and corporate executives—decided that the nation was ill-equipped to solve challenges independently in areas critical to China's future development. These included energy, environmental protection, and health.[9] Two documents issued by the State Council in January 2006—the "Medium- and Long-Term Strategic Plan for the Development of Science and Technology" (MLP) and the "Decision on Implementing the MLP and Improving Indigenous Innovation Capability"—laid out the central leadership's intention to place indigenous innovation at the core of China's developmental strategy.[10]

Apart from setting targets to further increase R&D spending to 2.5 percent of GDP and to reduce reliance on foreign technologies, the MLP selected a range of core industrial sectors for special treatment, energy among them.[11] It supplied a list of government instruments for achieving such goals, including the procurement of domestic technologies, the development of domestic

[9] Cao, Suttmeier, and Simon 2006, 38–39.

[10] OECD 2008, 389; Schwag Serger and Breidne 2007; State Council 2006. See also: Xinhua, 2006, "China Outlines Strategic Tasks for Building Innovation-Oriented Country," http://english.people.com.cn/200601/09/eng20060109_233919.html (accessed May 10, 2021).

[11] Specifically, the MLP called for a reduction of reliance on imported technology from 50 percent to 30 percent by 2020, measured as spending on technology imports as part of overall spending on domestic R&D and foreign technology purchases. Ernst 2011, 24.

Table 5.2 Select Industrial Policies for China's Wind and Solar Sectors

	China
Technology Push	Since **1986** R&D funding for applied research through "863 Program" **2008** "Indigenous Innovation" Initiative **2010** "New Energy" included under Strategic Emerging Industries **2015** Made in China 2025 Initiative
Market Pull	**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

technology standards, a range of tax benefits and subsidies for R&D, the improvement of intellectual property rights practices, the improved use of technology standards, and international collaborations to accelerate learning among domestic firms.[12] Central science and technology (S&T) programs, including the so-called 863 Program for applied research, received increased funding as a result, and funds for core research areas were adjusted accordingly. The 863 Program now included ten focus areas, including energy technologies, and sought to further increase the proportion of funds supplied to enterprises rather than to universities and research institutes, which had long won the majority of grants (Table 5.1).[13]

In the renewable energy sector, the indigenous innovation guidelines stimulated the aggressive expansion of renewable energy markets and increased support for domestic R&D activities. In 2006, the central government passed China's first renewable energy law, which provided a framework for introducing feed-in laws similar to those in Germany. The law also built the legislative foundation for cost-sharing mechanisms aimed at recovering the cost of renewable energy subsidies through rate-payer surcharges. The Medium- and Long-Term Plan for Renewable Energy Development, issued in 2007, fixed targets for renewable energy markets in China that had been introduced in the renewable energy law: the plan mandated that 15 percent of energy demand must be met from renewable sources by 2020.[14] It also called for the installation of 30 GW of wind turbines as

[12] A short overview of the MLP guidelines for implementation can be found in OECD 2008, 390. Annex F (*China's Policies for Encouraging Indigenous Innovation of Enterprises*) of the same volume lists policies in more detail. OECD 2008, 613–30.

[13] Tan and Gang 2009, 2–4.

[14] Lewis 2013, 53.

well as 1.8 GW of solar photovoltaic (PV), although both 2020 targets have since been revised to 200 GW for wind and 20 GW for solar, respectively.[15] In 2009, the central government eliminated individual feed-in laws set up in various provinces in the wake of the renewable energy law and 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.[16]

At the same time, a 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. For smaller installations, the Golden Roofs Initiative provided a subsidy of USD 2.63 per watt, covering up to half of the total installation cost. The Golden Sun Program reimbursed up to 70 percent of the installation cost for utility-scale installations.[17] These subsidies for a domestic solar PV market came after the global financial crisis had led many European governments to drastically reduce support for their local solar installations, a decision that had slowed global market development and created overcapacity among China's solar producers.[18] Cost reductions in solar PV technologies made these technologies more attractive for domestic use after decades during which wind turbines had held sway over local renewable energy markets.[19]

As a result of the renewable energy law and its accompanying regulations, the period of the Eleventh Five-Year Plan saw an unprecedented expansion of domestic demand for renewable energy technologies in China. Market opportunities and resources provided by the central government were increasingly restricted to domestic firms. Even though local content requirements for wind turbines were removed in 2009 and China's feed-in tariffs required no formal nationality requirements, foreign wind turbine manufacturers complained about being systematically excluded from government tenders and undercut by local competitors.[20] These manufacturers—many of which had established local manufacturing facilities in China—argued that central and subnational governments were using the government procurement clauses within the indigenous innovation legislation to purchase from domestic firms.[21] Many foreign

[15] Campbell 2011, 6–8; Lewis 2013, 53.
[16] Data compiled by Earth Policy Institute, 2020.
[17] Campbell 2011, 8.
[18] For an overview of the effects of the global financial crisis on the solar PV industry, see Bartlett, Margolis, and Jennings 2009.
[19] Goodrich et al. 2013, figure 1.
[20] See "China Shuts Out Foreign Businesses from Its $14 Billion Plan." *Business Insider*, June 4, 2009; Keith Bradsher, 2010, "On Clean Energy, China Skirts Rules," *New York Times*, September 8.
[21] Liu and Cheng 2011, 25–26.

firms ceased to participate in public tenders and subsequently scaled down their planned investments in China-based manufacturing facilities.[22]

Policies implemented after the release of the indigenous innovation guidelines aimed to close the remaining technology gaps between foreign firms and Chinese suppliers by encouraging the development of domestic capabilities. Government programs for international science and technology collaborations on wind and solar technologies, for instance, increasingly prioritized the academic exchange between universities and research institutes, rather than firms; and they no longer traded access to local markets in exchange for technology transfers.[23] Direct subsidies for renewable firms were now tied to the successful commercialization of new technologies. Starting in 2008, for example, Chinese turbine manufacturers were eligible for significant financial support for the first fifty turbines of 1 MW capacity or more, as long as they were indigenously developed, certified, and connected to the grid.[24] To consolidate the industry and increase technical standards among turbine producers, the Ministry of Industry and Information Technology (MIIT) in 2010 restricted the operation of turbine manufactures that could not produce wind turbines of 2.5 MW or more and that failed to meet a series of R&D and quality requirements.[25]

In the solar sector, which had received direct government subsidies only since the beginning of the Eleventh Five-Year Plan, central government policies now emphasized the domestic manufacture of production equipment, which most Chinese solar firms had previously sourced from Europe and the United States. In 2010, when the State Council released a list of seven "Strategic Emerging Industries" to replace the old pillar industries that had traditionally structured industrial policy, not only were renewable energy technologies included but so also was advanced manufacturing equipment.[26] This new emphasis on equipment manufacturing subsequently pervaded the Twelfth Five-Year Plan for the solar PV industry, released in 2012. That plan called for 80 percent of solar production equipment to be manufactured domestically by 2015, a goal that has not been met and since made its way into numerous subsequent policy documents.[27]

The state goal of achieving technological independence belied both the reality in global renewable energy sectors and China's domestic developmental trajectory as the world's largest manufacturer. By the time China's first domestic

[22] Author interviews: head of China operations, foreign wind turbine manufacturer, August 17, 2011; general manager, foreign wind turbine manufacturer, August 30, 2011.

[23] See Zhao et al. 2011. The International Science and Technology Collaboration Program on New and Renewable Energy set up by NDRC and MOST in 2007 resulted in 103 collaboration agreements with institutions in 97 countries. See Tan and Gang 2009, 5.

[24] Lewis 2013, 72.

[25] Kang et al. 2012, 1913; Lewis 2013, 73.

[26] State Council 2010; US-China Business Council 2013.

[27] Ministry of Industry and Information Technology 2012; National Energy Administration 2011; Wübbeke et al. 2016.

producers entered the wind and solar industries in the late 1990s, two decades of economic reform had already turned China into a large manufacturing economy. Between 1978 and 1998, China's per capita GDP had expanded nearly eighteenfold, from RMB 381 to RMB 6,796, and it would double again within six years.[28] New rules on private ownership had enabled a gradual restructuring of the state-owned sector. In the countryside, economic liberalization and fiscal decentralization in the 1980s had created incentives for rural governments to intervene aggressively on behalf of enterprises.[29] Along the coast, special economic development zones had proliferated, offering tax breaks, land deals, and development assistance to foreign investors and domestic manufacturers.

By 2003, fifty-four national economic and technological development zones (ETDZs), fifty-three national high-technology industrial zones (HTZs), and hundreds of economic development zones managed by local governments were competing to attract investment in manufacturing and, increasingly, in high-technology industries.[30] Manufacturing in China's development zones initially focused on consumer goods, textiles, and shoes—both Nike and Reebok sourced nearly half of their athletic shoes from Chinese factories in the late 1990s. By 2004, China had become the world's largest producer of electronics and communication equipment.[31] Nearly two-thirds of the world's laptop computers were manufactured in China in 2005.[32]

The shift or expansion to high-technology manufacturing occurred primarily at the hands of foreign firms, which had flocked to China's economic development zones in response to favorable investment policies. Between 1979 and 2000, China attracted USD 346 billion in foreign direct investment (FDI). Throughout the 1990s, China was second only to the United States on the list of the largest FDI recipients; 70 percent of FDI targeted the manufacturing industry.[33] By far the largest sources of FDI were manufacturing firms in Taiwan and Hong Kong, which used China's opening to foreign investment during the reform years to move labor-intensive export production to low-cost manufacturing locations in China's coastal development zones. Sixty percent of FDI arriving in China between 1985 and 2005 originated in Hong Kong, Taiwan, and Macau.[34] Eighty-eight percent of high-technology exports during the 1990s were manufactured by foreign-invested enterprises.[35] Although empirical studies found mixed

[28] China Statistical Yearbook 2007, chapter 3–1.
[29] Naughton 2007, 271–94; Oi 1995, 1136–38.
[30] Naughton 2007, 304, 409–10.
[31] Tomas Meri, "China Passes the EU in High-Tech Exports," in *Eurostat: Statistics in Focus*, 25/2009. Shoe manufacturing statistics cited in Landrum and Boje 2002, 84.
[32] In 2005, Taiwanese companies produced more than 70 percent of the world's notebook computers, 85 percent of which were manufactured in facilities in mainland China. Yang 2006, 7–12.
[33] Huang 2003, 6; Naughton 2007, 419.
[34] Naughton 2007, 413.
[35] Naughton 2007, 417.

evidence of direct technology transfers to local firms as a result of China's FDI-led development regime, foreign-invested firms provided training opportunities for staff in economic development zones, pushed local governments to continue to provide incentives for mass production, and attracted large supplier industries for materials, production equipment, export logistics, and other complementary capabilities required for large-scale manufacturing.[36]

China's domestic renewable energy firms had their beginnings in this era of manufacturing expansion and functional upgrading in economic development zones. Although central government economic policymaking pursued the goal of creating high-technology start-ups and national champion firms with skills in the *invention* of new technologies, entrants into the renewable energy industries focused largely on building skills in the *manufacturing* of wind turbines and solar PV technologies. Whether firms spun off from state-owned heavy machinery conglomerates, as proved common in the wind energy sector, or were founded by foreign-trained returnees, as was the case in many of China's solar firms, the legacy of mass manufacturing endured: It influenced hiring practices, templates for interaction with global supply chains, and the range of capabilities available to firms among local suppliers. As I lay out in detail in the remainder of this chapter, China's wind and solar firms, instead of building R&D capabilities in the invention of new technologies, emphasized their engineering skills in scale-up and mass manufacturing.

Even before the emergence of domestic wind energy markets and the rise of market demand for solar PV technologies in Europe, China's national S&T policies created incentives for firms to enter these industries. The central government supported technology spin-offs, provided funding for high-tech R&D, and offered start-up support in HTZs created as incubators under the so-called Torch Program. The domestic demand for wind turbines, fueled by China's 2003 Wind Power Concession Program, by subsequent feed-in tariffs, and by the rapidly growing export markets for solar PV technologies, further encouraged industry entry.

New wind and solar firms moved into the renewable energy sectors along different paths. Like Goldwind, China's first domestic wind turbine manufacturer, many wind turbine producers amounted to spin-offs from government research institutes or subsidiaries of state-owned (or formerly state-owned) enterprises. Goldwind began in 1997 as a spin-off from Xinjiang's Wind Energy Research

[36] Huang has argued that China's FDI-led development strategy has crowded out local firms by providing investment incentives and favorable tax policies predominately to foreign-invested enterprises. See Huang 2003. For a discussion of training and other benefits provided by foreign-invested firms, see Naughton 2007, chapter 17. Others have found mixed statistical evidence for direct technology transfer from foreign investors to local firms beyond their Chinese subsidiaries. See, for instance, Hu, Jefferson, and Jinchang 2005; Lemoine and Ünal-Kesenci 2004; Liu and Buck 2007.

Institute, after the 863 Program provided funding for the development of small wind turbines with 600 kW capacity.[37] In 2004, after domestic markets expanded, Dongfang Electric began producing wind turbines with a license from German REpower. Dongfang was itself a subsidiary of China Dongfang Electric Corporation, a centrally owned enterprise with a wide product portfolio that included power generation equipment, transformers, railway engines, and power converters.[38] Sinovel, a start-up backed by Dalian Heavy Mechanical and Electrical Equipment Engineering Company, began producing 1.5 MW turbines in 2006 with a license from Germany's Fuhrländer; it began offering a 3 MW turbine a few years later, at a time when European producers were still testing their 3 MW technology.[39] China's 2006 renewable energy law, which introduced feed-in tariffs for the wind industry and created the prospect for long-term growth in domestic markets, prompted other producers to follow. Mingyang, a privately owned supplier of switch-gears, frequency converters, and pitch control equipment for wind turbine manufacturers, began the production of its own 1.5 MW wind turbine in 2007.[40]

In the solar industry, Chinese scientists founded the majority of firms. Many of these scientists had received their training at the School of Photovoltaic and Renewable Energy at the University of New South Wales in Australia.[41] Research funding dispensed by the central government and support for high-technology start-up firms in China's High-Technology Development Zones attracted these scientists back to China. Many returned to their hometowns to open solar PV firms right around the same time that manufacturers were springing up in Europe and the United States. Trina Solar, today one of China's largest producers of solar wafers and modules, began as a solar PV installer for demonstration projects in 1997.[42] Yingli Solar followed in 1998, setting up its first facility in Baoding.[43] Suntech opened its first production plant in Wuxi in 2001.[44] In 2004,

[37] Osnos 2009. See also Chen Lei, 2011, "Goldwind: From Follower to Leader [金风科技：从追风到引领]," http://www.goldwind.cn/web/news.do?action=detail&id=201103310223342852 (accessed January 19, 2014).

[38] Dongfang Electric Corporation was originally founded in 1956. See company website at http://www.dongfang.com.cn/index.php/business/ (accessed January 19, 2014).

[39] Qin 2013, 598. See also Pu Jun and Wang Xiaocong, 2011, "Boom, Then Blowdown for Wind Energy's Sinovel," *Caixin Online*, November 21.

[40] China Ming Yang Wind Power Group Limited 2011. See also http://www.mywind.com.cn/English/about/index.aspx?MenuID=050101 (accessed January 19, 2014).

[41] See Alexander 2013. Other solar firms recruited Chinese citizens from elsewhere in the world. Wan Yuepeng, CTO of Trina Solar, for instance, completed a PhD at Aachen University and worked for New Hampshire–based equipment manufacturer GT Solar prior to returning to China. See http://www.ldksolar.com/com_team.php (accessed March 27, 2013).

[42] Trina Solar, 2013, "TSL: Company Milestones," http://media.corporate-ir.net/media_files/irol/20/206405/milestones.pdf (accessed January 19, 2014).

[43] For a list of all national-level high-tech industrial zones established under the Torch Program, see Cao 2004, 648, http://www.yinglisolar.com/en/about/milestones/ (accessed January 19, 2014).

[44] Ahrens 2013, 2–3.

after global demand for solar panels increased—the result of improvements to Germany's domestic subsidy regime for renewable energy—a number of additional firms entered the industry. CSUN was established in 2004 in Nanjing as a subsidiary of the China Electric Equipment Group, a manufacturer of electrical transformers and advanced composite materials. JA Solar began manufacturing wafers in Shanghai in 2005.[45]

Although the majority of solar PV start-ups did not share the same direct connections to manufacturing conglomerates that were common in the wind industry, executives at China's solar PV firms did bring substantial experience from their time in existing manufacturing industries, in particular in electronics and semiconductor production. The chief technology and financial officers at LDK Solar, for instance, had previously worked for a range of semiconductor, glass, and solar manufacturers, including GT-Solar and Saint Gobain, before joining LDK in 2007 and 2006, respectively. At JA Solar, the CEO and chief technology officer had managed factories for semiconductor firms such as SMIC and NEC before joining JA in 2008 and 2010, respectively. Similarly, the chief technology officer of Yingli had worked in chemical manufacturing before entering the solar industry.[46]

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.[47] Seven of the ten largest solar manufacturers and four of the ten largest wind turbine producers in the world were Chinese firms.[48] Tellingly, the majority did not focus on building capabilities in invention. Instead, they continued to license technology and source components and production equipment abroad, instead emphasizing the establishment of unique capabilities in scale-up and mass production.

Innovative Manufacturing in Wind and Solar Industries

When the first Chinese firms entered the wind and solar sectors in the late 1990s, production technologies for these areas had not fully matured; and low production volumes still allowed for experimentation and manual labor in bringing new technologies to market. Few foreign producers of wind turbines were manufacturing at scale, or if they were, they had begun doing so only recently. Engineering challenges in the commercialization of wind and solar technologies became critical in 2003, when the growing global demand for wind and solar

45 JA Solar Holdings 2007, 6.
46 Information compiled from company websites and annual reports.
47 Earth Policy Institute 2020.
48 Bebon 2013; IHS Solar 2013.

technologies no longer permitted trial-and-error approaches to mass production. Successful commercialization necessitated advanced production capabilities and tacit knowledge around design-for-manufacturing, yet Chinese firms still had to establish these skills in-house.

Those who have studied innovation in mass production have largely looked at process innovation, referring to changes and improvements in the manufacturing process itself.[49] Scholars have distinguished between such process improvements and product innovation, which refers to the introduction of new concepts and technologies that depart significantly from past practice.[50] In emerging industries such as wind and solar, however, the commercialization of new products presented challenges in the scale-up to mass manufacturing that could not be met through process innovation alone: changes to product designs were also needed. In the past, vertically integrated firms had translated between technological blueprints and manufacturing requirements within the four walls of a single company. As the global economy increasingly relocated manufacturing activities away from traditional centers of invention, it removed the need for such skills in firms that no longer possessed in-house manufacturing facilities. For manufacturing firms in developing economies, this removal opened the door to specialization, allowing a concentrated focus on precisely the type of engineering skills that were required to prepare advanced products for mass manufacturing.

The growing importance of capabilities in scale-up and commercialization coincided with an increased emphasis on the development of domestic innovative capabilities in China's national S&T policy framework. Between 2000 and 2006, China's domestic spending on R&D increased from RMB 89.6 billion to RMB 300 billion; R&D intensity, still below the targets set in the Tenth Five-Year Plan, grew from 0.9 to 1.4 percent of GDP over the same period.[51] Both the 863 Program and a second research program, the 973 Program, named after its inception in March 1997, dispensed more funds for technology development; and both offered designated budgets for energy technology research. China's 863 Program budget for energy technology doubled in 2001, providing funding mainly for R&D on low-carbon energy technologies.[52] The 973 Program provided RMB 8.2 billion for basic research between 1998 and 2008, 28 percent of which went to projects that targeted technologies in the fields of energy, resource conservation, and environmental protection.[53] Additionally, centrally funded

[49] OECD 2005, para. 163.
[50] Abernathy and Clark 1985; Abernathy and Utterback 1978; Porter 1986; Tushman and Anderson 1986.
[51] Ministry of Science and Technology 2007a, 2–3.
[52] Osnos 2009.
[53] Tan and Gang 2009, 4.

Table 5.3 Goldwind Wind Turbine Collaboration

Year	Program Goal	Technology Source
1998	600 KW turbine	Jacobs Energie, Germany (license)
2001	1.2 MW turbine (direct drive)	Vensys, Germany (license)
2005	1.5 MW turbine (direct drive)	Vensys Germany (license)
2010	2.5/5 MW turbine (direct drive)	Vensys Germany (joint development)
2012	10 MW offshore	Vensys Germany (joint development)

Source: CRESP 2005; Ministry of Science and Technology 2007; Author Interview, Beijing, March 23, 2015.

state key laboratories, which had supported strategic research topics in universities since the early 1980s, could be located within private businesses starting in 2007; and firms were encouraged to seek state key laboratory accreditation for their R&D programs.[54] Overall, central government R&D appropriations for renewable energy research increased from RMB 21.1 billion in 1996 to RMB 104.8 billion in 2008.[55]

From the beginning, producers of wind turbines and solar PV technologies took advantage of public R&D funding. Although such government grants increasingly stipulated the goal of technological independence, wind and solar manufacturers continued to collaborate with global partners. Multiple global pathways made technologies available to them. In the wind industry, Chinese firms enjoyed access to turbine technologies, first, through licensing and joint development agreements with foreign manufacturers. The founder of Goldwind reasoned that there was no need to replicate existing technologies. When government programs encouraged domestic turbine development, Goldwind licensed a design from a German firm and used government R&D funds to build engineering capabilities in commercialization instead (Table 5.3).[56] The vast majority of Chinese wind turbine manufacturers entered similar relationships with foreign partners to access turbine technologies. Among the thirty-one largest wind turbine manufacturers in China, at least sixteen entered license agreements with foreign firms, fourteen signed joint-development contracts, six autonomously developed wind turbine technologies, and three started joint

[54] Ministry of Science and Technology 2007b; OECD 2008, 462.
[55] Cao and Groba 2013, 12.
[56] Osnos 2009; Vensys 2017; Author interview, Beijing, March 23, 2015.

venture operations. Seven firms had both joint-development and licensing agreements with foreign firms.[57]

The second source of technology for China's domestic turbine manufacturers involved global suppliers, many of which eventually established local production facilities in response to local content requirements.[58] Foreign firms also began sourcing from Chinese suppliers and, in turn, helped these suppliers meet global technical standards.[59]

In the solar sector, Chinese scientists educated at the world's top solar laboratories founded the majority of firms. Research funding dispensed through the 863 and Torch Programs, together with support for high-technology firms in HTZs, attracted these scientists back to China. The technological skills of foreign-trained returnees obviated the need for licenses and joint development agreements common in the wind industry, but solar firms still tapped into global technology networks, in particular for production equipment. Foreign equipment manufacturers quickly established Chinese sales networks.[60] Foreign partners provided access to key technologies, capabilities, and components that Chinese wind and solar manufacturers could not establish in-house. But they had less ability to help Chinese producers scale new technologies to mass production.

In such collaborations, China's wind and solar firms focused their R&D efforts on building skills that could not be accessed in global supply chains: knowledge-intensive capabilities in scale-up and mass manufacturing that I refer to as *innovative manufacturing*.[61] These proficiencies built on existing manufacturing capabilities in China's economic development zones, yet they traveled far beyond mere fabrication and assembly, utilizing engineering and design knowledge to translate complex technologies into mass-manufacturable products. Innovative manufacturing included improvements to process designs long associated with manufacturing innovation, but also entailed far-reaching changes to product

[57] Compiled from Lewis 2013, 136–37; Wang 2010b, 197–203. Chinese wind and solar firms were generally able to obtain intellectual property through licensing and other legal arrangements with global partners. Perhaps in contrast to other industries, cases of IP theft were rare in China's clean technology sectors. A prominent exception was a case involving the Chinese wind turbine manufacturer Sinovel and the US component supplier AMSC and its Austrian subsidiary Windtec. Initially entering a successful licensing relationship, AMSC discovered the unauthorized use of its software in Sinovel wind turbines after Sinovel refused previously agreed-to purchases. AMSC alleged that Sinovel had stolen software source code to be used in Sinovel turbines, and Sinovel was eventually convicted of IP theft. Both companies suffered commercially as a result of the dispute, with AMSC losing a key customer and the majority of its revenue and Sinovel pulling out of major international markets. See Lewis 2015; Raymond 2018.

[58] Wang 2010b, 197–203.

[59] Information retrieved from company websites; the China Wind Power Center database (http://www.cwpc.cn); Li 2011b; Windpower Monthly 2005a, 2005b, 2006, 2008.

[60] Nussbaumer et al. 2007, 109.

[61] For a detailed discussion of innovative manufacturing in China, see Nahm and Steinfeld 2014.

designs to accommodate manufacturing requirements and meet cost targets for final products. Engineering teams in China's wind and solar firms met their production and cost targets through the substitution of materials, the redesign of particular components, and the reorganization of internal product architectures to allow for better and faster manufacturability at scale.[62]

As executives repeatedly highlighted in interviews, most firms relied on global partners to access new technologies, so what set them apart from one another in the highly competitive wind and solar market was their ability to achieve higher speeds and lower costs in manufacturing.[63] Heads of technical departments in wind turbine and solar PV manufacturing firms frequently discussed the importance of design capabilities for achieving cost and speed targets in the commercialization of renewable energy technologies, even when an external firm had originally developed those technologies. Many reported either significantly redesigning licensed turbine technologies or observing similar improvements in technologies licensed by local partners and competitors.

To specialize in innovative manufacturing was not a monolithic enterprise. Yes, these firms all needed advanced capabilities in product design; yet their work differed from the ideal of autonomous technology development that resided at the heart of Beijing's indigenous innovation strategy. Chinese wind and solar firms engaged in learning and industrial upgrading, but they did so without developing the full range of industrial capabilities required to invent, commercialize, and produce green energy technologies. In spite of government plans to create autonomous local enterprises, China's wind and solar firms developed highly specialized capabilities within collaborative relationships in global supply chains. Simply put, the firms opted for partnership.

China's renewable energy manufacturers established two divisions within their R&D facilities. A first group of engineers targeted applied research on new

[62] Author interviews: senior director manufacturing, Chinese solar PV manufacturer, March 21, 2017; lead engineer, Chinese generator manufacturer, December 6, 2016; director of China office, German turbine supply firm, March 31, 2017; senior VP global supply chains, Chinese solar manufacturer, interviewed March 13, 2011; CTO and director of R&D at Chinese solar manufacturer, both interviewed August 26, 2011; head of China operations, European wind turbine engineering firm, interviewed January 13, 2011; CEO, European wind turbine engineering firm, interviewed May 20, 2011; CTO, Chinese wind turbine manufacturer, interviewed August 29, 2011; CEO, Chinese solar cell manufacturer, interviewed August 10, 2011; president, Chinese wafer manufacturer, interviewed August 26, 2011. CEO, Chinese cell and module manufacturer, interviewed June 28, 2013. See also Nahm and Steinfeld 2014.

[63] Author interviews: R&D engineer, wind turbine manufacturer, March 24, 2015; 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, June 28, 2013; head of R&D, Chinese solar manufacturer, January 7, 2019. See also Nahm and Steinfeld 2014.

wind and solar technologies to meet and surpass the technological standards of foreign competitors, as intended by the central government programs. A second R&D division, by contrast, addressed the challenge of scale-up and mass production. It is in this second division that the most advanced Chinese wind and solar firms developed unique skills in bringing new technologies to market. The wind turbine manufacturer Mingyang in Zhongshan had 300 R&D staff in 2010; of those 300, only about one-third focused on the development of new technologies. The majority of engineers worked on the types of design changes required to bring technologies to mass production.[64] Similarly, Trina Solar, located in one of the manufacturing parks between Shanghai and Nanjing, reported that out of 2,488 employees working in its R&D division in 2015, only 842 focused on technology development. The remaining 1,746 engineers devised solutions to the challenges of commercialization in a designated test facility with so-called golden lines, production lines solely dedicated to R&D.[65]

These two-fold R&D activities explain why Chinese firms built strengths in bringing new technologies to market but were not able to match the early stage R&D activities of firms in other economies and thus remained dependent on foreign partners. Already in 2006, some of the world's most efficient solar PV modules in mass production were being made in Chinese manufacturing facilities, even as China could not match the conversion efficiencies of foreign R&D laboratories in experimental setups.[66] By 2015, the solar cells tested in Chinese laboratories still lagged in conversion efficiency, even if their distance to US and European technology had narrowed. Some of the most efficient solar modules in mass production, however, continued to roll off of Chinese production lines.[67]

Interviews with plant managers, R&D engineers, and chief technology officers in the largest Chinese wind and solar manufacturers revealed differences across firms in the deployment of such capabilities. Innovative manufacturing skills among China's wind and solar firms manifested in three different variants that resembled knowledge-intensive variations of reverse engineering, contract manufacturing, and export processing—manufacturing activities long at the center of economic development.[68] These variations were not mutually exclusive, and wind and solar producers often applied their engineering capabilities in multiple ways to solve the challenges of commercialization.[69]

[64] China Ming Yang Wind Power Group Limited 2011, 54.

[65] Trina Solar 2016, 89. Author interview, chief engineer, State Key Laboratory, March 29, 2015.

[66] Marigo 2007, table 1.

[67] Ball et al. 2017, 68–69.

[68] The role of such manufacturing activities in economic development and industrial upgrading is discussed in Ernst and Kim 2002; Gereffi 2009; Lüthje 2002; Minagawa, Trott, and Hoecht 2007.

[69] The discussion of innovative manufacturing over the following pages draws heavily on a collaborative project with Edward Steinfeld. See Nahm and Steinfeld 2014, 294–98.

A first form of innovative manufacturing, here referred to as backward design, resembled traditional processes of reverse engineering. By creating versions of existing products that were simpler and cheaper to manufacture at scale, Chinese entrants outcompeted foreign incumbents by undercutting them on price. In contrast to conventional reverse engineering, however, in which mature technologies are copied and cost advantages stem from differences in factor prices and scale economies, Chinese firms cut costs through changes to product designs.[70] Although backward design led to products that resembled the original archetypes, the new product versions could be scaled at lower cost and faster speed owing to the use of simplified components, cheaper materials, and better design for manufacturability. While backward design thus retained the core features of reverse engineering, it went a step further: firms created *new* products with distinct characteristics, rather than simply attempting to reproduce the original template.

Wind turbine technologies offered the perfect fit for backward design processes. The large number of mechanical components, the importance of product architecture for the manufacturing process, and the sophisticated material needs of advanced wind turbines made these technologies particularly suitable for design improvements. Out of twelve Chinese wind turbine manufacturers interviewed for this project, nine reported having either improved licensed turbine technologies through backward design or observed such improvements in technologies licensed by local partners and competitors. Yet even in the solar sector, where products possess far fewer components and are fabricated using nonmechanical production processes, manufacturers also used backward design strategies. One Chinese manufacturer of solar cells and modules reported buying a foreign equipment manufacturer to access technology and then reengineering parts for its production lines to save costs and time over equipment available domestically.[71] A competitor expressed frustration with the lack of speed exhibited by some foreign suppliers in adapting production lines to changing technology applications, and as a result shifted to local suppliers, who could more quickly—and cheaply—improve equipment designs for new manufacturing needs.[72] Although such instances of backward design in the Chinese solar sector focused on rapid customization rather than scale, they retained the principle's core feature: they improved on existing technologies through knowledge-intensive manufacturing innovation.

[70] For a discussion of reverse engineering in economic development, see Amsden 1989, 2001; Kim 1997; Kim and Nelson 2000.

[71] Author interview, senior VP global supply chains, Chinese solar manufacturer, March 13, 2011.

[72] Author interviews: chief engineer, State Key Laboratory, March 29, 2015; CTO and director of R&D at Chinese solar manufacturer, August 26, 2011.

The ability of Chinese firms to rapidly move complex products toward commercialization also manifested in the commercialization of new technologies. In many cases, such technologies originated from foreign partners who did not possess in-house manufacturing capabilities, who could not manufacture the product at a commercially viable price, or who were deterred by the capital and tooling costs of commercializing new technology. In other cases, Chinese firms used such capabilities to commercialize their own product innovations, birthed in the technology development divisions of their R&D facilities. What these cases held in common was their reliance on production knowledge to replace, redesign, and substitute parts until the product could be manufactured at a commercially viable price. In contrast to contract manufacturing, which relies on firms in developing economies to manage only the production process of foreign-owned designs and technologies, Chinese wind and solar producers improved the product designs themselves in the process of scale-up to mass production.[73]

In a third variant of innovative manufacturing, the presence of production know-how provided a platform for external innovators to integrate their technologies into existing wind and solar technologies already mass-produced in China. But the firms supplying the technology were more than just high-end component vendors who sold a product at arms-length to a Chinese competitor. Instead, vendors commercialized their technology in collaboration with a Chinese partner. The vendor contributed knowledge about a particular technology that might have applications to a product the Chinese manufacturer had already scaled up. The Chinese manufacturer, in turn, provided knowledge about production, about the use of existing production technology to apply the component technology at scale, and about projected improvements to the original product as a result of these innovations.

Manufacturing as a platform for product development became especially common in the interaction between manufacturers and component suppliers who relied on customers not just for demand but also for the engineering skills and product knowledge required to integrate new components and materials.[74] As China grew into a hub of commercialization for the most advanced renewable energy technologies, Chinese firms used innovative manufacturing capabilities to find applications for novel components, materials, and production equipment developed by global firms.[75] Although the duration of such collaborations varied, six out of seven solar PV suppliers interviewed for this project reported working with Chinese solar manufacturers on the commercialization of new

[73] For a discussion of noninnovative contract manufacturing in the context of the electronics industry, see Lüthje 2002.

[74] Author interview: CEO of American nanomaterial manufacturer, October 13, 2011.

[75] Neuhoff 2012.

technologies. In the wind sector, suppliers of complex components such as gearboxes and generators similarly described collaborating with Chinese customers to integrate their largest and most advanced technologies.[76]

Innovative Manufacturing in Global Supply Chains

Although some firms expanded into multiple production steps and displayed different degrees of vertical integration, virtually no Chinese manufacturer established the technological competencies to bring an idea to mass production without external input. The capabilities of renewable energy firms remained too narrow to autonomously develop and commercialize new technologies. In all three variants of innovative manufacturing, wind and solar firms relied on collaboration in global supply chains to access talents and resources they did not establish in-house.

Initially, firms in China's renewable energy fields relied on foreign firms to tap into the technologies required for industry entry. In the wind industry, Chinese firms had access to foreign wind turbine technologies through licensing agreements and joint development agreements with foreign manufacturers. Wu Gang, the founder of Goldwind, reasoned that there was no need to replicate existing technologies. When government programs encouraged domestic turbine development, Goldwind licensed a design from Germany's Jacobs Energie and used R&D funds to solve production challenges instead.[77] The vast majority of Chinese wind turbine manufacturers entered similar relationships with foreign partners to access global technologies. Sinovel signed joint development agreements for a 1.5 MW turbine with Fuhrländer of Germany in 2003, followed by agreements with Austria's Windtec for 3 MW and 5 MW turbines in 2007. Dongfang Electric purchased a license for a 1.5 MW turbine from Germany's REpower in 2004 and entered a joint development agreement for a 2.5 MW turbine with the German wind engineering firm Aerodyn in 2005.[78] Nordex entered a joint venture with Ningxia Electric Power Group, and REpower set up a joint venture turbine assembly firm with North Heavy Industrial Group, both in 2006.[79]

China's domestic turbine manufacturers also sourced technology from global suppliers, many of which eventually established production facilities in

[76] Author interviews: engineer, Chinese gearbox supplier, January 4, 2016; plant manager at a German gearbox supplier, May 16, 2011; plant manager at a German generator manufacturer, May 17, 2011.
[77] Osnos 2009.
[78] See Zhang et al. 2009, 559.
[79] Compiled from company websites.

China as foreign turbine manufacturers attempted to meet strict local content requirements. The early foreign suppliers to Chinese turbine manufacturers included the Swiss multinational ABB; the German firms Euros, Bachmann, Jake, and VEM; the Danish blade manufacturer LM; and the Austrian control systems firm Windtec (now part of US-based AMSC).[80] FAG/Schaeffler of Germany, a bearings manufacturer, opened a facility in China in 2006; Bosch Rexroth, a gearbox manufacturer, and SKF, a Swedish bearings multinational, followed in 2008. As foreign turbine manufacturers set up facilities in China, they not only brought suppliers with them but also trained local firms. Gamesa of Spain opened its first facilities in China in 2005; Vestas opened a blade factory in Tianjin in 2006, the same year that GE began the assembly of turbines in Shenyang. Nordex of Germany and Suzlon of India opened plants in Dongying and Tianjin in 2007. Foreign manufacturers began sourcing from local suppliers such as NTC, a generator producer, and Nanjing Highspeed Gear, a gearbox manufacturer, and in turn helped these suppliers meet global technical standards.[81]

Unlike China's wind turbine producers, which entered the industry from a position of technology lag, many of the original solar companies were founded by returning scientists trained at the world's top solar laboratories. The skills and training of these foreign-trained returnees obviated the need for technology licenses and joint development agreements common in the wind industry. But solar firms still tapped into global technology networks, in particular for production equipment. As I discussed in Chapter 4, the first German suppliers of cell and module production lines began selling their products to China's solar firms as early as 2000. Other foreign equipment suppliers quickly followed and set up sales networks in China, particularly as European and US-based solar manufacturers only slowly expanded production facilities.[82]

Many international suppliers of production equipment, particularly those offering turnkey lines, went unchallenged by domestic competitors. As late as 2014, no producers of turnkey production lines existed in China, though a number of Chinese firms began to offer equipment that solar manufacturers could modify and connect to construct their own production lines.[83] For complicated production equipment and supplies—including chemical vapor deposition equipment, screen printers, firing furnaces, and silver pastes—Chinese firms continued to rely on foreign suppliers.[84] Since solar producers from around the world sourced from and cooperated with the same producers of manufacturing equipment to

[80] Wang Q. 2010, 197–203.
[81] Retrieved from China Wind Power Center database (http://www.cwpc.cn), Windpower Monthly, and Li 2011a.
[82] Nussbaumer et al. 2007, 109.
[83] de la Tour, Glachant, and Ménière 2011, 765.
[84] Ball et al. 2017, 137–38.

incorporate new technologies into their production machinery, sourcing equipment from external firms was not just a way to access instruments and machinery that remained unavailable internally. It also offered access to global technological developments and pooled knowledge—resources that solar producers risked losing if they relied on production equipment developed in-house.[85]

Collaboration remained essential to the viability of China's specialization in innovative manufacturing, even as China's wind and solar producers acquired ever more advanced technological capabilities. Challenging the notion that technological upgrading would entail moving beyond manufacturing to higher value-added activities, renewable energy producers continued to rely on external capabilities through relationships with third-party firms; but they invested in skills that could not be accessed in global supply chains. Such collaboration took place in a variety of legal relationships, ranging from joint development agreements to licensing contracts.

In a typical example, a German firm granted a license to a Chinese wind turbine supplier to produce a generator, one of the core turbine components. Because of engineering constraints, the German firm had been unable to incorporate the most cost-effective fan model into its generator design. The Chinese licensee, however, in the process of scaling production of the licensed generator, redesigned the original model to accommodate the cheaper fan. The backward design capabilities of the Chinese firm permitted it to realize a product alternative that the German firm had dismissed as unworkable. Once the alternative was demonstrated to be feasible, the German firm agreed to pay for this proprietary information through reverse licensing.[86] In this case, the Chinese firm contributed production knowledge within a formal contractual relationship. In other cases, however, Chinese firms used their skills to develop cheaper, mid-level products that competed directly with the product archetypes and their originator firms.[87] Particularly in the Chinese domestic market, many established multinationals were unable to engage in such cost-driven design processes and lost market share to cheaper alternatives as a result.[88]

Innovative manufacturing capabilities also appeared in firm partnerships centered on the commercialization of new technologies. In 2009, for instance, a Chinese wind turbine producer acquired a ten-year exclusive license for the

[85] de la Tour, Glachant, and Ménière 2011, 764. Author interviews: CTO of solar PV manufacturer, May 23, 2011; head of research and development, Chinese solar manufacturer, January 7, 2019.

[86] Author interviews: plant manager, German generator manufacturer, May 17, 2011; executive, Chinese generator manufacturer, August 26, 2011.

[87] This phenomenon has occurred in other industrial sectors; see Brandt and Thun 2010; Ge and Fujimoto 2004.

[88] Author interviews: director of China office, German turbine supply firm, March 31, 2017; head of China operations at foreign wind turbine manufacturer, August 30, 2011; executive, foreign wind turbine manufacturer, November 11, 2011; head of China operations, foreign wind turbine manufacturer, August 17, 2011.

manufacture of a groundbreaking, new-to-the-world wind turbine design from a German supplier. The German firm selected the Chinese manufacturer from multiple potential partners, choosing largely on the basis of manufacturing capabilities that would ensure reliability for the product, speed in commercialization, and marketable viability for the project as a whole.

Although the European firm developed this turbine design—a new turbine technology that offered greater reliability and versatility through new and lightweight components—the design for manufacturability occurred during small batch production on the site of the Chinese manufacturer. Engineers employed by the Chinese firm made design changes to simplify tooling and assembly processes and, in cooperation with other local firms, reduced costs by localizing sourcing and by introducing substitute materials. This particular turbine concept proved especially challenging, because its novel product architecture required all the components to be produced in-house.[89] Additional design adjustments were made during the process of scale-up to accommodate requirements for mass production. Reflecting on the partnership, the head of the China office for the German supplier emphasized the importance of the skills brought by their Chinese partner. "The turbine is now completely different from the prototype because of the design changes that occurred in China to make it manufacturable. Nobody else was willing to take that risk, and willing to put in the time and effort to make this new idea work. It took seven years to get it right, but now they are doing very well with the product."[90]

The cooperation between US-based Innovalight and the Chinese solar cell manufacturer JA Solar illustrates the third variety of innovative manufacturing, in which a foreign firm relied on China's manufacturing infrastructure as a platform for product development. A Silicon Valley start-up founded in 2002, Innovalight developed a nanomaterial with potential applications in products ranging from integrated circuits and displays to solar PV. With Department of Energy funding and support from the National Renewable Energy Laboratory (NREL), the firm developed an understanding of how the nanomaterial, a silicon ink, might be applied in the solar PV industry. However, while Innovalight and NREL could determine how the material might improve a single solar cell, neither had the know-how required to apply the material in a cost-effective manner in high-volume solar PV production. The firm was unable to raise the capital needed to build a solar PV production facility.[91]

[89] Author interviews: head of China operations, German wind turbine supplier, April 1, 2017 and January 13, 2011; CEO, German wind turbine supplier, May 20, 2011; CTO, Chinese wind turbine manufacturer, August 29, 2011.

[90] Author interview, head of China operations, German wind turbine supplier, April 1, 2017.

[91] Wang 2011.

In 2009, nearly out of business, Innovalight found a partner in Chinese cell manufacturer JA Solar. Looking to gain an edge over its competitors, JA Solar made the decision to invest in the collaborative development of a component that could substantially improve the efficiency of its main product. After a year of joint R&D, the two firms announced the successful production of high-efficiency solar cells using Innovalight's silicon ink technology. In 2010, the two firms signed a three-year agreement for the supply of silicon ink, as well as a strategic agreement for the joint development of high-efficiency cells.[92] The process of joint development with JA Solar finally verified Innovalight's silicon ink technology as a product capable of contributing value in solar PV. Now established as a legitimate player in the solar industry, Innovalight began licensing its technology to other solar manufacturers.[93]

Contrary to expectations that firms who worked together would become more similar over time, collaboration actually allowed firms to reinforce the distinctiveness of their different industrial practices. Technological cooperation allowed firms to jointly develop successive generations of renewable energy technologies, yet the fundamental division of labor remained durable over time. The US strength in invention, Germany's specialization in complex components and production equipment, and China's focus on technological innovation within commercialization and scale-up were interdependent and mutually reinforcing.

The Manufacturing Economy

China's wind turbine and solar PV producers made use of their nation's national science and technology infrastructure to develop their skills in innovative manufacturing. At the same time, the technological learning underway within these firms relied heavily on the repurposing of institutions within the manufacturing economy. These institutions retained their value precisely because firms no longer had to be one-stop shops: institutions no longer had to support the full range of activities required to invent and commercialize new technologies within national borders.

In contrast to science and technology funding, which often involved top-down administrative structures and directives set by China's central government ministries in Beijing, resources for the manufacturing economy came largely from subnational governments. Often these resources were provided in outright defiance of central government plans, which had encouraged local governments to push firms toward invention.[94] For China's wind and solar firms, local policies

[92] JA Solar 2010.
[93] Stuart 2012.
[94] Cao, Suttmeier, and Simon 2006; Kroll, Conlé, and Schüller 2008, 172–77.

for the manufacturing economy provided an important supplement to the central government's focus on technological independence and its narrow definition of innovation as invention.[95] Firms relied on local government support to construct the physical manufacturing plants they needed to succeed in new forms of mass production, but they also repurposed that local support to establish new engineering capabilities. Just as firms had utilized central government science and technology policies to respond to opportunities for scale-up and commercialization, so entrepreneurial firms used resources for mass production provided at the local level for industrial upgrading in ways not anticipated by the state.

The importance of local government policy for industrial upgrading in the wind and solar sectors corresponds to the central role played by subnational administrations in China's political economy since the onset of economic reforms. In the 1980s, a series of fiscal and administrative reforms had made local governments dependent on local tax revenue while granting them decision-making autonomy in local economic affairs. Fiscal decentralization aimed to promote growth-enhancing economic measures at the local level while carving out space for localities to experiment on economic policy.[96] The central government sought to further encourage experimentation in local policymaking by evaluating local officials on a series of development outcomes, rather than prescribing the specific policies required to achieve those outcomes.[97] In a word, they encouraged creativity. Even though fiscal decentralization underwent a reversal in the 1990s—a move aimed at improving the revenue situation of China's central government—local governments continued to wield discretion in economic governance and enjoyed considerable autonomy in the implementation of central directives, key features of China's post-Mao political economy.[98]

In addition to experimenting with local growth-enhancing policies, subnational governments also implemented and financed many national policies, including programs introduced under China's indigenous innovation strategy. Research and development appropriations of the subnational governments rose in accordance with central government budget increases, growing from RMB 10.6 billion in 1996 to RMB 69.9 billion in 2006.[99] By 2015, R&D appropriations of the subnational governments had increased to RMB 338 billion, far surpassing the RMB 248 billion set aside by central government agencies.[100]

[95] Nahm 2017a.

[96] Jin, Qian, and Weingast 2005; Oi 1995.

[97] Although social and environmental factors have been added to the cadre evaluation system over time, economic parameters have been paramount. For an introduction to cadre evaluation in China, see Edin 2003; Landry 2008, chapter 5; Whiting 2004, 106–12.

[98] The process of fiscal recentralization is described in detail in Huang 2008, chapter 3.

[99] Ministry of Science and Technology 2007a.

[100] China Science and Technology Statistical Yearbook 2016.

Although the central government's directives increasingly emphasized a broad reorientation away from the mass production of standardized commodities and toward an innovation-based development strategy, local administrations remained primarily concerned with meeting immediate economic targets and raising local revenue. R&D appropriations at subnational levels were diverted toward programs that yielded more immediate economic results. In practice, this shift entailed supporting the manufacturing activities of local firms, often making financial support conditional on meeting production targets and tax revenue requirements. Even as they implemented central-level directives to support lab-based R&D and product innovation, local officials quietly prioritized measures to enhance growth in their existing industrial base. If we look, for example, at the provincial implementation plans of China's 2009 decision to support seven strategic emerging industries (SEIs), we find striking differences across localities, with local administrations picking between six and ten sectors and selecting local SEIs to match to the existing industrial base. In provinces such as Jiangxi, solar PV industries were included on this list; other localities disregarded renewable energy industries in their interpretation of the original directive.[101] The implementation of central government policies thus provided an opportunity for localities to adjust these policies to match their local needs. It seems important to note, however, that local economic policy did not always produce optimal outcomes. Embracing local development and rapid growth, some local policymakers also produced unintended negative consequences, most notably when localities refused to stop supporting industries already characterized by overcapacity and a lack of scale economies.

Wind and solar firms could access two sets of manufacturing resources at the local level. First, they benefited from investment incentives, such as tax breaks and discounted lands, that offered general support for the manufacturing economy. These financial incentives were offered relatively uniformly across China's economic development zones and industrial parks and aimed to attract foreign—and, increasingly, domestic—investment. Second, firms benefited from the resources, institutions, facilities, and infrastructure provided by localities to support the existing local industrial base. Such institutions were regionally divergent, as they targeted the needs of specific industrial sectors in the local economy.

Although China's HTZs, established under the Torch Program in the late 1980s, provided incubator services for small and medium-sized high-technology enterprises, the economic constraints placed on local governments encouraged a reorientation toward mass manufacturing and export processing in these

[101] For details about provincial SEI implementation plans, see US-China Business Council 2013, 16–22.

high-technology zones. According to a 2013 study by Heilmann et al., out of a sample of fifty-three HTZs, thirty-nine deviated from their original purpose to promote domestic R&D activities and instead focused on mass production.[102] For local governments, high-technology zones had become convenient vehicles to increase economic growth and tax revenues within their jurisdiction; production, rather than innovation, appeared to many officials as the most promising use of HTZs.[103] Although the original definition of HTZs excluded production activities, China's high-technology zones became the fastest-growing regions precisely because of the manufacturing facilities that they successfully attracted.[104]

Accordingly, many of the preferential policies available to firms in China's HTZs supported mass production rather than the construction of R&D labs or the creation of new ties to local universities and research institutes. Across most HTZs, firms were exempted from income tax for two years after becoming profitable, after which their rates rose to a mere 7.5 percent for three years and topped out at 15 percent after that, a substantial discount on the 33 percent income tax imposed on businesses outside such zones. Additional tax benefits existed for foreign-invested enterprises and firms producing "advanced technologies," a category that generally included wind turbines, solar panels, and their components. For newly established firms seeking to build manufacturing facilities, including those in wind and solar sectors, HTZs cut building taxes, accelerated planning permits, waived taxes and import tariffs on imported parts and equipment, and allowed rapid depreciation for high-tech equipment.[105]

Localities further competed for investment by offering discounted land rates to firms seeking to establish manufacturing facilities.[106] The development and sale of land for urban construction became one of the most important sources of revenue for subnational governments after fiscal recentralization in the 1990s reassigned a large share of overall tax revenue back to the central government.[107] In development zones, however, local officials were willing to forgo these profits on land because production facilities presented an appealing source of future tax revenue, and productive output remained an important factor in the cadre evaluation system. Because HTZ administrators knew about land (and tax) packages being offered by neighboring municipalities and were willing to match their own deals to compete, land prices became relatively uniform across development zones. Moreover, mandatory compensation levels for rural farmland converted

[102] Heilmann, Shih, and Hofem 2013, 903.
[103] Breznitz and Murphree 2011, 78.
[104] Sutherland 2005, 91.
[105] Liu and Martinez-Vazquez 2013, 4; Sutherland 2005, 95.
[106] Kremzner 1998, 628; Kroll, Conlé, and Schüller 2008, 191.
[107] For a discussion of land as a source of revenue for municipal governments, see, for instance, Lin and Yi 2011; Rithmire 2013; Whiting 2011; Zhao 2011.

to industrial use—levels determined by the central government—set a lower price boundary of sorts. A senior official at one of the Torch Program HTZs, Suzhou New District, explained:

> If you represent a manufacturing company and they want to come to Suzhou, you will come to different investor parks. Suzhou New District will hopefully be one of them. But Wuxi and Changzhou will compete with us. Our function is to recommend Suzhou New District and try to persuade them to put their investment here. In Suzhou we have at least five national level investor parks. There are more than ten provincial and city level investor parks. So there are at least 15–20 parks which are all competing. And that's just Suzhou. The benefits that we offer are pretty much the same across industrial parks. We cannot lower the taxes because we are not allowed to subsidize that way. We can speed up approval and help firms with the bureaucracy. We cannot lower the electricity price because that's not determined by us. Same with water. We cannot control the price for that locally. Wuxi and Changzhou give some subsidies to recruit high-level talent employees, which is one way to attract firms. What we can do is to lower the price of land, but not indefinitely. The land is never free. That also is beyond our control. Before we transfer the land to the companies, we have to relocate the farmers on the land. And that requires quite a bit of money, as compensation levels are centrally determined. After they are relocated, we need to tear down everything; and then we need to pay fees to the provincial authorities and the central government. So there is high burden for the local government, and we have to pass on that cost to some extent.[108]

As less and less agricultural land was available for industrial development in China's sprawling HTZs, local officials grew increasingly selective about the kinds of industries targeted and the types of incentives offered to firms. High-tech industrial sectors—independent of central-government guidelines that encouraged the preferential treatment of high-tech firms—were particularly sought after because they promised higher returns on smaller plots than the manufacturing of consumer products that had dominated economic development zones during the 1990s.[109] To ensure that firms would rapidly contribute to the local economy, local administrations made tax breaks and land deals conditional on meeting production targets and revenue requirements. At times, firms were contractually obliged to build facilities with a predetermined manufacturing capacity by a particular date or risk losing government grants, tax reductions, and discounts on land prices. In other cases, local governments informally exerted

[108] Author interview, senior official at Suzhou New District HTZ, January 9, 2012.
[109] Author interview, senior official at Suzhou New District HTZ, January 9, 2012.

pressure on firms to rapidly scale production. The CEO of one European wind turbine engineering firm reported that a Chinese collaborator "constructed a 25,000 square meter facility practically overnight, because local officials had provided financial support and wanted to see results."[110] The president of a solar start-up disclosed that steeply discounted land prices required meeting tax revenue targets; otherwise, fines equal to the land discount would be imposed.[111]

Most of China's wind and solar firms were established in the growing number of HTZs created under the Torch Program, building their manufacturing capabilities in an environment that not only offered investment incentives but also encouraged rapid scale-up and mass production. Goldwind built its first manufacturing facilities in a high-tech industrial development zone in Urumqi's Xinshi District, created under the Torch Program in 1994. There, Goldwind participated in a tax refund program for high-tech manufacturing enterprises that returned RMB 15 million in taxes to local firms in 1999 alone.[112] In 1998, the Baoding municipal government supported the creation of Yingli Solar in Baoding's High-Tech Industrial Zone with an RMB 166 million investment. The local administration required the establishment of 3 MW of production capacity, an ambitious goal for a single firm at a time when the United States, then the global leader in PV production, boasted a national production capacity of 54 MW.[113] Trina Solar relocated its operations to a Changzhou HTZ in 2002 to qualify for preferential income taxes, but it moved to a neighboring zone in 2004 after its original tax discount expired.[114] Canadian Solar and GCL Solar opened manufacturing facilities in Suzhou's New District HTZ.[115] Mingyang, China's largest private wind turbine manufacturer, set up headquarters in the National Torch High Technology Industry Development Zone in Zhongshan, Guangdong province, in 2006.[116] Mingyang subsequently opened manufacturing facilities in other parts of China, including in the Jilin High-Tech Industrial Development Zone, a Torch HTZ, and Tianjin Binhai High-Technology Zone, a state-level HTZ that targeted renewable energy manufacturing.[117] In 2010, after the company was listed on the New York Stock Exchange, its annual report disclosed RMB 111.1 million in cash grants by local governments to support R&D, the improvement of manufacturing facilities, and the acquisition of land.[118]

110 Author interviews: CEO, European wind turbine engineering firm, May 20, 2011; CTO, Chinese wind turbine manufacturer, August 29, 2011; senior official at Suzhou New District HTZ, January 9, 2012; CEO, European wind turbine manufacturer, August 17, 2011.

111 Author interview, president, solar PV start-up firm, August 24, 2011.

112 Urumqi Year Book 2000, 116.

113 Baoding Year Book 1999, 111.

114 Trina Solar 2008, 36.

115 Author interview, senior official at Suzhou New District HTZ, January 9, 2012.

116 Guang Dong Mingyang Wind Power Technology Co. Ltd 2007.

117 Tianjin Yearbook 2010, 241–42.

118 China Ming Yang Wind Power Group Limited 2011, 53.

High-tech development zones and local government officials offered a range of additional services that encouraged local firms to rapidly increase production output. For firms setting up production facilities, the HTZ administrations acted as scale-up consultants of sorts, fast-tracking planning permits and navigating the Chinese bureaucracy not just for foreign investors but also for domestic ones.[119] More importantly, however, local governments offered access to financing, channeling bank loans and other funding to firms in development zones. Local S&T offices often demonstrated willingness to invest directly in new energy firms, if only to show their commitment to central government directives on technological innovation. The grants and incentives described earlier are illustrative of this kind of investment.

The special focus on new energy industries in national S&T plans appealed to China's state-owned financial institutions, leaving them willing to lend to wind and solar companies. But local governments were critical brokers in such deals, particularly when the first wind and solar firms were founded. Loans were frequently guaranteed by municipal government entities or by local state-owned firms that partnered with wind and solar firms. The city of Wuxi, for instance, invested USD 6 million in return for a 75 percent equity stake in the solar PV producer Suntech in 2001, after the company's founder, Shi Zhengrong, had compared offers from a number of local high-tech development zones. To fund the rapid expansion of Suntech in the following years—by 2006, Suntech ranked as the world's third-largest producer of solar panels—local officials brokered a series of bank loans for the company.[120] For a production facility launched in 2005, an RMB 200 million investment was financed through such connections.[121] In 2007, Yingli Solar borrowed USD 17 million from the Bank of China, backed by a local state-owned firm.[122] In 2009, Trina Solar secured a five-year credit line of USD 303 million from a syndicate of banks to expand its manufacturing capacity.[123] Not only was local government support critical in securing this loan, but local guarantees also allowed Trina to obtain waivers on loan conditions usually attached to large investments in high-risk, emerging industries.[124]

Access to large-scale financing of course provided no guarantee for upgrading. Localities at times lent indiscriminately and contributed to overcapacity in global renewable energy markets. Between 2009 and 2011, the capacity utilization of existing solar PV manufacturing plants fell from just over 60 percent in

119 Sutherland 2005, 95–96.
120 Ahrens 2013, 3–4. See also Kevin Bulls, 2011, "The Chinese Solar Machine," *MIT Technology Review*, December 19.
121 Wuxi Yearbook 2006, 293.
122 Yingli Green Energy Holding Company Limited 2008, F-28.
123 Trina Solar 2010, F-30.
124 Trina Solar 2013, F-35–36.

2009 to just under 50 percent in 2011.[125] Even though, in the aggregate, only half of China's solar PV plants were running at capacity, solar PV firms continued to receive credit to expand their manufacturing facilities, preventing industry consolidation and protecting firms that were no longer able to compete.

Yet access to local financing also provided the basis for engineering capabilities in innovative manufacturing: these funds guaranteed the infrastructure within which such skills could be applied, and they did so in ways that the limited central-government R&D funding alone could not. Both during the infancy of the wind and solar sectors in the early 2000s and again after the 2009 financial crisis, wind and solar manufacturers in China successfully raised capital, even as funds dried up in the United States and Europe. Media reports suggest that the China Development Bank alone extended USD 29 billion in credit to fifteen solar and wind companies; others have calculated that China's publicly listed wind and solar companies took out some USD 18 billion in loans with loan guarantees from municipal governments.[126] Although little reliable information exists on what interest rates such deals entailed, it is safe to assume that at least some of these loans were provided at submarket rates.[127]

Although firms could not buy their way into the seasoned knowledge and particular engineering skills needed for commercialization, the availability of such funds for production facilities enabled the most capable of China's wind and solar firms to forge ahead and specialize in innovative manufacturing. In interviews, the foreign partners of solar firms frequently praised the R&D conditions in Chinese manufacturing facilities, where access to capital allowed firms to dedicate entire production lines—Golden Lines—to testing and experimenting with new technologies under production conditions.[128] Lacking such facilities themselves, R&D engineers in Europe and the United States struggled to obtain time slots during which they could conduct such tests using regular production lines.[129]

High-tech development zones provided access to the financial capital required to build capabilities in mass production; at the same time, they also attracted the *human* capital necessary for leading expertise in rapid commercialization. Between 1990 and 2006, China's S&T personnel—defined in China as staff who spend at least 10 percent of their time in activities "closely related to the production, development, dissemination, and application of knowledge in natural sciences, agricultural science, medical science, engineering and technological

125 Zhao, Wan, and Yang 2015, 183.
126 Bradsher 2012; Sustainable Business News 2012.
127 Deutch and Steinfeld 2013.
128 Author interview, chief engineer, State Key Laboratory, March 29, 2015.
129 Author interviews: CEO, Chinese solar manufacturer, August 20, 2011; CTO and director of R&D, Chinese solar manufacturer, August 26, 2011; CEO, German equipment manufacturer, May 10, 2011; CTO, German equipment manufacturer, May 11, 2011.

science, humanities and social sciences"—nearly doubled, from 23 to 41 million. Scientists and engineers constituted more than two-thirds of S&T personnel. The share of such workers with university degrees increased from 10 million in 2000 to 14.5 million in 2005, with a growing percentage of S&T workers employed by enterprises, rather than by universities and research institutes. By 2006, nearly half of S&T employees worked in large and medium-sized enterprises, up from 36 percent during the early 1990s.[130]

A disproportionate number of this young and educated workforce gravitated to high-technology development zones. In 2000, for instance, when the first wind and solar firms were just beginning to engage in the commercialization of new technologies, enterprises in China's Torch Program HTZs jointly employed a workforce of 7.5 million, a third of whom held university degrees. Although the Ministry of Science and Technology estimated only 30,000 staff with masters' degrees and 4,000 graduates of doctoral programs at work in HTZ enterprises that year, the figures far exceeded average Chinese educational levels at the time.[131] For wind and solar firms, HTZs thus presented a rich environment within which to recruit engineering staff, men and women who not only held above-average levels of educational achievement but also came to the table with experience in mass production from a range of other sectors, including foreign-invested firms that had come to China during the 1990s and settled in high-tech zones.

In addition to such general incentives, local governments provided resources, institutions, facilities, and infrastructure to support the existing local industrial base. Local conditions in high-tech development zones remained relatively uniform in what basic resources they offered to attract investment and in the stipulations (scale-up and mass production) they attached to their support.[132] Once localities had successfully attracted firms, however, a second set of policies and institutions stepped forward, supporting the activities of local firms in a more targeted manner. Such resources, policies, and institutions differed depending on the composition of the local economy. But they held something important in common: these policies supported rapid commercialization and mass production through the creation of new capabilities in the local economy, rather than through financing ever-larger production facilities.

Municipal governments themselves were active agents in reinventing and structuring the local economy. They interpreted central directives to promote strategic industries in ways that supported the existing industrial structure.

[130] Simon and Cao 2009, 67–79.

[131] Ministry of Science and Technology data cited in Sutherland 2005, 96.

[132] A large literature has documented different regional political economies in China, emphasizing differences in institutions, training of local officials, sequencing of economic reforms, and local economic rules. See, for instance, Rithmire 2013; Segal 2003; Thun 2006.

Although many of the early wind and solar firms began in the proximity of their parent companies or near the hometown of their founders, municipalities later attracted supplier firms and companies from related industrial sectors to create cluster effects and synergies. Wuxi, the city where Suntech had its beginnings in 2001, attracted glass manufacturers, producers of production equipment, and firms supplying silicone and other materials required for PV production. Semiconductor firms, which rely on a production method that bears similarities to the process that produces a solar cell, also settled in local HTZs.[133] Baoding, where Yingli had started the domestic solar PV industry in 2001, ultimately branded itself as a "green city," attracting a wide range of renewable energy firms and suppliers with complementary capabilities to its local industrial parks. The local government also targeted foreign equipment manufacturers and component suppliers at international conferences, including at the 2004 Global Wind Power Exhibit held in Beijing, less than 100 miles from the city.[134]

In other cases, particularly among late entrants, domestic wind and solar firms sought out high-tech development zones specifically for their existing industrial base. A history of shipbuilding and the presence of related supplier industries, including bearings manufacturing, persuaded Sinovel to open its first manufacturing facilities in Dalian.[135] Tianjin became a popular destination for domestic wind turbine producers after successfully attracting a wide range of foreign wind turbine manufacturers and their suppliers, including REpower, Sinovel, and Vestas.[136] In Changzhou, where Trina Solar and EGing Solar were producing cells and solar PV modules, the municipal government counted 109 firms that manufactured products and components for power generation equipment, including transformers, inverters, electrical insulation, and switching equipment.[137]

The agglomeration economies born from local government coordination promoted collaboration between foreign and domestic firms. For domestic manufacturers seeking to upgrade their capabilities in manufacturing, however, these local economies also created supplier networks that allowed the purchase of large quantities of raw materials at short notice. They permitted close interaction with suppliers to fine-tune equipment and adjust material composition to match product designs and manufacturing processes. For engineering teams seeking to accelerate product commercialization, regional economies thus offered a wide range of tools and partners focused precisely on the large-scale production of renewable energy technologies. In interviews, firms confirmed the benefits of

[133] Wuxi Yearbook 2003, 219; 2006, 292.
[134] Baoding Year Book 2004/2005, 155.
[135] Dalian Yearbook 2007b, 130–39.
[136] Tianjin Yearbook 2010, 241–42.
[137] Changzhou Yearbook 2005, 173.

these local environments. The president of a solar PV manufacturer explained his company's chosen location as the result of a decision to operate in proximity to other solar PV manufacturers who were likely to have used production equipment available: his engineering teams could acquire this equipment to cheaply test the manufacturing of their new product designs.[138] Others emphasized the availability of local suppliers to collaborate on substitute materials or new equipment design, describing how these partnerships enabled them to move rapidly through multiple configurations until the right setup was pinpointed.[139]

Beyond the benefits that firms naturally derived from agglomeration economies, specialization in local industrial composition also permitted local governments to design more targeted institutions to support firms in the process of developing knowledge-intensive capabilities. In contrast to the broad national educational reforms that increased the number of graduates from China's engineering schools over time, local administrations created educational facilities for vocational training and continuing education that matched the needs of their home firms. These local colleges did not aim to graduate engineers with doctoral degrees; rather, they focused on creating a manufacturing workforce capable of understanding manufacturing blueprints while grasping the requirements of mass production. Regardless of whether such programs allowed firms to send existing workers for continuing education or trained high-school graduates for manufacturing jobs, many of these vocational colleges, set up by local governments in China's high-technology institutes, collaborated with local firms. For instance, the municipal government in Changzhou set up a program for technological upgrading in manufacturing firms as early as 1997, around the time that Trina Solar was founded as a solar installation company. The city estimated that about 25 percent of local large- and medium-sized enterprises had employees with Computer Assisted Design training (CAD), with a total of 5,000 CAD-trained workers in the city. To augment this number and promote advanced manufacturing skills in the local workforce, the city set up CAD demonstration platforms, established training programs, and offered loans to local companies seeking to upgrade their manufacturing infrastructure and improve the skill level of their employees.[140]

Other locations with sizable renewable energy industries launched similar programs, including in Changzhou, Baoding, and Urumqi.[141] In Wuxi, the local government founded a vocational college for S&T training in 2003. By 2005, the

[138] Author interview, president, solar PV start-up firm, August 24, 2011.

[139] Author interviews: CTO and director of R&D at Chinese solar manufacturer, August 26, 2011; CTO, Chinese wind turbine manufacturer, August 29, 2011.

[140] Changzhou Yearbook 1998, 288.

[141] Changzhou Yearbook 2004, 249–50; Baoding Year Book 2004/2005, 523; Urumqi Year Book 2007c, 226.

school was offering applied vocational training programs for 6,000 students in collaboration with Suntech, Sony, and thirty-seven other firms with facilities in the region.[142] In some cases, local enterprises themselves took the initiative to set up such programs, collaborating with the local government and other firms for support. Spearheaded by Dalian Daxian Group, a supplier of electronic components, vocational training was offered in Dalian for electromechanical technicians, supplying workers with knowledge of mechanical components and electronic circuitry to local industrial sectors, including wind turbine manufacturing.[143]

At the same time that wind and solar manufacturers were rapidly increasing the average training levels of their educated workforce, they were increasingly automating their production lines to avoid the high turnover rates associated with unskilled labor. Although innovative manufacturing capabilities continued to reside in designated engineering teams and did not extend into the manufacturing workforce in the same way that advanced manufacturing capabilities in Germany did, the training of manufacturing staff permitted Chinese firms to translate design and process changes into manufacturing practice more rapidly. Efforts to increase the skills and training of local members of the existing workforce thus complemented central government innovation policy, which focused on technology development but paid little attention to the types of skills required in commercialization and production.

In addition to promoting workforce training, municipalities supported the technology commercialization efforts of local firms by funding individual commercialization projects and improving the R&D infrastructure available in the local economy. Such R&D infrastructure included China's 800 universities and 5,000 research institutes, 60 percent of which were located in close proximity to one of the high-technology industrial zones.[144] Many of these institutions set up laboratories working on technologies of importance to industrial sectors; municipal chronicles boast an increasing number of patent activities and journal citations for local research laboratories. In Baoding, for example, Hebei University of Technology established a School of Energy and Environmental Engineering in the early 2000s, after the arrival of Yingli and other renewable energy companies prompted the city to promote itself as a green technology cluster.[145] Although almost all renewable energy firms indicate some connections to research institutes, collaborative R&D activities mostly occur with other firms.[146]

142 Wuxi Yearbook 2006, 305.
143 Dalian Yearbook 2007b, 140.
144 Heilmann, Shih, and Hofem 2013; Sutherland 2005, 96.
145 Author interview, senior official, Baoding Municipal Government, January 7, 2012.
146 Sutherland 2005, 96.

Local programs focused not on laboratory research but on the commercialization of new technologies and the transition to mass production, thus, proved more central to the success of innovative manufacturing. Almost all localities set up municipal innovation funds, providing grants for innovation-related activities in local firms. Often these grants funded activities to overcome challenges in the commercialization of new technologies, rather than to create such technologies themselves. Although most grants went directly to firms, localities also used the programs to publicly fund facilities such as test centers, thereby providing complementary capabilities for firms in the local economy.

In Dalian, the municipal government supported Sinovel in 2006 with the commercialization of a 1.5 MW turbine technology based on a license from a German firm. In the process, engineers adapted the turbine for deployment under harsh climate conditions with temperatures as low as -40 degrees Celsius. Two local suppliers, Dalian Tianyuan Electrical Machinery and Dalian Wazhou Group, supplied components for the new turbine. The local government helped Dalian Wazhou construct a test platform for industrial-scale precision bearings to aid the commercialization of new bearing designs. Beyond supporting the commercialization of wind turbine components, however, this testing platform enabled the commercialization of bearings for other local industries, such as shipbuilding and railway engines.[147] In collaboration with Suntech, in 2006 the Wuxi government initiated a so-called 530 Program, providing funds to attract Chinese engineering graduates back into local high-tech development zones and offering grants of RMB 1–3 million for the commercialization of promising technologies. By 2012, 876 local firms were participating in the 530 Program, and available funds had grown to RMB 2.5 billion.[148] In Baoding, the provincial government funded the development of two public engineering centers in the local high-tech development zone, a center of virtual engineering and an engineering center of blade development, both of which offered access to advanced computer workstations and test facilities. The government emphasized the importance of industry associations in setting up these facilities to meet the needs of the local industry and boost the competitiveness of local firms.[149]

Local government policies, training institutions, and innovation support programs did not add up to a comprehensive strategy for industrial upgrading. Rather, they presented ad hoc responses to the perceived needs of local industrial sectors, to directives on innovation from the central government, and to the desire of local officials to promote economic growth. For wind and solar firms, these policies created a broad range of resources capable of bolstering

[147] Dalian Yearbook 2007b, 130–39.
[148] Wuxi Yearbook 2008, 241.
[149] Baoding Year Book 2004/2005, 155.

engineering capabilities and funding the expansion of manufacturing facilities. But just as central government policies had not deliberately created institutions to support the establishment of capacities in innovative manufacturing, so local governments and high-tech development zones did not strategically choose capabilities in technology commercialization as an overt goal. At the local level, policymaking was instead driven by the much more immediate necessity of growing the economy through the rapid scale-up and mass production of potentially game-changing technologies. China's wind and solar firms utilized this manufacturing infrastructure to respond to new opportunities, laying their engineering expertise in innovative manufacturing on top of a strong foundation of local institutions supportive of mass production. The specialization in innovative manufacturing entailed advanced capabilities in product design, yet it differed from the conception of autonomous technology development at the core of Beijing's indigenous innovation strategy. Chinese wind and solar firms engaged in learning and industrial upgrading, but they did so without developing the full range of industrial capabilities required to invent, commercialize and produce green energy technologies. In spite of government plans to create autonomous local enterprises, China's wind and solar firms developed highly specialized capabilities within collaborative relationships in global supply chains.

Conclusion

Policymakers and industry associations in the West long suspected a centralized government effort behind China's rise in renewable energy sectors. Political economists focused on China frequently raised an opposite set of observations: from the perspective of statist literatures on economic development, which have provided a more nuanced perspective on the role of the state in fostering industrial upgrading, the development of innovative capabilities in China's wind and solar sectors was unexpected because of the fragmentation of the Chinese state. Among other East Asian late developers, centralized and hierarchical planning bureaucracies orchestrated targeted policy interventions to support technological learning and industrial upgrading. China lacked such centralized institutions.[150] Although the central government in Beijing provided various incentives for technology transfer and the establishment of advanced R&D capabilities in Chinese firms, the responsibility for policymaking was distributed across numerous ministries and administrative levels. China lacked

[150] On strategic government intervention among the East Asian developers, see Amsden 1989, 2001; Evans 1995; Johnson 1982; Wade 1990.

the institutions to implement the concerted policy effort necessary to prompt upgrading in high-technology industries in a centralized manner.[151]

This fragmentation of industrial policy implementation was particularly visible in policies to promote domestic innovation, where different levels of government demonstrated divergent priorities. Central government plans called for the establishment of autonomous technological capabilities in virtually all segments of the wind turbine and solar supply chains.[152] Literature on China's decentralized development model focused on the ways in which incentives for local governments to create short-term economic growth collided with these long-term central government plans, creating an implementation gap between central goals and local outcomes.[153] Divergent policy goals at subnational levels were here regarded as a threat to the implementation of central government policies, as they offered firms the option of shirking their duty by prioritizing short-term economic gains over long-term policy goals.[154]

In this chapter, I have argued that collaborative advantage allowed Chinese wind and solar firms to use the fragmented industrial policy framework to establish knowledge-intensive capabilities focused on preparing complex technologies for mass production. As in Germany and the United States, firms entered global supply chains with specialized capabilities that relied on collaboration with others. Although these skills fell short of government goals, they nonetheless represented a form of industrial upgrading. Chinese firms repurposed policies and institutions intended for the manufacturing economy to establish new knowledge-intensive capacities within manufacturing itself, incrementally building on China's industrial legacy of mass production. The state enabled such industrial upgrading among China's wind and solar producers not only by providing the resources required for technological learning, but, as I have argued here, by attracting foreign-invested high-technology manufacturers into China's economic development zones. The end result was the establishment of an industrial ecosystem for mass production eminently capable of supporting a new generation of innovative manufacturing.

China's wind and solar firms have achieved sustained growth despite divergent—and often outright conflicting—government policies, which have not followed the hierarchical, centralized, and highly disciplined template of the East Asian developmental states. And China's renewable energy firms have avoided the main hazard associated with participation in such fragmented global production systems, namely the possibility of becoming trapped in low-skill and

151 See, for instance, Huang 2002; Thun 2006, 52–60.

152 See, for instance, Ministry of Science and Technology 2012; National Energy Administration 2012.

153 Amsden 1989; Johnson 1982; Kostka and Nahm 2017; Nahm 2017.

154 For a discussion of policy bundling in China, see Kostka and Hobbs 2012, 768–70.

low-value activities within global supply chains.[155] Instead, Chinese capabilities in scale-up and commercialization have attracted global innovators, allowing Chinese firms to bring wind and solar technologies to market, even if they do not do so alone. At least in renewable energy industries, Chinese firms learned to compete on skills, not on labor cost. In consequence, wind and solar production did not chase labor cost to cheaper manufacturing locations in the Chinese interior or in neighboring economies, even as wage differentials remained large and growing.[156]

At the same time, however, such upgrading-within-manufacturing required Chinese firms and regulators to assume risks. Participation in global processes of technology development required Chinese firms to make large investments in manufacturing capacity, often funded by state-owned banks and local governments. In contrast to German suppliers of components and production equipment, which maintained customers in several industries despite small firm sizes, China's investments were industry-specific. In the wind and solar sectors, where demand continues to rely on demand-side subsidies, the fate of China's innovative manufacturers depends not just on their ability to innovate and further reduce cost, but also on government policy in China and abroad. The global financial crisis, which led many European governments to cut or eliminate subsidies for wind and solar products, created overcapacity in global renewable energy sectors. Antidumping legislation against Chinese solar panels has further threatened export markets, as have widespread calls in the United States for economic decoupling from China.[157] In times of crisis, Chinese firms were thus left with the most capital-intensive part of the global innovation processes.

A number of firms have declared bankruptcy as a result. Suntech, for instance, exported 38 percent of its solar panels to Spain in 2008. By 2009, after the Spanish government had all but shut down its domestic support for renewable energy markets, Spanish demand accounted for less than 3 percent of Suntech's revenue.[158] By 2013, the company, once the largest solar manufacturer in China, had filed for bankruptcy protection.[159]

Ultimately, the sustainability of China's specialization in innovative manufacturing could depend on the ability of China's manufacturers to apply their capabilities in scale-up and commercialization to a wide range of industrial sectors. Breznitz and Murphree, in a study on China's electronics industry, found that manufacturers there also embarked on a manufacturing-centric upgrading

[155] Steinfeld 2004.
[156] In 2009, the wage gap between urban workers in coastal provinces—where most of China's renewable energy manufacturing is located—and urban workers in interior provinces was 55 percent, up from 28 percent two decades earlier. Li et al. 2012, 62.
[157] US.International Trade Commission 2012.
[158] Ahrens 2013, 4.
[159] Bradsher, 2013b.

trajectory.[160] Thun and Brandt similarly found that in the machine tools and automotive sectors, Chinese firms benefited from engineering capabilities in advanced manufacturing.[161] Germany's small and medium-sized wind and solar suppliers, which improved and adapted their core capabilities over decades and applied them to successive industrial sectors, illustrate that diverse strengths in manufacturing can, in principle, be the source of long-term advantage.

The importance of manufacturing institutions for economic development and technological innovation was not lost on central government planners in Beijing, as the renewed push to support upgrading-within-manufacturing through China's Made in China 2025 initiative illustrates. If the experience of China's renewable energy industries is any guide, however, it will be up to entrepreneurial firms, not the state, to identify new applications for advanced skills in manufacturing and use a broad range of institutions to support such strategies.

[160] Breznitz and Murphree 2011.
[161] Brandt and Thun 2010.