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CHINA'S RENEWABLE ENERGY REVOLUTION

John A. Mathews and Hao Tan

China's Renewable Energy Revolution

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Preface

This book results from a long-standing collaboration that has seen the authors develop our interest in China and its energy strategies over many years. John Mathews approaches the topic from his interests in East Asian industrial development strategies that go back 20 years or more, where China and its renewable energy revolution constitute the latest chapter in this remarkable saga. Hao Tan approaches the topic as a young researcher with an interest in industrial dynamics, firm strategies and internationalization, particularly in the context of the energy sector which is vital to the global economy. This collaboration has seen us publish numerous papers in the refereed literature, and culminated in the publication of a major article in September 2014 in the world's leading science journal *Nature*, on 'building energy security through manufacturing' with China depicted as a principal exponent of such a strategy. This book is in a real sense an elaboration and extension of the argument advanced in this article published in *Nature*.

Rather than approach the topic of energy in the manner of neoclassical economics, concerned with costs and price fluctuations and the role of taxes such as carbon taxes, we probe China's renewable energy revolution in terms of its industrial dynamics, manufacturing strategies and impact on global political economy. We describe China as the world's first country to begin a serious process of liberating itself from fossil fuels with all their geopolitical entanglements as well as spoliation of the local and global environment. Thus we see China is the world's first to break out because the country has both motive – the catastrophic pollution, the need to upgrade its industrial capacity, and concerns over energy security– and the means – a strong state willing to intervene to change energy trajectories. We describe China's support for renewable energies as determined, serious and relentless – indeed, as if the country's future depended on its successful building of an energy system based on manufacturing.

Energy security through the manufacture of renewables, then, is our theme – a very different perspective from one informed by conventional economics or conventional environmental arguments grounded in concerns over climate change. Our argument is that China is primarily motivated by concerns over its immediate pollution problems, as well as issues of energy security and industrial development in the medium and longer run, which could only be exacerbated if it were to continue a 'Business as Usual' energy pathway based on fossil fuels. Renewables make abundant sense for China precisely because they offer real energy security, based in turn on the fact that the energy generation devices needed (wind turbines and solar cells initially) are the products of manufacturing, and whose production utilizes all the skills that a country like China has built in manufacturing processes and the creation of their associated value chains. They also open up unlimited opportunities for a country eager to upgrade its industrial structure and move up the value chain for its vast working population. The fact that such a commitment to renewable energy industries also promises the fastest and surest way to reduce carbon emissions is, we argue, a highly convenient side-effect. In our view China's energy strategies are likely to form the foundation of the country's soft power in coming decades.

Our aim in writing this book has been to present China's renewable energy strategies and the revolution that they are accomplishing in a critical but favourable light, so that they might be better understood by the wider scholarly and public policy communities. A related aim is to engage with discussions on energy policy and industrial development in China itself, so that a perspective from us as researchers based outside China can be added to the debate.

We would like to acknowledge the contribution of two scholars in particular to this project. Professor Mark Selden, senior research associate at the East Asian Studies program at Cornell University, has been an inspiration and support for our project, publishing several of our articles as we built our argument in his influential *Asia-Pacific Journal:*

Japan Focus. Professor Anthony Payne, director of the Sheffield Political Economy Research Institute (SPERI) at Sheffield University, has been a source of encouragement and advice; we thank him for including this book in the SPERI series on *Building a Sustainable Political Economy*. And HT would like to acknowledge Professor Mei-Chih Hu at National Tsinghua University in Taiwan and Professor Hubert Schmitz at the Institute of Development Studies at Sussex University for their continuing support and advice.

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List of Abbreviations

AIIB	Asia Infrastructure Investment Bank
CACE	China Association for the Circular Economy
CDB	China Development Bank
CEC	China Electricity Council
CGNP	China General Nuclear Power Group
CNPC	China National Petroleum Corporation
CNREC	China National Renewable Energy Centre
CPIA	China Photovoltaic Industry Association
CPTA	China Patent & Trademark Office
CRC	China Rail Corporation
CREIA	China Renewable Energies Industry Association
CSPG	China Southern Power Grid
CV&ADs	Countervailing and Antidumping Duties
CWEA	Chinese Wind Energy Association
EHVAC	Extra-High-Voltage Alternating Current
EIA	Energy Information Administration (US)
EM-MNEs	Emerging Market Multinational Enterprises
EPC	Engineering, Procurement and Construction
ERI	Energy Research Institute, NDRC (China)
FSTS	Foreign sales to total sales (proportion)
FYP	Five Year Plan
GNP	China General Nuclear Power group
Gtce	Gigatonnes of coal equivalent
HSR	High-Speed Rail
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IEA	International Energy Agency

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IGCC	Integrated Gasification Combined Cycle
IPR	Intellectual Property Right
IRENA	International Renewable Energy Agency
LEDs	Light Emitting Diodes
MEP	Ministry of Environmental Protection (China)
MIIT	Ministry of Industry and Information Technology (China)
MST	Ministry of Science and Technology (China)
NBS	National Bureau of Statistics (China)
NEA	National Energy Administration (China)
ND&RC	National Development & Reform Commission (China)
NPTC	State Nuclear Power Technology Corporation
PBoC	People's Bank of China (central bank)
PMDD	Permanent Magnet Direct Drive (wind turbines)
PRC	People's Republic of China
SC	Supercritical (thermal power generation)
SEIs	Strategic Emerging Industries
SERC	State Electricity Regulatory Commission (China)
SGCC	State Grid Corporation of China
SIPO	State Intellectual Property Office (China)
SPC	State Power Corporation (disbanded in 2002)
SPGC	Southern Power Grid Corporation
TW	Terawatts (trillion watts)
UHVAC	Ultra-High-Voltage Alternating Current
UHVDC	Ultra-High-Voltage Direct Current
USC	UltraSupercritical (thermal power generation)
WGQ3	Shanghai Waigaoqiao No.3 Power Station
WTO	World Trade Organization
WWS	Water, Wind, Solar – as sources of renewable energy

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1
Introduction

Abstract: *China's renewable energy revolution is a work in progress where the building of the world's largest manufacturing system is based on the world's largest energy system created, as in the case of previous industrial powers, from reliance on fossil fuels. But China is reaching the limits of such a system, in terms of environmental pollution and energy/resource security, and so is embarked on a serious and sustained creation of a complementary system based on power generation from water, wind and sun, plus some continuing adherence to nuclear power. China's investments in its green energy system dwarf those of other countries. China's renewable energy revolution may be framed as the world's first case of a country breaking free of carbon lock-in by building its own renewable energy industries – 'building energy security through manufacturing'.*

Keywords: 12th Five Year Plan; carbon emissions; carbon lock-in; China; coal; energy security through manufacturing; environmental pollution; fossil fuels; renewable energy

Mathews, John A. and Hao Tan. *China's Renewable Energy Revolution*. Basingstoke: Palgrave Macmillan, 2015. DOI: 10.1057/9781137546258.0008.

The world has yet to come to grips with the scale of China's commitments to renewable energies. It is not widely appreciated that China has built a renewable energy system powered by water, wind and sun (WWS) which is larger than the renewable systems built by the United States, Germany, India and Spain combined. While the scale of China's commitment to building coal-fired power stations is widely recognized and deplored, the fact that these fossil fuel capacity investments are approaching their peak, and look set to decline in the near future, is less widely recognized. Even less well appreciated are the reasons guiding China's vast commitments to renewable energy sources – reasons that have much more to do with cleaning smog-choked skies and water, building new industrial capacities, and enhancing energy security than with reducing carbon emissions (important as this latter goal might be). Meanwhile the global impact of China's commitment to renewables, in terms of driving down costs not just for itself but for everyone else, is still barely appreciated.

In this monograph we tackle these issues, in what might be called the political economy of China's energy revolution. We spell out in a succinct and up to date fashion the basic facts and trends, focusing on China's vast additions to its renewable energy capacity and generation of renewable electrical energy as complement to its equally vast additions to its black, coal-fired capacity and generation of thermal power. We provide clear data on the capacity additions, on the electric energy generated, and on the investments being made, all of which dwarf those of other countries, and on how they are demonstrably growing greener at the margin. We look at the macro trends, both in terms of China's energy system as a whole, and its most important constituent, namely the electric power sector, and at the micro trends at the level of firms and their strategies. We emphasize that China demonstrably views its 'Big Push' to renewables not just as an environmental strategy but as a developmental and business strategy, with renewables industries such as those producing wind turbines, solar cells, batteries, LEDs or electric vehicles as pillars of the economy and as export platforms for the future.[1]

The thesis that we defend in this study is that China is employing industrial strategies to great effect in building and expanding a number of industries related to renewable energy, energy efficiency and resource efficiency, and is indeed a major case for the demonstration of the efficacy of such strategies.[2] Through its implementation of these industrial strategies China is achieving or approaching world leadership in green sectors. Our goal is to demonstrate that China's strategies are working and are having positive impact both in China – reducing catastrophic levels of pollution and enhancing energy and resource security – and globally, through dramatic reductions in costs and prices and the framing of an alternative model of low-carbon development that works. At the same time we recognize that the pollution from China's build-up of a coal-fired manufacturing industrial system is having shockingly deleterious impact in China itself and globally, through carbon emissions that add to those already created by the industrialized countries. We recognize that it is an open question whether China's greening strategies are going to be able to drive the creation of new cleantech sectors before the older carbon-intensive sectors create irreversible damage.

We draw implications from this analysis of both macro and micro trends, and situate China's energy strategies in their global and historical context. China's strategies may be viewed as comparable to the coal-based strategies that took Britain to world economic leadership in the 19th century, and the oil-based strategies that took the US to world leadership in the 20th century. China's 21st century strategies which are focused on the scaling-up of renewable sources of electric power have implications for the modernization and urbanization of China, in terms of the smart grid, high-speed rail and of the diffusion of electrified energy access on the part of more than a billion people – an unprecedented expansion of industrial strength, combined with an unprecedented strategy for enhancing energy security based on manufacturing rather than access to fossil fuel resources.

Since nations' energy systems have a strong influence on the kind of industrial choices open to the country, we emphasize in this study that China's focus on renewables is opening up many more industrial options. As costs of generating electric power fall, utilizing renewable sources like water, wind and sun, so the prospects for industrial activities such as solar-powered desalination become more attractive. Outside China, the impact of plunging prices for oil and coal is clearly visible – from choices being made by minerals producers in Chile's Atacama desert (see a Case Study in Chapter 6) to expand production utilizing renewable power sources, to those made by food producers who can now utilize solar-powered greenhouses to produce their own clean water and clean environment for growing a variety of foods at vast scale.

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China's black and green energy economy

Before embarking on our analysis of the greening of China's economy and energy system, it is necessary to acknowledge the size of its black economy and the scale of the pollution that currently afflicts the country. Just as China has telescoped into three and a half decades developmental processes that took decades if not centuries to unfold in earlier countries, so its pollution problems have also accelerated and fed on each other in a way that creates a toxic soup. The video sensation 'Under the Dome' by Chinese investigative reporter Chai Jing, vividly captures the scale of China's pollution problems, bringing home their immediate and human impact.[3] Chai Jing emphasizes that China's smog is a result of a concatenation of pollution problems coming on top of each other – pollution from coal burning in heavy industry, pollution from dirty road vehicles, particularly diesel trucks that flout their environmental permits, pollution from gasoline vaporization which adds further polycyclic aromatic hydrocarbons (all carcinogenic) to the toxic mix, as well as other sources.

'Under the Dome' carries a powerful message, urging Chinese citizens – particularly younger people to whom the video is directed – to tackle the problems at source, by insisting that the present laws (all of which could contain the pollution if enforced) be applied and acted on. One of the most telling quotes in her film is the petrol station owner who blocks an impromptu inspection of fuel dispensing equipment (which is clearly unguarded) by telling the Environment Ministry inspectors that they 'have the responsibility but not the authority'. Chai Jing is calling for citizens in China to uphold that authority – in a social movement that could emulate the effect just over half a century ago of Rachel Carson's *Silent Spring* in the then heavily polluted USA.[4]

To gain a feel for the scale and significance of China's ongoing energy revolution, we shall examine first its contrasting 'black' (fossil fuelled) and 'green' characteristics.[5] The electric power generation system, which consumes half the country's coal and has been responsible for much of the carbon and soot pollution that has wracked China, provides a sharp contrast between the black and green aspects of China's energy system. The black features are captured in the story of the rise of China's power output and coal consumption in recent years, as shown in Figure 1.1.

The two headline points to make from Figure 1.1 are that (1) China's rate of energy production grew rapidly during the first decade of the

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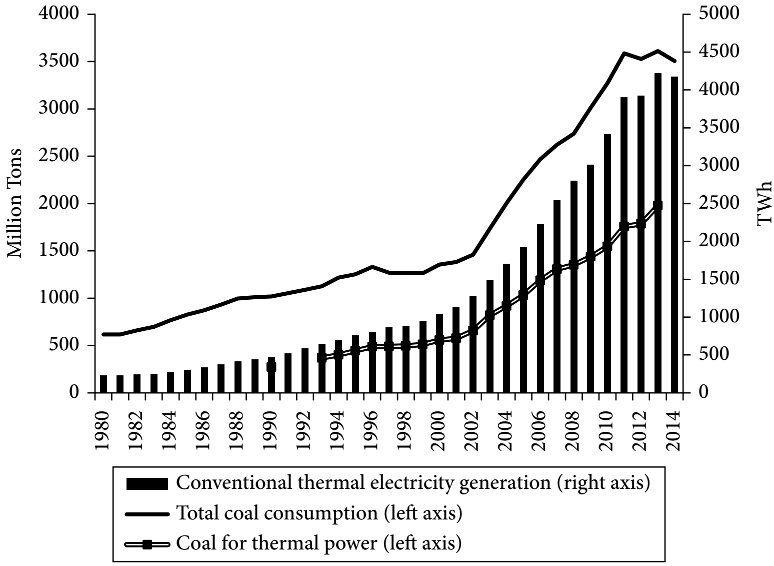

FIGURE 1.1 *Chinese thermal power generation and rising coal consumption up to 2014*

Sources of primary data: The data for the total coal consumption (up to 2012) and thermal electricity generation (up to 2011) is available from the US EIA. The data of coal consumption for thermal power up to 2012 is available from the National Bureau of Statistics (NBS) of China. The data for the total coal consumption in 2013 and 2014 are available from the China Coal Industry Association and NBS respectively. The data for the thermal electricity generation in 2012 to 2014 are available from the China Electricity Council. The data for the coal consumption for thermal power in 2013 is available from chinapower.com.cn, a website by the China Electric Power Promotion Council.

century, based largely on coal, while (2) this dependence on coal, with all its pollution implications, appears now to be peaking. The year 2001 was the inflection point – which coincides with China's entry to the World Trade Organization (WTO). This signalled to the world that China was 'open for business' and manufacturing started to migrate to China in a big way – calling for drastic expansion of the energy system. In the time-honoured way, replicating the actions of the West in the 19th century and Japan in the 20th century, what was expanded initially was the coal-burning system.[6] Now there appears to be a second inflection point at 2014, signalling that China is reining in its heavy coal dependence.

It is a fact that China has driven its energy revolution with coal – just like every rising industrial power before it. But the speed and

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concentration of China's experience is unprecedented. China now burns more coal than the rest of the world combined – a telling fact emphasized in 'Under the Dome'.

The striking aspect of this first chart (Figure 1.1) is that it shows that China's spurt in using coal to drive its energy revolution appears already to be peaking. Electric power generated from fossil fuels (largely coal) – termed 'thermal generation' – reached a peak in 2013 and actually declined in 2014 – an extremely important milestone for China. Total coal consumption declined also in 2014, so that it now hovers around 3,500 million tonnes (or 3.5 Gt). In fact coal consumption dropped 2.9 percent on the 2013 total – the first time this has happened this century. It means that carbon consumption generally (fossil fuels) could be peaking shortly, too, by 2020 or earlier, and following that, carbon emissions as well (perhaps by 2025 or earlier), according to some recent studies such as the *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* carried out by the Energy Research Institute in China.[7] This would be important for China, and for the world.

At the same time, China is ramping up its renewable energy power system, best captured in the remarkable story of wind power generation and its growth. As shown in Figure 1.2, wind power generation started

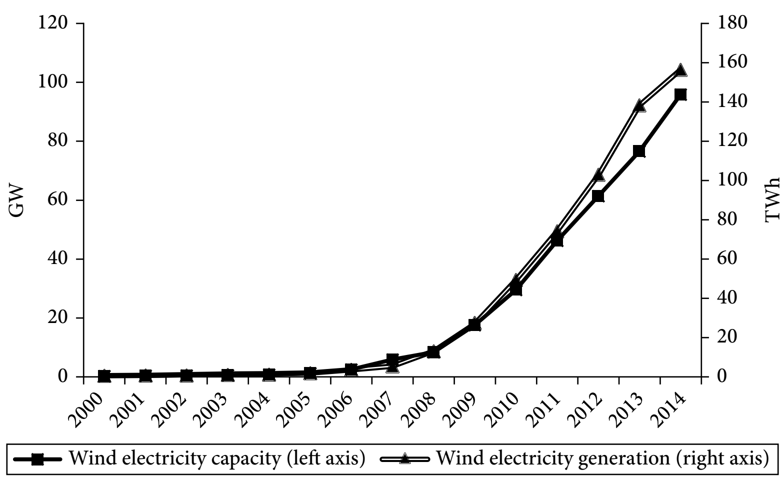

FIGURE 1.2 *China's wind power generation, 2000–2014*

Sources: Data up to 2007 is available from the BP Statistical Review of World Energy 2014; data for the years 2008–2014 is available from the China Electricity Council.

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to double every 18 months in the mid-2000s and has grown rapidly to become the largest wind power system in the world.

We shall examine the rise of China's wind power industry in detail in following chapters, but for now it is worth pointing to the rapid rise in the industry, from the mid-2000s, once the Chinese leadership had decided that wind power would be a good bet as counterpart to nuclear and as an alternative to fossil fuelled expansion. China's cumulative installed wind turbine capacity rose from just under 1 GW at 2004 to 95 GW at the end of 2014, and the windpower generation from around 1.3 TWh in 2004 to 156 TWh in 2014 – by which time it was the largest wind power system in the world. This was a 100-fold expansion in wind power in a decade. We shall argue that windpower was a fortuitous choice, in that it put China's energy trajectory onto a sound footing; domestic energy security was to be ensured by China's own manufacturing capabilities in producing wind turbines, solar PV cells and the components that feed into these end-products.

Although other countries regard renewables as of interest because of their contribution to decarbonization of the energy system and hence to climate change mitigation, we argue that renewables in China have been treated primarily as an industry of the future, as an export platform and as a source of energy security in that all the products of the industry can be manufactured at home, and require no fossil fuel imports from frequently dangerous parts of the world. The advantages that flow in the form of lower carbon emissions are a fortunate side-effect.

For those who argue that China can only secure a low-carbon energy future by relying on nuclear power, we respond that the data prove otherwise. Figure 1.3 shows that wind power has overtaken nuclear as a source of power both in terms of capacity additions (wind overtaking nuclear in 2007–2008) and in terms of electric energy generated and supplied to the grid (wind emerging in the lead by 2013 – a position further strengthened in 2014).[8]

Wind power capacity has outweighed that of nuclear power since 2009; the former reached 95 GW in 2014 while the latter accounted for just 20 GW in 2014. In terms of generation, power generation based on wind exceeded nuclear power generation in 2012, and in 2014 wind electricity accounted for 156 TWh compared with 126 TWh from nuclear power stations.

The green aspects of China's energy revolution, focusing largely on hydro (water), wind and solar rather than nuclear as a real alternative

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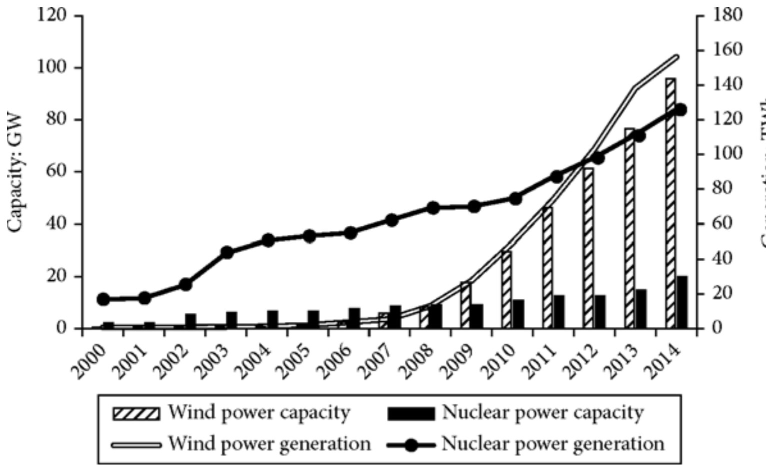

FIGURE 1.3 *Electricity generation: wind power vs. nuclear in China*

Sources of primary data: Data up to 2007 for wind power capacity and generation is available from the BP Statistical Review of World Energy 2014; data for the years 2008–2014 is available from the China Electricity Council; data for nuclear power capacity up to 2007 is from the EIA International Energy Statistics database.

to fossil fuels, are the subject of this monograph. We wish to emphasize the point that China has created the largest renewable power system on the planet – a system that far exceeds that of other industrial powers. Indeed China's renewable power system is comparable to the entire power systems created by France and Germany combined, encompassing their fossil fuelled, nuclear and renewable systems. It is larger than the renewable power systems created by the next four countries – the United States, Germany, India and Italy. The scale of China's creation of renewable power is vividly illustrated in Figure 1.4. Here we have to use 2013 data – but the results for 2014 from China (discussed in Chapter 2) indicate that China has already increased its lead.

China's commitment to renewables is illustrated historically in Figure 1.5, revealing that the proportion of renewables (WWS) started its inexorable rise in 2005–2006, when China made its historic commitment to wind power and which has now been joined by a commitment to solar. The proportion of renewables (WWS) in China's power capacity has been rising steadily, from just over 20 percent in 2006 to around 30 percent in 2013 – as shown in Figure 1.5, exceeding even the estimate made in the country's 12th Five Year Plan (FYP).

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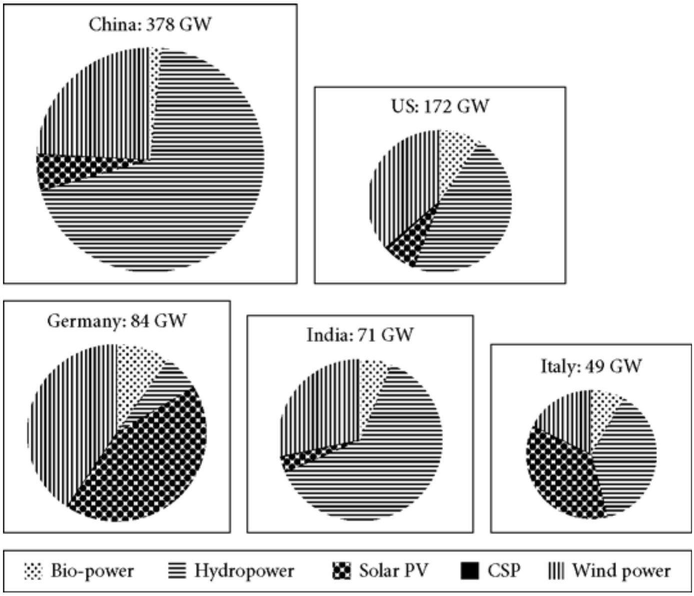

FIGURE 1.4 *Renewable electric power capacity, China and other countries, 2013*

Source: Based on and updated from REN21(2014) *Global Status Report*, available at http://www.ren21.net/REN21Activities/GlobalStatusReport.aspx

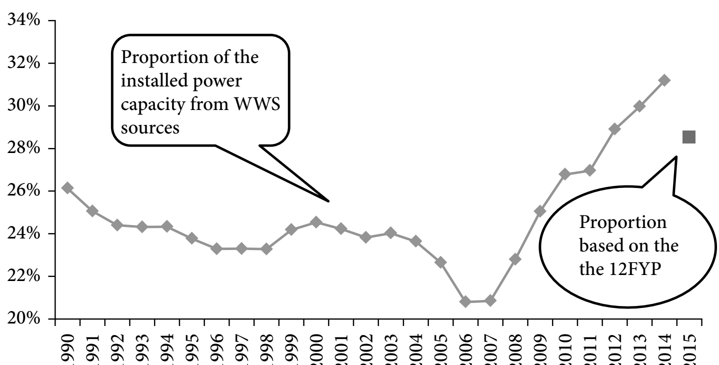

FIGURE 1.5 *Proportion of installed power capacity from renewable sources (hydro, wind and solar): 1990–2014, and 2015 target based on the 12th FYP*

Sources of primary data: Data for wind and solar power capacity up to 2013 are available from *BP 2014 Review of Statistics*, data for the total electric capacity and the hydroelectric capacity up to 2012 is available from the US EIA; other historical data are available from the China Electricity Council. The 2015 target is based on the Energy Development 12th Five Year Plan released by the State Council in 2013.

Again, we are not seeking to under-state China's black economy problems by emphasizing this dramatic expansion of the green electric economy. We recognize that it is an open question whether China's greening will outrun its blackening. But we do wish to emphasize that the best hope for the country lies in this nascent green revolution. And for the world to recognize the enormity of the revolution that is already under way it has to be documented, clearly and objectively – as we do in this text.[9]

It is also worth noting that unlike other countries, China is prepared to engage in clearly articulated industrial strategies that actively seek to transform the economy and set targets for new directions – such as for the displacement of fossil fuelled energy systems by green energy systems. There have been targets for such energy displacement in the 11th FYP covering the years 2006–2010, and in the 12th FYP, covering the years 2011 to 2015. Many of these targets have already been exceeded – such as the target for WWS capacity additions to reach close to 30 percent by 2015 – which as we have noted, was already reached by 2014. Now in face of severe air pollution problems, three government agencies – the National Development & Reform Commission (ND&RC), the National Energy Administration (NEA) and the Ministry of Environmental Protection (MEP) – introduced an 'Air Pollution Control Program' in 2014, in which a number of new, aggressive renewable energy-related targets have been developed for 2017. Then the *Energy Development Action Plan* (2014–2020), released by the State Council in November 2014, set further targets for 2020. These targets are for WWS capacity to grow to 550 GW (plus 50 GW nuclear) by 2017 and by 2020 to reach 650 GW (hydro 350 GW, wind 200 GW and solar 100 GW) plus nuclear 58 GW.[10] These are huge goals in themselves and far beyond the capacity of any other country, and yet in China's case, apparently eminently achievable, putting the country well on the way to its first trillion watts from renewable power.[11] It is the act of setting such feasible and credible targets that differentiates China and demonstrates its efficacy in driving its green industrial strategy.[12]

It is not just in power additions that China's commitment to building a renewables system is evident. In terms of investment in its power grid (its 21st century great infrastructure project) again we see investment in the renewables aspects of the grid greatly exceeding investments in thermal power generation, as shown in Figure 1.6. And again, the scale of China's investments exceeds those of any other industrial country – as we shall review in the following chapters, and as acknowledged by international organizations such as UNEP (2015).

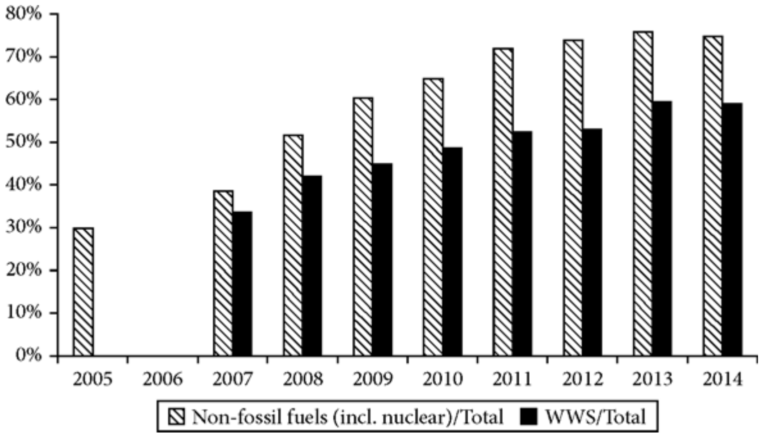

FIGURE 1.6 *Investment on non-fossil fuels-based and WWS-based projects as proportion of the total investment in power generation projects*

Sources of primary data: Data since 2007 is available from the CEC; the figure for 2005 is based on data in a report by the State Electricity Regulatory Commission (2011).

Of course it is not certain that China's green investments will outrank its black investments in time to reduce its carbon emissions fast enough. There may be setbacks and reversals, and maybe the fossil fuel vested interests in China will prevail and hold back the renewables tide in China, as has happened elsewhere. But we are reasonably confident that this will not happen, for the reason that China is utilizing its renewable energies revolution as a means of clearing its black skies and water, and in the medium-term as a means of ensuring its energy security and building up its new industrial capacity. China seems to be following a path where, as we put it in an article we published in *Nature* in September 2014, a smart country can 'Manufacture renewables to build energy security'.[13] For China, renewables are about much more than climate change. Other countries are likely to learn from China in this regard – as Germany has apparently already done, as it drives forward its *Energiewende* ('energy transformation') which is promoting renewables vigorously. Other developing countries like India are also moving rapidly to raise their renewables activities – as the only medium-term prospect for the country that both guarantees energy security and provides a low-carbon way forward.[14] In this sense China's green growth strategies are setting a new standard for industrial development and already sparking emulation elsewhere.[15]

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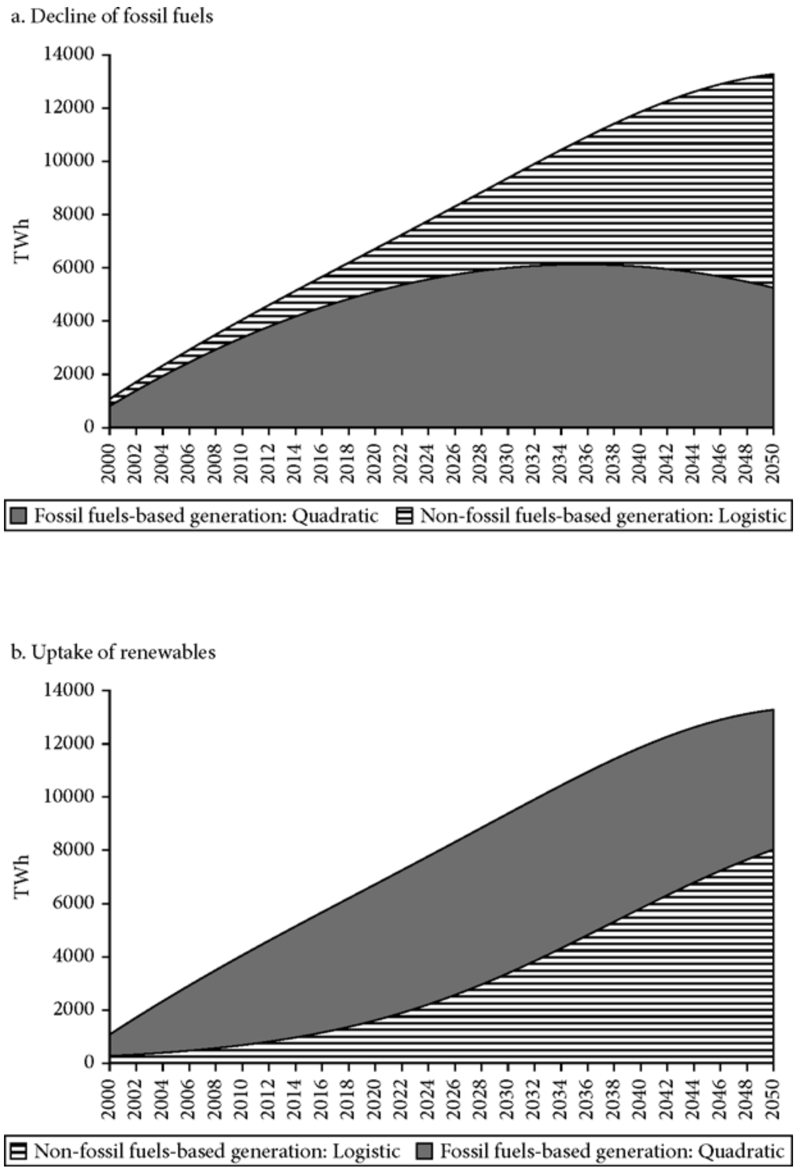

FIGURE 1.7 *China's energy pathways to 2050: fossil fuels versus renewable energies*
Source: Authors. Based on sources discussed in text.

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Our picture of China's energy future is one where its green aspects overtake its black features, in a pathway of transition known in industrial dynamics as a logistic curve. This is a curve which is better suited than simple linear extrapolations because it takes account of the fact that as commitments are made in a new trajectory, so they become self-reinforcing. In business terms, the more entrepreneurs commit to a new pathway, the more that others will seek to follow them, until the new direction becomes self-reinforcing, self-sustaining and irreversible. That is how we view China's renewable energy revolution – as depicted in Figure 1.7a and 1.7b. (Here we depict just the electric power system, which is an important, and growing, component of the total energy system. Our chart corresponds to Figure 2.11 in Chapter 2.) The green is likely to succeed the black, in an S-shaped logistic trajectory of substitution. We shall provide the evidence justifying this chart as we proceed in presenting the argument.

Features of China's renewable energy revolution

We need to add some further features to this initial overview of China's energy revolution and the industrial strategies being pursued to drive it. The first is that China's energy revolution is premised on making electric power available to all. This is seldom mentioned but is fundamental to the view that China's expansion of wealth and income depends on completion of an energy infrastructure based on electric power – now available to 99.7 percent of China's population, according to World Bank data.[16] But creating universal access to power remains a central goal in China, while the shift to greater levels of industrial and especially manufacturing activity is also to be powered by electricity, whether from the electric grid or from distributed electric generation facilities and not directly by the burning of fossil fuels.[17] This goal is to be accomplished by building the manufacturing industries that can supply all the renewable energy devices that China needs and the power system to utilize them, rather than through relying solely on securing access to fossil fuels around the world.

Second, the greening of China's energy system is accompanied by intensive investment in making the existing system more energy efficient and less polluting – a task just as important (arguably) as building a new green energy system alongside the polluting fossil fuelled system. It is a fact that China has built some of the largest energy-intensive industries in the world – such as aluminium production, steel production and

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cement production, where China accounts for 46 percent, 50 percent and no less than 60 percent respectively of the global totals. Here is where enormous efforts have been expended to reduce the energy intensity of these activities, through both improvements in production efficiency, technological upgrading and administrative intervention to shut down older and more polluting plants. The data indicate that China is on target to achieve energy efficiency ratings comparable to the rest of the world. Figure 1.8 reveals that China's energy intensity (measured as tonnes of energy consumed per $1,000 of GDP) has been diminishing steadily (with a small 'hump' just after 2001 when the country started its huge industrial expansion and a smaller hump at the conclusion of the

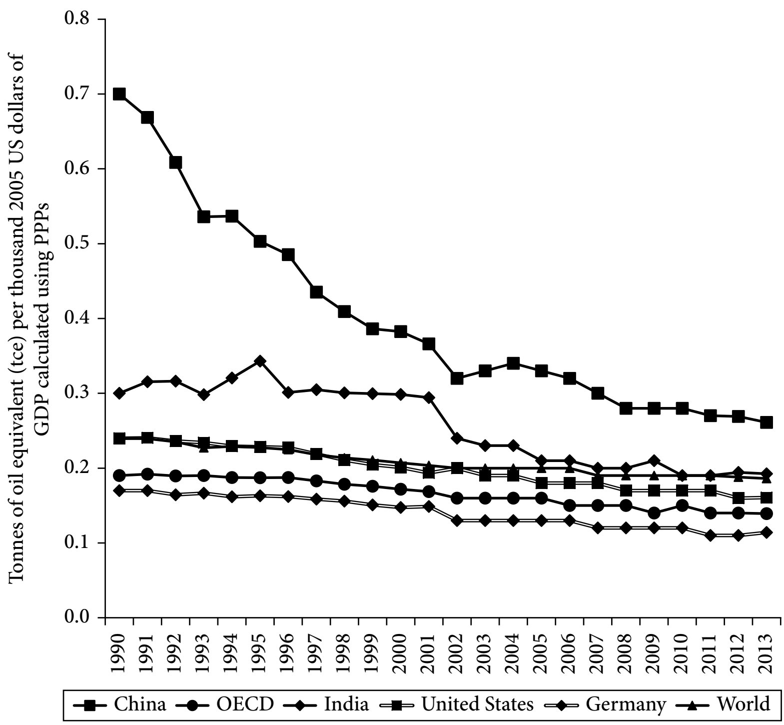

FIGURE 1.8 *Energy intensity of China vs other countries*

Sources: Authors. The energy intensity data for the year 1990, and the years 2001–2011 are available from OECD database; the data for the year 2012 and 2013 are estimated by authors based on the real GDP growth data available from the OECD Economic Outlook database, and the primary energy consumption data available from BP World Energy Statistics Review 2014. The energy intensity data for the years 1991–2000 are estimated by authors based on data available from the EIA International Energy Database.

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11th FYP) and is now approaching the world average – with plenty of room for further improvement.

Under the 12th FYP, energy intensity in China is targeted to be reduced by 16 percent below 2010 levels by 2015. In the year 2014 China reduced its energy intensity by 4.8 percent, according to the National Statistics Bureau.[18] China has set the target of a further cut of 3.1 percent in energy intensity by 2015, according to Premier Li Kejiang's government work report made to the National People's Congress in March 2015. Under the 12th FYP the State Council issued a comprehensive work plan specifying 50 detailed measures to cut pollutants and reduce energy intensity.

A third issue is China's contribution to global carbon emissions. Carbon intensity (carbon emissions per unit GDP) is likewise targeted to be reduced by 17 percent below 2010 levels by 2015,[19] as part of a comprehensive target to reduce carbon intensity by 40–45 percent below 2005 levels by 2020 – a commitment made at the Copenhagen Conference of the Parties in 2009. China's carbon intensity has been trending down, as shown in Figure 1.9.

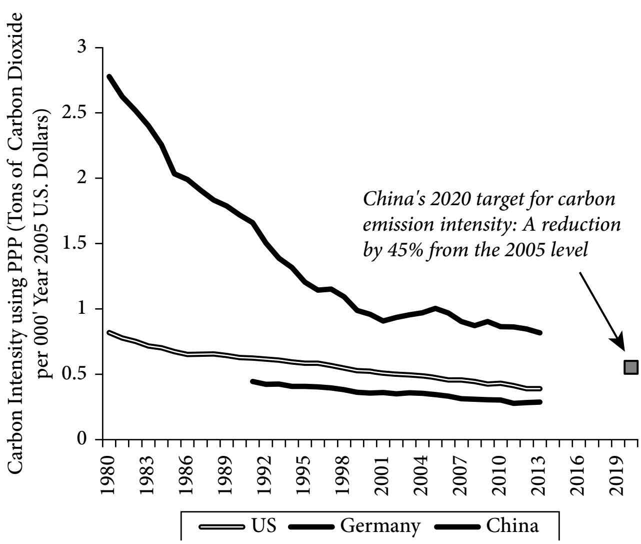

FIGURE 1.9 *China's carbon intensity, 1980–2013*

Sources of primary data: Carbon intensity data up to 2010 is available from US EIA; carbon intensity figures in 2012 and 2013 are estimated by authors based on based on the real GDP growth data available from *Euromonitor* and the carbon emissions data from *BP 2014 World Energy Statistical Review*.

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Carbon intensity is one thing – but absolute levels of carbon emissions is another; the total emissions can increase while energy intensity falls, because of the effect of economic growth. It is now widely cited and emphasized that China is the world's largest carbon emitter, as well as polluter with other greenhouse gases, and hence a rising contributor to global warming. This is undeniable – and yet again it needs to be put into historical perspective. Climate scientists now describe the world's best chance of staying within a global temperature rise of 2 degrees Celsius (the minimum now considered feasible and one where climate changes may be kept within bearable dimensions) is for cumulative carbon emissions to be kept within 1 trillion tonnes.[20]

Industrial development by the West has already used up at least half of this scientifically 'allowable' carbon budget. So China's additions come on top of this. We shall discuss the details later, but here let us report our conclusions, that China's carbon emissions resulting from its energy revolution are likely to peak before 2030 (and perhaps well before this date) and may result in just over 110 billion tonnes (Gt) of carbon being emitted from the consumption of fossil fuels for the period between 2014 and 2050 – as shown in Figure 1.10. This is our best estimate of the global implications of China's energy revolution on the world's emissions of

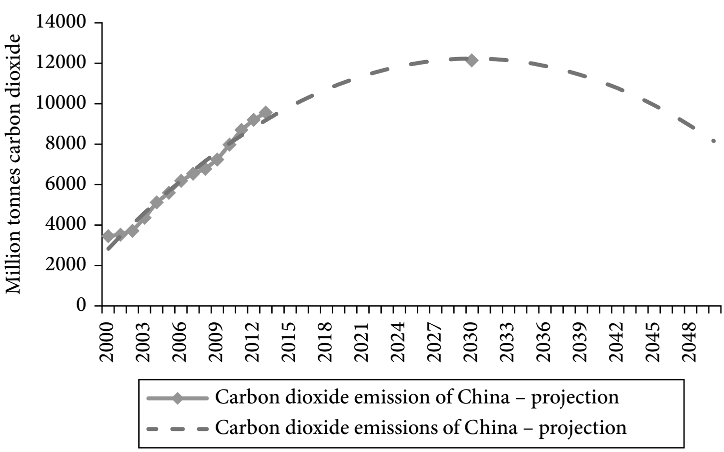

FIGURE 1.10 *China's carbon emissions – past and projected*

Sources: The historical emission data is available from the BP 2014 World Energy Statistical Review; the peak emission target in 2030 is according to the US-China Climate Deal announced in Nov 2014; the quadratic polynomial curve is estimated by authors.

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carbon and its likely impact on climate change – a worst case conclusion that we emphasize is quite likely to be improved upon in practice.

In the China-US Joint Announcement on Climate Change in November 2014, China set a target for the peaking of carbon dioxide (CO_2) emissions to occur around 2030 and with the aspiration to peak earlier.[21] The announcement, though, did not indicate at which level China's carbon emissions are likely to peak. Many studies have focused on this question. For example, researchers from the World Resources Institute argue that the new announcement will push the peak time forward (earlier), resulting in probably 10 billion metric tons of CO_2 being emitted per year in China by around 2030.[22] However this may be seen by some to be optimistic given that China's emissions in 2013 already reached 9.5 Gt of CO_2[23] According to the 'continued effort' scenario of the MIT-Tsinghua joint research project, a scenario which is mid-way between the 'no-policy' scenario and the 'accelerated effort' scenario, CO_2 emissions from China would peak at around 12.1 Gt per year between 2030 and 2040.

We take this figure as a benchmark for now, and draw Figure 1.10, where peaking in carbon emissions is depicted (conservatively) as occurring around 2030 or earlier. Over the whole period between 2014 and 2050, China is expected to emit approximately 400 Gt of CO_2 in total, or 110 Gt of carbon, from burning fossil fuels; this is about one tenth of the global 1 trillion tonnes carbon 'budget' set to keep temperature rises to within 2 degrees Celsius.[24] By contrast, the presently developed countries in North America, Europe and Japan contributed over half of this global carbon budget. China the latecomer is by comparison likely to be much cleaner – despite its reputation for being a black economy.

The year 2014 saw a momentous event in the form of the first slackening of global CO_2 emissions. CO_2 emissions stabilized at just under 32 Gt (gigatonnes) – or 8.7 Gt carbon.[25] In making this announcement, the International Energy Agency (IEA) acknowledged China's efforts in improving its energy efficiency, cutting its use of coal, and building its energy systems on the basis of water, wind and sun. Our emphasis in this text is that China is indeed cutting its carbon emissions, as fast as is physically and technically possible. Our estimate of its likely future carbon emissions is offered as a means of demonstrating the scale of these emissions compared with those that have come before.

If there is a global climate problem (as indeed there is) then it cannot be laid at the feet of China. As an industrial latecomer it has inherited

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a situation created by others. But in building its green industries it is certainly contributing to a solution – while adding its own carbon emissions to the cumulative total. China in our argument is drastically scaling-up its green energy system for immediate political reasons at home – to address the dreadful toxic pollution problems – and to address medium-term problems of energy security. But it is certainly a convenient truth that as fast as China greens its economy, so it will contribute to peaking and then reducing global carbon emissions overall.

To be precise concerning the carbon emissions saved by China's greening so far, consider the point that China in 2014 generated 5,545 TWh of electric energy, with strictly green (WWS) sources accounting for 1,245 TWh. Now 1,245 TWh of electric energy is equivalent energetically to very nearly 150 million tonnes of coal equivalent (mtce) – or around 220 million tonnes of raw coal. So China's greening efforts so far are eliminating carbon emissions that could have resulted from burning 220 million tonnes of raw coal in the year 2014 alone.[26] But in the short term (over the course of the next decade) China's carbon emissions can be expected to continue rising. This too is an unavoidable part of China's energy revolution.

Given the successes achieved by China's energy revolution, it is strange that other advanced countries are not emulating the programs and investments in build-up of renewables that China is pioneering. Germany has certainly taken note, and is moving rapidly towards a renewables energy economy through its *Energiewende* ('energy transformation'). But it is surprising that Japan has not yet followed suit – given that renewables are all about manufacturing, and Japan is the world's preeminent manufacturing nation. We wonder how long the Japanese business and political elite will allow this state of affairs to continue.[27]

In these introductory comments we would also like to highlight ways in which China's renewable energy revolution maps to the literature on greening of economies, industrial dynamics and international political economy. In their recent paper on path dependence, innovation and the economics of climate change, Aghion et al. (2014) note that government intervention is needed to drive an economy onto a new green trajectory – a point amply supported by the China experience. Rodrik (2014) discusses green industrial strategies and makes the point that policies designed to promote green industries are actually wealth-enhancing, unlike trade policies aimed at protecting established industries – again amply supported by the China case. In terms of international political economy, Klare (2012) argues that access to resources will constitute the next round of international violence, unless countries find ways to reduce their dependence on fossil fuels; again our argument is that China must be viewed as a prime case of a country seeking to avoid such entanglements through its emphasis on building renewables. Zysman and Huberty (2013) for their part argue that green growth strategies need to be brought down to earth if they are to be effective – they need to be brought 'from dream to reality'; and again we would point to China as a prime case of a country that takes such a pragmatic and highly effective approach to greening its industrial system.

Finally we need to underline the point that while we see favourable trends in China's greening of its energy system, and recognize favourable policies being put in place such as the incipient Feed-in Tariff policies and creation of carbon markets, we also recognize that China has many legacy policies in place that favour fossil fuels and obstruct the shift to renewables (see Box 4.2 in Chapter 4 for discussion on this point).[28] Now let us describe the overall trajectories of China's energy revolution, in their macro aspects, before examining the particular renewable energy industries that are driving the transition.

Notes

1 The 'Big Push' is a developmental idea that views the process as involving interconnections across multiple sectors, first formulated in the 1940s by Rosenstein-Rodan; we view the shift to renewables as likewise involving initiatives across several sectors.
2 There is an expanding literature on such green industrial strategies; see, for example, Rodrik (2014) or Lin and Xu (2014). We will engage with this literature as our study unfolds.
3 See the video documentary/talk on YouTube, at: https://www.youtube.com/watch?v=T6X2uwlQGQM
4 Rachel Carson published *Silent Spring* in 1962.
5 Christina Larson used this contrast in her posting 'The great paradox of China: Green energy and black skies', *Yale Environment 360*, 17 August 2009, at: http://e360.yale.edu/feature/the_great_paradox_of_china_green_energy_and_black_skies/2180/
6 Note that the Chinese leadership has committed to 'cap' the expansion of coal consumption at 4.2 Gt by 2020, according to the country's Energy Development Strategic Action Plan (2014–2020) – with important implications for carbon emissions.

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7 http://www.efchina.org/Reports-en/china-2050-high-renewable-energy-penetration-scenario-and-roadmap-study-en

8 The US climate scientist James Hansen is a prominent exponent of such a perspective. While we readily acknowledge Dr Hansen's contribution to climate science, we query his insistence that China's energy future has to be nuclear. See his Congressional testimony at: http://www.foreign.senate.gov/imo/media/doc/Hansen_Testimony.pdf

9 We are adding to an already considerable literature that examines China's renewable energy strategies – but sometimes with different emphasis from our own. Recent overviews are provided by Dent (2015), Lewis (2013), or Martinot and Li (2007). Of Chinese scholars, Hu (2006a; 2006b; 2011) has argued consistently that green development is 'the inevitable choice for China'.

10 The targets for 2017 are specified in the *Air Pollution Control Program* released in March 2014, and are as follows: hydro 330 GW; wind 150 GW; solar 70 GW (so WWS in total 550 GW); plus nuclear 50 GW.

11 See the 2020 goals from the Energy Development Action Plan (2014–2020), released by the State Council in November 2014, at: http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm (in Chinese). The details of the Plan were released in English in 'China unveils energy strategy, targets for 2020', *China Daily*, 19 November 2014, at: http://usa.chinadaily.com.cn/china/2014-11/19/content_18943912.htm

12 In the related context of Korea, Kim and Thurbon (2015) refer to that country's pursuit of green growth strategies as a case of 'environmental developmentalism'; we see this phrase as applying (with different policies) also to China.

13 See John Mathews and Hao Tan, 'Manufacture renewables to build energy security', *Nature*, 11 September 2014, available at: http://www.nature.com/news/economics-manufacture-renewables-to-build-energy-security-1.15847

14 An early version of this argument was made by one of us (JM) at the website of the Sheffield Political Economy Research Institute (SPERI), 'What does China's renewable energy revolution mean?', 14 August 2014, at: http://speri.dept.shef.ac.uk/2014/08/20/chinas-renewable-energy-revolution-mean/

15 Earlier contributions to this debate by JM are collected in the references, as Mathews (2006; 2007; 2008; 2009; 2010; 2012a; 2012b; 2013a; 2013b; 2013c; 2014).

16 See World Bank 'Access to electricity' data, at: http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

17 Premier Li Kejiang stressed this universal access to power as goal in his government work report to the National People's Congress meeting in March 2015. See 'China edging closer to universal power access', *People's Daily*, 5 March 2015, at: http://news.xinhuanet.com/english/2015-03/05/c_134041776.htm

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18 http://www.stats.gov.cn/tjsj/zxfb/201502/t20150226_685799.html (in Chinese).

19 See China's 12th Energy Development FYP

20 A total of 1 trillion tonnes of carbon translates into 3.65 trillion tonnes of carbon dioxide. (The conversion factor is multiplication by 44/12, reflecting the molecular weights of C and O.)

21 http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change

22 http://www.wri.org/blog/2014/11/numbers-china-us-climate-agreement

23 http://www.chinafaqs.org/files/chinainfo/ChinaFAQs-Taking_Stronger_Action_1.pdf; also see more details at: http://globalchange.mit.edu/CECP/files/document/MITJPSPGC_Rpt267.pdf . Those projections are made using the China-in-Global Energy Model (C-GEM) (Qi et al. 2014)

24 See the IPCC's Fifth Assessment Report. Emissions of C are equated to emissions of $CO_2 \times 12/44$.

25 http://www.iea.org/newsroomandevents/news/2015/march/global-energy-related-emissions-of-carbon-dioxide-stalled-in-2014.html

26 See the Appendix for further details on this and similar calculations.

27 One of us (JM) commented on this point at the website of the Japan Renewable Energy Foundation. See JM, 20 March 2015, at: http://jref.or.jp/en/column/column_20150320.php

28 See the comment by one of us (HT) on this theme posted to the website of the Institute of Development Studies, 'Greening China: Tackling bad industrial policies should be a priority', 16 March 2015, at: http://www.ids.ac.uk/opinion/greening-china-tackling-bad-industrial-policies-should-be-a-priority

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2
Major Trends in China's Energy Revolution

Abstract: *China's energy system is demonstrably greening at the margins. This is revealed through analysis of the relative proportions between renewable energy sources and fossil fuels as well as nuclear power. The industrial dynamics of the overall transition to a clean energy system are driven by concerns to reduce pollution levels and enhance energy security. In China's energy revolution, the scale of production drives down costs and expands the market, in a process of circular and cumulative causation. China's distinctive approach lies in its promoting its energy revolution through industrial strategy and five year plans, with well-formulated targets and their shaping of investment strategies. China's energy revolution not only involves building new renewable industries but also tackling the challenge of reducing energy consumption in key energy-intensive industries.*

Keywords: 12th Five Year Plan; China; cost reduction; energy intensity; energy learning curves; industrial dynamics; logistic uptake of renewables; renewable energy industries

Mathews, John A. and Hao Tan. *China's Renewable Energy Revolution*. Basingstoke: Palgrave Macmillan, 2015. DOI: 10.1057/9781137546258.0009.

Underpinning China's impressive growth for the past three and a half decades, and the manufacturing engine that drives this growth, is an energy system that is now larger and more formidable than any yet created on the planet. Because China's growth in industrial output has been powered by coal, China counts its total energy system in terms of units of coal equivalence (rather than the barrels of oil equivalent that are used to describe Western energy systems). We deal first with primary energy trends at the level of the economy as a whole.

Primary energy trends

China's energy system as a whole has grown rapidly, with the government committed to a target maximum of 4.8 Gt (billion tonnes) of coal equivalent per year by 2020. This is an easy to remember statistic – and if initiatives taken to introduce renewables are also measured in tonnes of coal equivalent, then they provide an immediate handle on the reduction in carbon emissions (decarbonization) that such initiatives imply. In 2013 China's share of fossil fuels in primary energy consumption was just over 90 percent – and projected to fall to 85 percent by 2020.

The complementary goal for the scaling-up of renewables was set by the State Council in the *Energy Development Strategic Action Plan,* released in November 2014 for the years 2014–2020. This plan undoubtedly will form the energy component of the 13th Five Year Plan (FYP), covering the years 2015–2020 and currently under development. Under this plan, the level of clean energy (defined in China as renewables plus nuclear) is to rise to 15 percent by 2020, up from 9.8 percent at the end of 2013. Under the Joint US-China announcement on climate change, issued in November 2014, a commitment to raise *clean energy sources to 20 percent of total primary energy by 2030* was made. We show these trends in China's overall projected primary energy system in Figure 2.1. The figure portrays those targets against the total projected energy consumption up to 2030.[1]

We can extend the trajectory, and project the share of non-fossil fuels in China's total energy system up to 2050 by when the share could well have achieved 50 percent or higher (or achieving 50 percent even earlier).[2] We do so at the end of this chapter, to illustrate the power of logistic industrial dynamics, driving the uptake of renewables.

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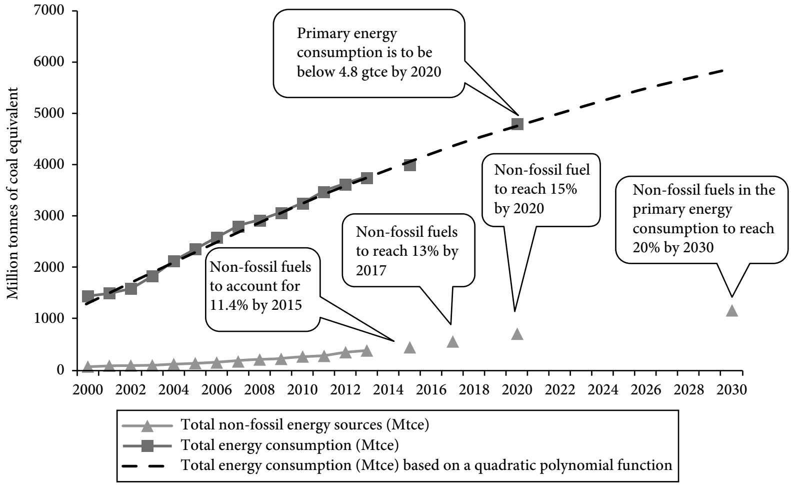

FIGURE 2.1 *China's trends in primary energy, with rising proportion of clean sources, 2001–2030 (proj)*

Source: Authors, the historical data are available from the National Statistics Bureau of China, and the projections are based on various government policy documents.

The commitment to reach 20 percent clean energy sources by 2030 is in fact an enormous commitment, one that amounts in itself to a genuine energy industrial revolution. According to the press release issued along with the US-China Accord it will involve China in adding around 1000 GW of clean power – on top of the enormous 378 GW of renewable and 15 GW of nuclear power that China had already built by 2013 (with corresponding totals of 444 GW for renewables and 15 GW nuclear in 2014) – as depicted in Figure 1.4. There is an official Chinese target of 650 GW of clean power to be sourced from water, wind and sun by 2020.[3] The new target would mean around 800 to 1000 GW of zero-carbon energy sources being brought online by 2030 or even earlier.[4] The new commitments are putting China on track to be the planet's renewable energy superpower.

Of course these targets for renewable energy capacity additions would mean little if they were exceeded by further additions of coal-burning thermal capacity. But the trends already indicate that the system is greening faster than it is blackening – and our argument is that the industrial dynamics of technology substitution would support the green outrunning the black in the immediate future, up to 2020 and then

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beyond. Significant new targets adopted by China in November 2014 *on the annual primary energy consumption, which is set at 4.8 billion tonnes coal equivalent by 2020,* implies a lowering of annual increases in energy consumption to 3.5 percent for the years 2015 to 2020. Energy consumption can be disarticulated from economic growth because of improving energy efficiency as measured by reducing energy intensity. As China raises its proportion of clean energy sources (based on hydro, wind, solar PV and concentrated solar), so it is reducing its reliance on coal. In fact the growth in coal consumption has been getting smaller each year – from 9 percent growth in 2011 down to just 2 percent growth in 2013 and a fall by 2.9 percent in 2014 – meaning that coal consumption could well be peaking, and is likely to continue falling after 2015. This would be consistent with China's coal production declining in 2014 and thermal power generation (burning coal to produce electricity) also declining in 2014. *This is a momentous triple milestone for China and for the world.*

There are two dominant trends to trace out in this connection – the declining dependence on coal and the complementary rising dependence on renewable energy sources.

Declining dependence on coal

China's coal consumption has been rising relentlessly, increasing by around 10 percent per year over the decade from 2001 to 2011. But growth in consumption of coal slowed in 2012 and 2013 to less than half these growth rates, to reach a level of 3.6 Gt in 2013. Then, as noted, consumption actually declined in 2014 – down by 2.9 percent on the 2013 level. If this slowdown in consumption is confirmed in 2015, it means that China's decades-long reliance on coal to fuel its energy revolution may be coming to an end. The 4.2 Gt 'cap' that the State Council has imposed on coal consumption by 2020 may never be reached.

At the same time the share of coal in primary energy consumption is to be reduced to less than 62 percent by 2020. This proportion of coal in primary energy consumption has been falling from around 76 percent in 1990, to just under 70 percent in 2000 where it stayed for most of the decade of the 2000s, and falling to around 65 percent by 2013. These trends promise to be continued, leading to coal dependence reducing, and reaching probably less than 50 percent overall before the year 2030. We show China's coal consumption trends in Figure 2.2, based on the

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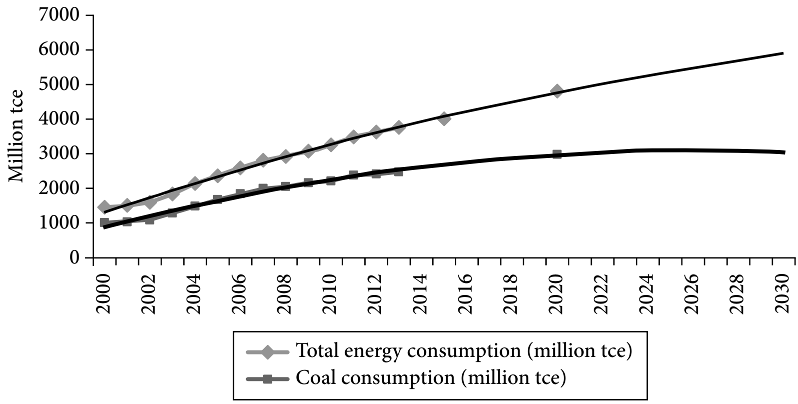

FIGURE 2.2 *Total energy consumption and coal consumption in China*

Source: Authors, based on the historical data available from the National Statistics Bureau of China, and targets specified in various government policy documents.

historical data from China's National Bureau of Statistics and using quadratic polynomial functions to sketch out a convex curve, we project the trends of the total energy consumption (in terms of coal equivalent) and the total coal consumption (in terms of million tonnes of coal and tonnes of coal equivalent).

While the share of coal in primary energy consumption has been falling (slowly) the growth in overall energy consumption has meant that absolute levels of coal consumption have still been rising. Where then can we expect the peak in China's coal consumption to occur? Some scholarly estimates put China's peaking in overall coal consumption by as early as 2015, at a level of 3.9 Gt of raw coal consumption (Li 2014), that is, below and well in advance of the 4.2 Gt 'cap' imposed by the State Council for 2020.

Several research reports and experts in the field argue that coal demand in China will peak by 2020 or earlier. For example, the CEO/Chief Engineer of the Coal Planning & Research Institute of China, Li Ruifeng, projects that coal consumption will peak at 2020 at 4.1 Gt, or 2.8 billion tonnes of coal equivalent (Gtce), after which coal consumption will decline by 0.33 percent per year until it reaches 3.9 Gt (or 2.7 Gtce) in 2030.[5] Standard & Poors' research report released in July 2014 'assume[s] the coal demand growth in China will decelerate to low single digits before flattening by 2020'.[6] Citigroup also states in its 2013 report *The Unimaginable: Peak Coal in China* that it believes that a scenario

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of 'flattening or peaking of thermal coal demand for power generation in China by 2020' is likely.[7] On the other hand, the International Energy Agency (IEA) in its *Medium-Term Coal Market Report 2014* (see in particular box 3.3 on p. 74) suggests that coal consumption peaking before 2019 is 'possible' but unlikely. Instead the IEA projects that the coal consumption will grow at 2.6 percent annually – in our view a most unlikely trend.[8]

Our next chart depicts China's coal consumption overall, peaking before 2025. The total area under this curve gives a reliable estimate of the total coal to be burnt by China as it ramps up its energy system and scales up its renewable energy systems that are displacing coal consumption.

Alternatively, in case Figure 2.3 appears too crowded, we separate out the process of coal consumption in Figure 2.4, showing coal consumption itself, both overall and in the power generation sector. We envisage coal consumption peaking by 2025 or even earlier.

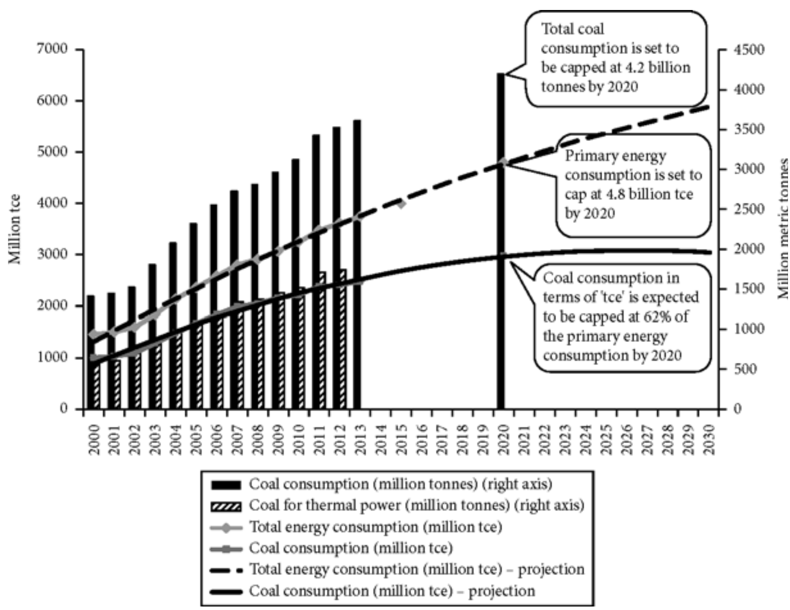

FIGURE 2.3 *Total coal burnt in China and energy consumption, 2000–2030 (proj)*

Source: Authors, based on data available from the National Statistics Bureau of China, and targets specified in various government policy documents. Note that we depict overall energy consumption in mtce (LHS), while we show coal consumption in raw metric tonnes (RHS).

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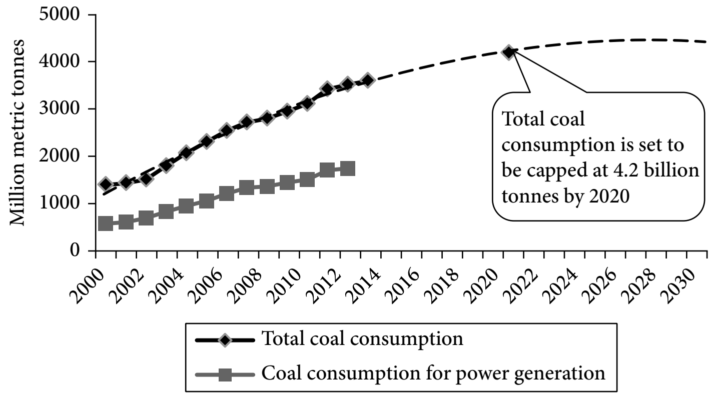

FIGURE 2.4 *Total coal consumption and coal consumption for thermal power generation*

Source: Authors, based on data available from the National Statistics Bureau of China, and targets specified in various government policy documents.

Our conclusion is as follows. According to the projections based on our convex curve (the quadratic polynomial function), we expect that China's total energy consumption will grow at an average annual rate of 2.1 percent between 2020 and 2030; peaking at below 6 or 7 Gtce; while total coal consumption will probably flatten around 2020 at a level approx. 4.2 Gt raw coal (or 3 Gtce) and then decline after 2025. All indications are that the official cap on raw coal consumption of 4.2 Gt by 2020 is set to be enforced, and that coal-burning will decline thereafter – implying that coal consumption will peak at 4.2 Gt in 2020 or earlier. We discuss China's likely carbon emissions, based on these data, in Chapter 6.[9]

The largest burner of coal in China has been the electric power sector, and this is where the most important changes in energy patterns have been occurring.

China's electric power system

China's electric power system has grown to be the largest in the world, rated in 2014 at more than 1.2 trillion watts (or terawatts TW). China's electric power capacity overtook that of the United States (which stands at around 1.1 TW) in 2011. The actual electrical energy generated has been following a steep upward curve, as shown in the following figure, reaching 5,545 TWh in 2014 – up 3.2 percent on the 2013 total.

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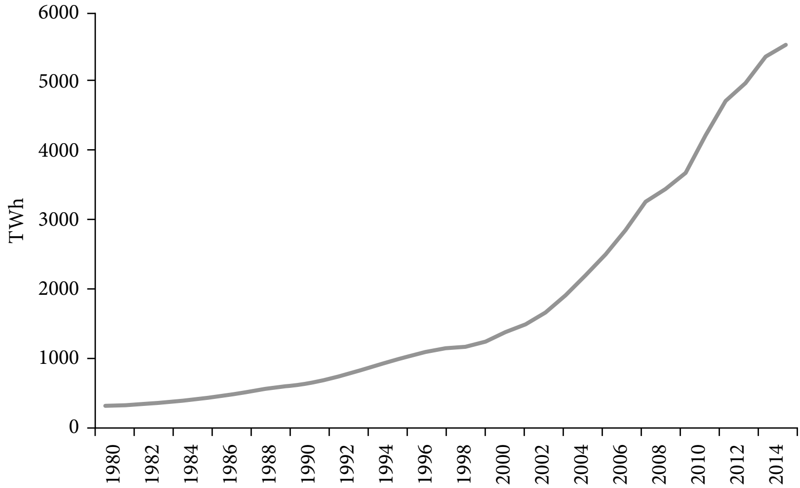

FIGURE 2.5 *China electricity generation, 1980–2014*
Source of primary data: China Electricity Council.

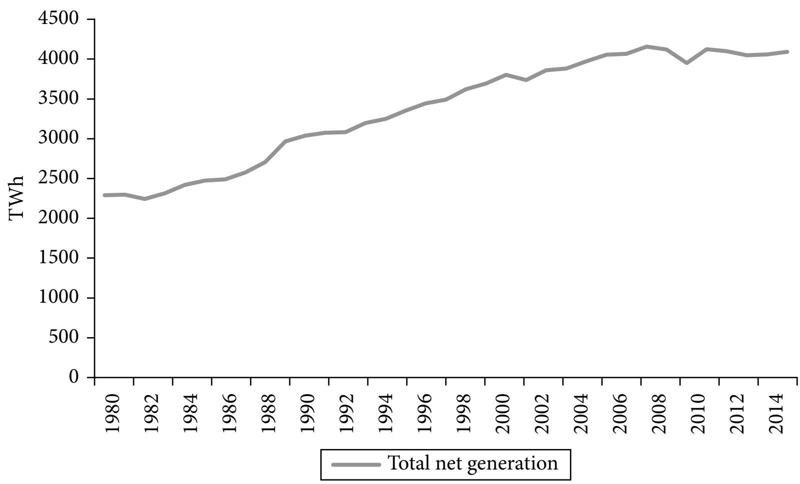

FIGURE 2.6 *US generation of electric energy, 1980–2014*
Source of primary data: US EIA.

By contrast, the US generation of electric energy peaked in 2010 at just over 4 trillion kWh – and is not rising further because of energy efficiency improvements.

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Fossil fuels have since China's industrial revolution been the dominant source of the country's electric power, accounting for 76 percent of generating capacity in 2008 and declining to 67 percent by 2014 (i.e. accounting for two thirds) – and targeted in official estimates to reduce to below 62 percent by 2020. We show the changing proportions of thermal power generation capacity in China's electrical power system, in Figure 2.7.

Note that in capacity terms, it is correct to state that China now has raised its non-thermal capacity to close to one third of its total power system (and its strictly water, wind, solar – as sources of renewable energy [WWS] green capacity to 31 percent), while according to the projections in the Energy 12th FYP issued in 2013, China expected that the WWS would account for 29 percent of the total power generating capacity by 2015. Such a projection has been exceeded by the actual development of non-fossil fuelled generating capacity to date.

In terms of actual electrical energy generated, China's system is now the largest in the world, generating as noted above 5,545 billion kWh in 2014 (or 5,545 TWh). Whether and at what level China's overall electric power growth will peak is an open question; the more that electricity comes to depend on renewable sources, the more opportunities are likely to be discovered for the use of electric power. What is important is the peaking of coal-fired or thermal electric power.

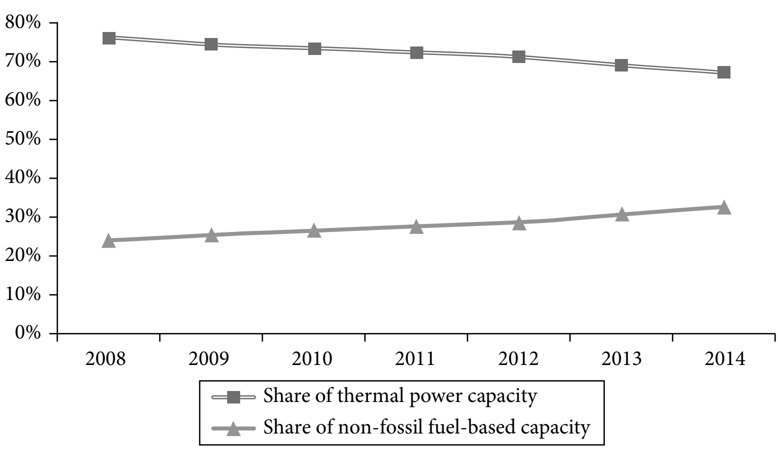

FIGURE 2.7 *Shares of electric generating capacity utilizing fossil fuel sources compared with non-fossil fuel-based electric capacity, 2008–2014*

Source of primary data: China Electricity Council.

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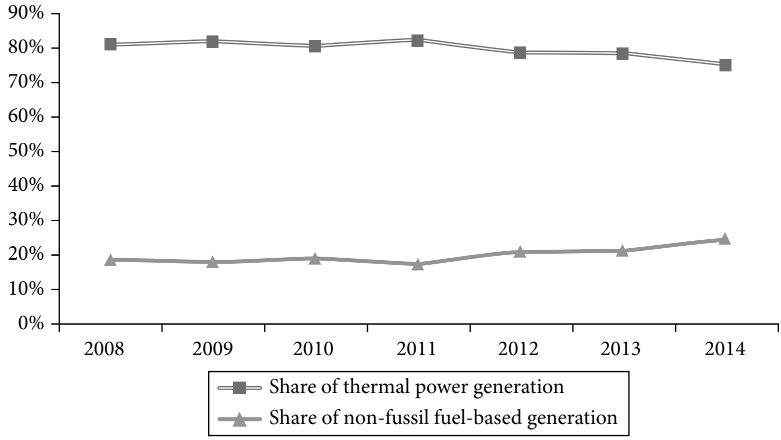

FIGURE 2.8 *Shares of electricity generated from fossil fuel sources compared with non-fossil fuel-based electricity generation, 2008–2014*

Source of primary data: China Electricity Council.

China's changing proportions of thermally generated electrical energy versus energy generated from green sources (WWS) as well as nuclear (i.e. non-thermal) is not as dramatic as for the capacity data, because the electrical energy generation system is a big ship that is slow to turn around. The changing proportions in actual electrical energy generated are shown in Figure 2.8.

The share of the fossil fuel-based power generation has fallen from 81.2 percent in 2008 to 75.2 percent in 2014 – a 6 percent reduction over six years, or approximately 1 percent per year reduction; while the share of the total non-fossil fuel-based electricity generation increased from 18.8 percent to 24.7 percent over the same period. By extension, we can expect this proportion to reach 30 percent by 2020. *The main point is this: China in 2015 is already generating a quarter of its electricity from non-thermal sources.*

We note that the figures cited here provide the correct formulation of the current contribution of thermal sources to China's electric power generation. The correct proportion is 75.2 percent, and not the widely quoted 'approx. 80 percent' as cited repeatedly by the IEA and reproduced by authors such as Matthew Kahn in *Science*.[10] We insist on this because the careless formulation 'approx. 80 percent' paints China as blacker than it really is – and underplays the enormous efforts being

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made to green the energy system. The targets involving WWS shares in total primary energy; in electric power generating capacity; and in electric energy actually generated, are shown in Box 2.1 for clarity.

BOX 2.1 *Chinese government's energy-related targets for 2015, 2020 and 2030*

Several recent policy documents issued by the Chinese government specify energy-related targets for the country over the immediate and medium-term future. These include the country's *12th FYP for Energy Development*, which covers the period 2011–2015; the *Air Pollution Control Program for the Energy Sector* and the *Energy Development Strategic Action Plan*, both issued by the ND&RC 2014; and the *China-US Joint Climate Change Announcement* in November 2014.

The *12th FYP for Energy Development* specifies that by 2015 the non-fossil fuels should account for 11.4 percent of the total energy consumption in China, increasing from 8.6 percent in 2010. The Plan projects that the electric generation capacities based on hydro power, wind, solar and nuclear technologies will reach 290, 100, 21 and 40 GW respectively, which in total would account for just over 30 percent of the total electric generating system as projected in the Plan for 2015 (1490 GW). Note that the projection for solar power capacity in the Plan has since been overtaken, and the new target has been set as 35 GW for 2015.

The *Air Pollution Control Program* released by the State Council in 2013, and its implementing plan in the Energy Sector that was introduced by the ND&RC in 2014, were mainly a response to the air pollution problems such as smog in China. Several medium-term targets up to 2017 were specified. Those include a target of utilizing more than 13 percent of non-fossil fuels and less than 65 percent of coal in total energy consumption, and the electric generating capacities based on hydro power, wind, solar and nuclear technologies reaching 330, 150, 70 and 50 GW respectively in 2017. Nuclear power should provide over 280 TWh of electricity in 2017; and the amount of biomass energy to be utilized should reach over 70 million tce.

The *Energy Development Strategic Action Plan* (2014–2020) published in November 2014 further specifies targets up to 2020. According to the Plan, the total energy consumption in 2020 should be below 4.8 Gtce, in which at least 4.2 Gtce should be supplied

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domestically; and the consumption of coal should be below the level of 4.2 Gt raw coal. Non-fossil fuels should account for at least 15 percent of the total energy consumption, while the share of coal should be capped at 62 percent. More specifically, the electric generating capacity based on hydro power, wind, solar and nuclear should reach 350, 200, 100 and 58 GW respectively, or 708 GW in total including 650 GW of WWS capacity. The Plan also specifies the utilization of geothermal energy to reach 50 million tce. In total, it can be inferred that the consumption of non-fossil fuel-based energy should reach 0.72 Gtce in 2020, which would account for 15 percent of projected total energy consumption (4.8 Gtce).

Finally, the China-US Joint Climate Change Announcement in November 2014 specifies that non-fossil fuels in China are to account for over 20 percent of the primary energy consumption by 2030. The announcement does not specify the amount of China's primary energy consumption anticipated by that date. However, our projection based on a quadratic polynomial function indicates that the total energy consumption of China probably would reach around 6 Gtce in 2030, and thus the non-fossil fuels could account for 1.2 Gtce (20 percent). If all of this were used to generate electrical power it would amount to nearly 10,000 TWh of renewable electric energy.

As to the question whether China's electric power system is greening or further blackening, the China electric power system is demonstrably greening at the margins, at the point of change. As we will discuss in Chapter 4, all the data for additions to the system in 2014 indicate that it is greening more than it is blackening. First, in terms of total electricity generated, thermal generation actually decreased in 2014 while generation from WWS sources increased by 20 percent, or by 200 TWh in absolute terms. Second, in terms of capacity additions, more capacity was added from non-thermal sources (56 GW) than from thermal sources (45 GW) – with thermal sources being exceeded even by strictly green capacity additions (from WWS) of 51 GW. (We indicate below why we think it plausible that there could be capacity additions for thermal in 2014 but a reduced amount of electric energy generated.) Third, in terms of financial investment, the year 2014 again indicated that green sources were invested in at a much higher rate than non-green (thermal) sources. Investment data also indicate how rapidly China is upgrading its electric power grid to become a 'strong and smart grid' utilizing information technology

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to better manage the grid and allow it to accept fluctuating sources (i.e. renewable sources such as solar and wind). The State Grid Corporation of China (SGCC) is reported to have invested RMB 340 billion in its grid in 2014, and is expected to invest a further RMB 420 billion (US$67.7 billion) in 2015 – far more than is being invested by any other country. China indeed is now investing more in its transmission system than in power generation systems – an extremely important milestone.

Since so much hangs on the success of China's energy reforms, and in particular on its efforts to build the world's largest renewable power system – far larger than anything attempted in the West – it is important to report accurately on the system as it evolves, in order to comprehend the overall direction of change. Certainly it remains the case that China's electric power system is still largely coal-based, and a lot more coal is going to be burnt before the system can be described as more green than black. But the direction of change is clear – and this needs to be acknowledged, and factored into global energy discussions.

Future projections for China's energy system

We close this discussion by offering our own projections as to China's future electric system, based on the convex dynamics of the system's overall development and the logistic dynamics of the uptake of renewables. We do this to demonstrate in a realistic fashion where the system appears to be headed, and incorporating the most recent results in our future projections.

We start by noting the projections of China's official and semi-official energy modellers, such as those made by China's National Centre for Electric Power Planning and Research (NCEPP&R), in 2013, and most recently by the China National Renewable Energy Centre (CNREC) in 2015.[11] According to the NCEPP&R projection's 'middle scenario', China would generate 7500 TWh in 2020, rising to 10,500 TWh in 2030, and 13,100 TWh in 2050. Its electric generation capacity would reach between 2500 and 2800 GW in 2030 (2.5 and 2.8 TW), by which time non-fossil fuels-based capacity would account for about 40–50 percent of the total. Both total electricity generation and electric capacity would reach their maximum levels by 2050. According to this projection, as depicted in Figure 2.9, non-fossil fuel sources would account for more than half of China's generating capacity by mid-century.

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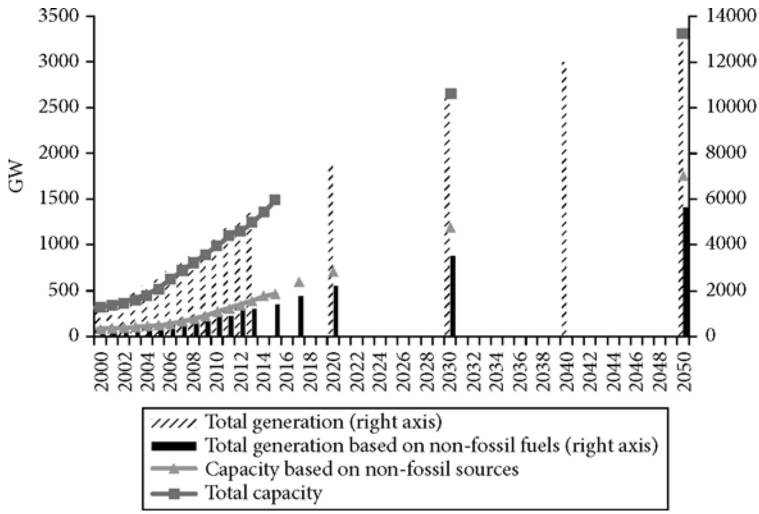

FIGURE 2.9 *Projections for electric generation and capacity up to 2050, made by the National Centre of Electric Power Planning and Research 2013*

Source: Authors, the historical data is based on *BP Statistical review 2014*; the targets between 2015 and 2020 are based on various government policy documents. The figures after 2020 are based on projections made by the National Centre of Electric Power Planning and Research, China.

More ambitious projections are offered by the CNREC study released in summary form in April 2015, where the share of renewables in primary energy is envisaged as growing to more than 60 percent by 2050, and the share of renewables in electric power generation as growing to 85 percent by 2050. We depict the projections in the Study for China's power generation in the so-called high renewable energy penetration scenario, where fossil fuels are expected to grow to a maximum of about 5500 TWh annually by 2025, and for renewables to eventually generate over 13,000 TWh in 2050, in the following chart (2.10).[12]

Now in this book we are concerned to indicate what China's 'real' energy revolution is likely to look like, where we see renewable sources (WWS) playing a larger role than is given in the NCEPP&R projections but not as optimistic as in the recent CNREC projections. We are not trying to provide a forecast, but to ask rather what would be a plausible trajectory that China's energy system would follow if aggressive targets were set for mid-century.

The point is that China's build-up of renewables will not follow a simple linear progression (as sometimes assumed by sources such as the IEA

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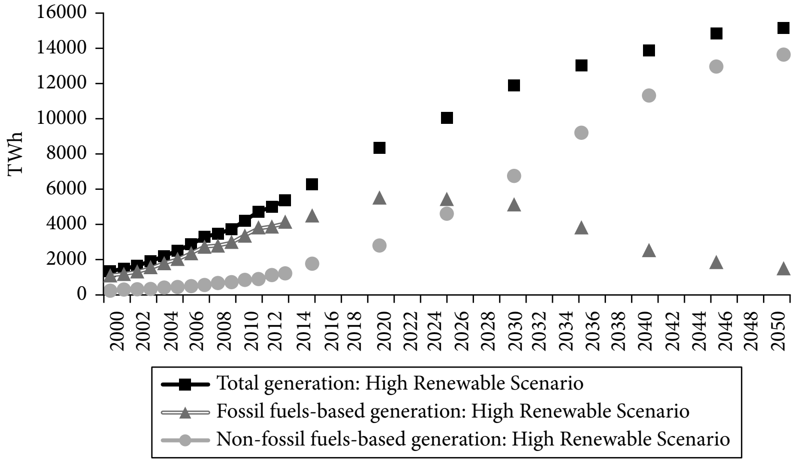

FIGURE 2.10 *Power generation in the 2050 high renewable energy penetration scenario*

Source of primary data: 'China 2050 high renewable energy penetration scenario and roadmap study', available at http://www.efchina.org/Reports-en/china-2050-high-renewable-energy-penetration-scenario-and-roadmap-study-en.

or OECD), but can be expected to follow logistic, or S-shaped, industrial dynamics. This means that as investments in renewable systems accumulate, they will become self-reinforcing, and lead to further such investments. We plot China's recent electric power investments in Figure 2.11 and carry them forwards to 2020, 2030 and to 2050, in accordance with official projections, but fitting logistic curves to them. We follow a distinctive procedure. First we map out the total electric power curve as an outer envelope, following a parabolic trajectory; next we map renewables trajectories within it, following logistic dynamics. This represents, in other words, a non-linear approach to capturing energy industrial dynamics.

We depict China's energy trends therefore in terms of three fundamental curves – an outer convex curve representing total electric power, an inner parabolic curve representing build-up then decline of coal, and a logistic curve representing the build-up of renewables in electric power generation. We set what we consider to be a realistic end-point for the build-up of renewables, namely 70 percent of capacity by 2050 and 60 percent of electricity generation. The resulting 'realistic' curves are shown in Figure 2.11a and b.

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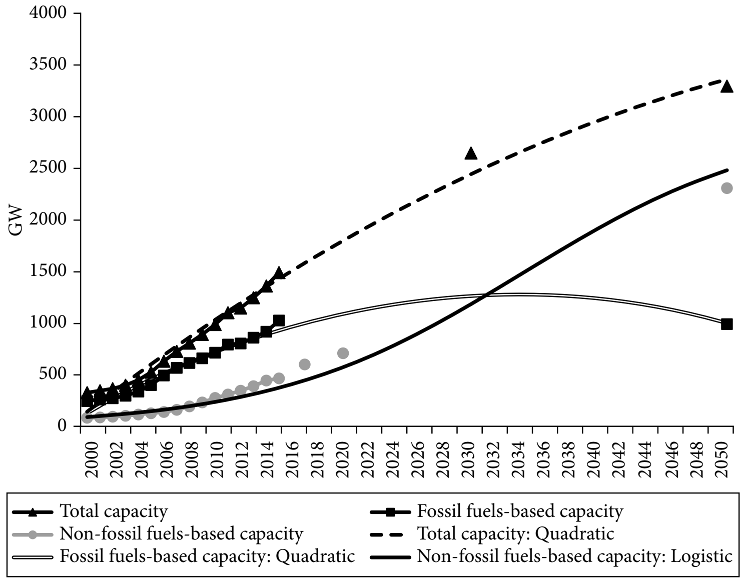
a. Capacity of the power system



b. Electric energy generation

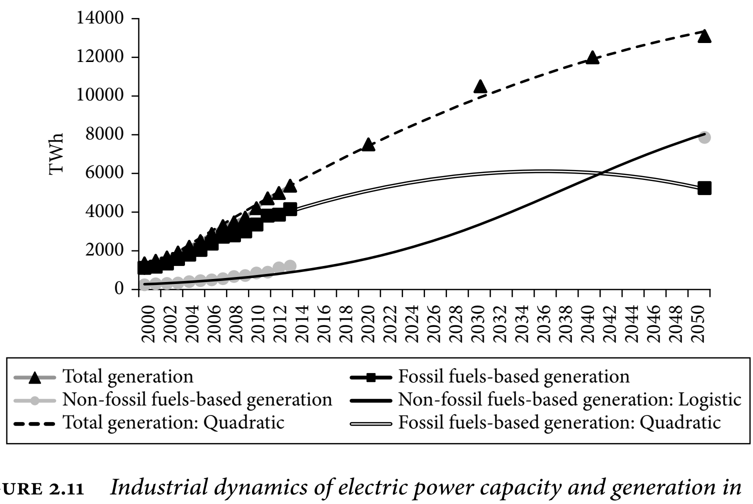


FIGURE 2.11 *Industrial dynamics of electric power capacity and generation in China: 2000–2050 (proj)*

Source: The historical data are available from the EIA International Energy Statistics database and the BP 2014 World Energy Statistics Review. The projection data of the total electric generating capacity in 2030, 2040 and 2050 are available from the National Centre of Electric Power Planning and Research in its 'middle scenario' projection. The projection data for the three curves are generated by two quadratic models (for the total electricity capacity and the fossil fuel-based capacity respectively) and a logistic model (for non-fossil fuel-based capacity) by the authors.

For the outer parabolic curve, we have a trajectory for the total electric power system that follows historic points up to the year 2014 (reaching 1,360 GW (1.36 TW) by that date), and then further points spaced out to 2015 and 2020 according to the most recent official projections, and then to 2030, 2040 and 2050 based on our 'realistic' estimates. This outer curve reaches 3.3 TW by 2050 in terms of capacity, and just over 13,000 TWh in terms of actual generated electric energy. We then draw through this our own smooth parabolic curve ('quadratic model for total electricity') to indicate the shape of China's likely total electric energy trajectory up to the year 2050.

We depict coal-burning and other fossil fuelled thermal electric power generation on the chart as a convex curve, showing it increasing from 603 GW in 2008 up to 916 GW in 2014, then projected to peak at a capacity of 1.3 TW by around 2030, or at an electric generation level of just under 6,000 TWh. This corresponds to our discussion above of the likely peaking of coal consumption and thermal power generation. In accordance with non-linear industrial dynamics, the significance of fossil fuel sources can be anticipated to decline rapidly thereafter (and thereby relieve pressures on China's fossil fuel supplies from around the world).[13]

For renewables uptake we have the inner logistic curve, where we depict firstly the historic points for non-fossil energy sources (including nuclear) up to the year 2014, and then points beyond this date based on official projections up to 2020, and then our own logistic curve reaching around 2.3 TW of non-fossil capacity by 2050 (accounting for 70 percent of the total) and close to 8,000 TWh of electric energy (accounting for 60 percent of the total). Our capacity curve shows renewables overtaking fossil fuels by around 2030, when they each account for 50 percent of capacity; renewables then pull away to reach 2.3 TW by 2050, accounting for 70 percent of total capacity, while fossil fuels decline. Our electric energy generation curve shows the same process in a slightly less emphatic fashion, where renewables generation overtakes fossil fuels by around 2040.

Overall then we see China building 1 TW of renewable capacity by around 2030 – in line with the commitments made at the US-China summit of November 2014 and generating around 3000 TWh of renewable electric energy. If achieved, this would set China on track to be the first country to achieve such a milestone. Indeed it would not be surprising to see China build 2 TW of renewable power through manufactured systems by the year 2040, and 2.3 TW by the year 2050. This is what might best be described as a 2-TW 'Big Push', involving unprecedented commitment to

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enhancing energy security through manufacturing industries rather than traditional fossil fuel extraction and processing industries. We discuss the manufacturing and resource challenges of meeting this target of 2.3 TW capacity in Chapter 6 – where we will demonstrate that the demands and challenges are certainly considerable, but eminently feasible – particularly for a manufacturing power like China.

Our projections are more ambitious than those already offered by the NCEPP&R and less ambitious than those offered in 2015 by the CNREC. Our concern is not so much to offer ambitious but perhaps unrealistic trajectories as to engage with the political economy of China's renewable energy transition. As stated, we see this transition as world-historic because it is based not on fossil fuel extraction but on a growing capacity to manufacture renewable energy devices, and thereby offering real energy security. We submit that the Figure 2.11 provides at least a plausible model of China's likely greening of its electric power sector – the source of 50 percent of its carbon emissions. We do not offer it as a forecast (because the data extend too far into the future) but as an estimate of possible future trends based on realistic assumptions and targets. Inspection of Figure 2.11 shows that renewables would account for half of the total power capacity by around 2030 – just 15 years away. By then the transition to renewables would be self-sustaining and irreversible. China would have become the planet's renewables superpower.

Notes

1 See Appendix for an explanation of the energy units used.

2 Note that bodies such as the Energy Research Institute in China have carried out studies based on proportions of renewable energy in China's primary energy consumption as high as 60 percent, and concluded that such a high renewable energy penetration scenario is both technically feasible and economically affordable in China (see http://www.efchina.org/Reports-en/china-2050-high-renewable-energy-penetration-scenario-and-roadmap-study-en). However in this book we choose to base our discussion on more conservative scenarios, for the sake of balance among different projections.

3 As noted earlier, this is made up of 350 GW of hydropower, 200 GW wind power and 100 GW solar power, to be achieved by 2020.

4 See the Fact Sheet issued by the US White House to accompany the US-China Joint Statement on Climate Change, 11 November 2014, at: https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c

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5 http://news.xinhuanet.com/energy/2014-03/05/c_126222158.htm Note that we are using a conversion factor of 1 tonne coal = 0.68 tonne coal equivalent, or conversely 1 tonne coal equivalent = 1.45 tonne coal.

6 See the report (p. 9) at: http://www.carbontracker.org/wp-content/uploads/2014/09/2014-07-21-SP-Carbon-Constraints-Cast-A-Shadow-Over-The-Future-Of-The-Coal-Industry3.pdf

7 https://ir.citi.com/z5yko80HEXZtoIax1EnHssv%2Bzm4Pc8GALpLbF2Ysb%2Fl21vGjprPCVQ%3D%3D

8 See also https://www.chinadialogue.net/blog/7601-Peak-coal-in-China-not-likely-until-2-2-s-says-IEA/en

9 For an explanation of the difference between tonnes coal and tonnes coal equivalent, see Appendix.

10 See Matthew Kahn, 'Fueling the future', *Science*, 16 January 2015, where he states 'China uses [coal] to generate roughly 80% of its electricity' – an assertion sourced to the International Energy Agency (IEA).

11 http://paper.people.com.cn/zgnyb/html/2013-02/18/content_1199495.htm (in Chinese).

12 Our presentation is based on projections provided by the China National Renewable Energy Centre (CNREC) that anticipate renewables accounting for as much as 60 percent of primary energy and 85 percent of electric power generation by 2050. See *China 2050 High Renewable Energy Penetration and Roadmap* study (summary only available in April 2015) at: http://www.efchina.org/Reports-en/china-2050-high-renewable-energy-penetration-scenario-and-roadmap-study-en

13 According to the State Grid Corporation, China will have 1.7 TW of generating capacity by 2020, 59 percent of which will come from coal-based (thermal) sources. Our own projections match this prediction.

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3

China's Energy Producing and Using Industries – Industrial Dynamics

Abstract: *China's energy revolution can be traced through the industrial dynamics operating in specific sectors, encompassing fossil fuels and non-fossil fuels. Having built the world's largest coal industry China now faces the challenge of winding it down. In terms of oil and gas it is a matter of expanding to secure access to sources around the world. The principal achievements are the creation of new industries based on wind, solar photovoltaic and now a series of new technologies such as those based on light-emitting diodes, energy storage and electric vehicles. Much policy initiative is focused on building these new industries, as well as on reducing high levels of energy consumption (and carbon emissions) in key energy-intensive industries such as steel and cement.*

Keywords: biopower; coal industry; energy industries; energy-intensive industries; hydropower; nuclear power; oil and gas industry; solar photovoltaic; solar power; windpower

Mathews, John A. and Hao Tan. *China's Renewable Energy Revolution*. Basingstoke: Palgrave Macmillan, 2015. DOI: 10.1057/9781137546258.0010.

In Chapter 2 we discussed the general trends in China's energy revolution, and its macro-level driving conditions. Now we wish to probe more deeply into the industrial dynamics of the various sectors that contribute to China's energy revolution, both the fossil fuel industries themselves and the renewable energy industries, as well as the energy-intensive industries such as aluminium, steel and cement production and the transformations being effected within them. We do so in order to demonstrate how the sectoral-level industrial dynamics are contributing to shape China's energy industrial revolution, and how government policies are impinging on these industrial dynamics.

The birth and evolution of industries has long been a topic of intense interest in the field of industrial dynamics. Research in the field usually starts as an investigation of key industry features, or 'stylized facts', such as firm size distribution, growth and changes over time.[1] We focus in this chapter on the key industries that have significantly driven and been impacted by China's energy revolution. Those include fossil fuel mining and extraction industries; the energy sector based on non-fossil fuel sources; and energy-intensive industries – as well as manufacturing industries that produce equipment for utilizing renewable energy such as solar PV and wind turbines. A closer examination of the transformation in the electric power sector itself, and its greening, will be the focus of the next chapter.

We start with fossil fuels, and particularly coal, as the fundamental industry that has powered China's energy industrial revolution. We then examine the industrial dynamics in the major non-fossil fuel power industries, including hydroelectricity, wind, solar, bioenergy and nuclear power, in regard to their development and resource potentials. This discussion is followed by an examination of the industries that manufacture solar PV and wind turbines. We conclude this chapter with a review of several energy-intensive industries that are responsible for a considerable share of energy consumption in China and which have been the subject of focused efforts to reduce their energy utilization (energy intensity) and carbon emissions.

Fossil fuel industries

Coal industry

Driven by its enormous appetite for the energy released by the burning of coal, China has become the largest coal producer and consumer in the

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world. Coal has long been the primary energy source in China, accounting for over 70 percent of the total energy use for most of the 2000s and falling to around 65 percent by 2013 as alternative energy sources have been brought online. The coal industry in China has experienced a boom followed by a drastic fall in the past two years (Figure 3.1). Owing largely to oversupply in the 1980s and early 1990s, China's coal industry became stagnant in the mid-1990s. However, production started to pick up in the 2000s, driven by the rapid growth of the economy, especially after China joined the World Trade Organization (WTO) and emerged as the workshop of the world. The central government imposed drastic reforms to consolidate and restructure the industry, creating a few coal production giants such as Shenhua Energy and driving out the smaller and less efficient mining operators. The growth of China's coal production reached a peak in the early 2000s, achieving annual growth rates of 18 percent in 2003 and 15 percent in 2004. Since then the growth has slowed down, as non-thermal sources of energy have come online. China produced about 890 million tonnes of coal in 2013, accounting for almost half of the coal production in the world (Figure 3.2). A declining trend has been most obvious in the past two years, where the growth

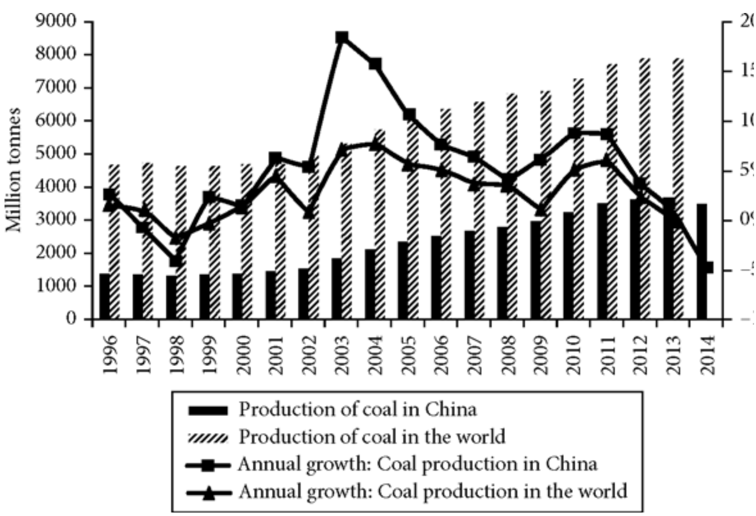

FIGURE 3.1 *Coal production and its growth: China and the world*

Source: Authors. Based on data available from *BP 2014 Statistical Review*. The 2014 coal production statistics of China are available from the NBS of China.

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has quickly dropped from 8 percent in 2011, to less than 4 percent in 2012, and almost no growth in 2013. In 2014, *coal production in China actually declined* for the first time in one-and-half decades, falling to 3.87 Gt (down 2.5 percent compared with the level in 2013) – as shown in Figure 3.1.[2] This corresponds to the fall-off in coal consumption and thermal power production in 2014 as noted in Chapter 2. Official statistics indicate that the decline has continued into the early months of 2015 when we are writing this Book.[3] The decline in coal production might be bad news for the coal sector, but it is good news for the world's climate and for China's strategy of building energy security on the basis of manufactured renewables.

China's dominance of the global coal scene is shown vividly in Figure 3.2, which depicts China as accounting for very nearly half of global coal production.

Coal has been increasingly used for thermal power generation in China, a phenomenon reflecting the trend of electrification. Thermal power generation accounted for about 40 percent of the total coal consumption in the year 2000 rising to just less than 50 percent of the total coal consumption in 2012 (Figure 3.3).[4] In 2012, around 1.7 Gt coal was used for thermal power generation, followed by 0.87 Gt burnt directly by end users (Figure 3.4). One of the key strategies that China has to combat its severe smog issue is to reduce the total consumption of coal and in particular reduce the amount of coal burnt directly by the

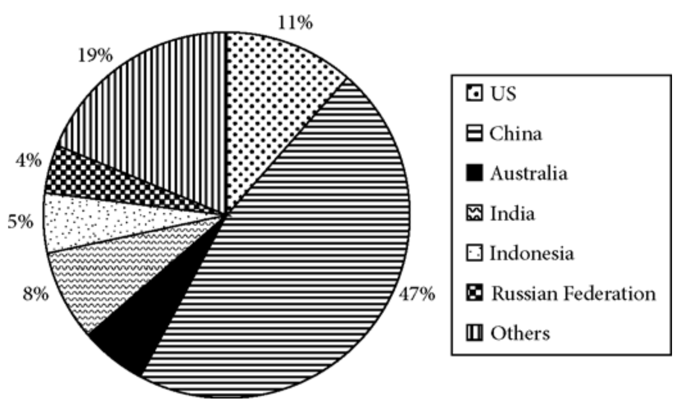

FIGURE 3.2 *Share of coal production by country, 2013*
Source: Authors. Based on data available from *BP 2014 Statistical Review.*

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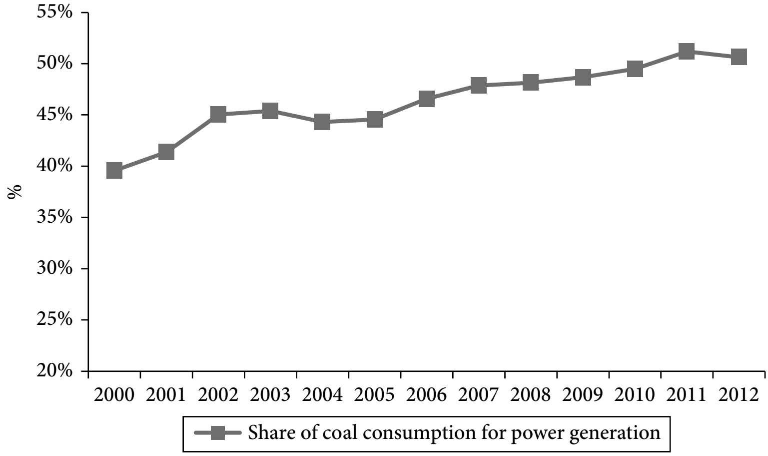

FIGURE 3.3 *The share of coal consumption for thermal power generation in China*
Source: Authors. Based on data available from the National Statistics Bureau, China.

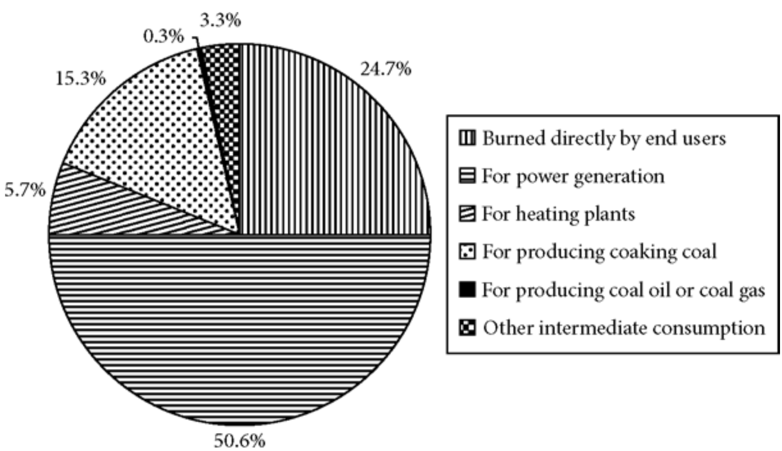

FIGURE 3.4 *Coal consumption in China, 2012: where the coal was burnt*
Source: Authors. Based on data available from the National Statistics Bureau, China.

power generation industry. Note too that nearly 25 percent of coal burnt is in end-user industries – where cement and steel production figure strongly; this is where efforts are focused to reduce energy intensity and, through that, levels of coal consumption.

China has had to make enormous efforts to build a coal industry that could supply the vast needs of the power generation industry and wider industry (including domestic heating). Huge new companies like *Shenhua* have been created through consistent policies of consolidation and closure of small, inefficient coal operations. Figure 3.5 shows the financial performance of the coal mining industry during the last decade. For the whole coal mining industry, the 2000s was its golden age, when the profit of the industry accounted for one-fifth of the total profits of the entire Chinese mining and manufacturing sector, thanks to the appetite of the economy for coal and the resulting increases in the coal price. Its profit as the percentage of the income of the industry remained high even during and after the Global Financial Crisis. But the financial performance of the industry has rapidly declined from its peak in recent years. Meanwhile, the price of coal in China has dropped by over 35 percent since 2012, according to the price index released by the China Coal Industry Association.[5]

The Chinese coal mining industry is dominated by large state-owned enterprises (SOEs), such as Shenhua, China Coal Energy, Shanxi Coal International Energy Group, Yang Quan Coal Industry group and

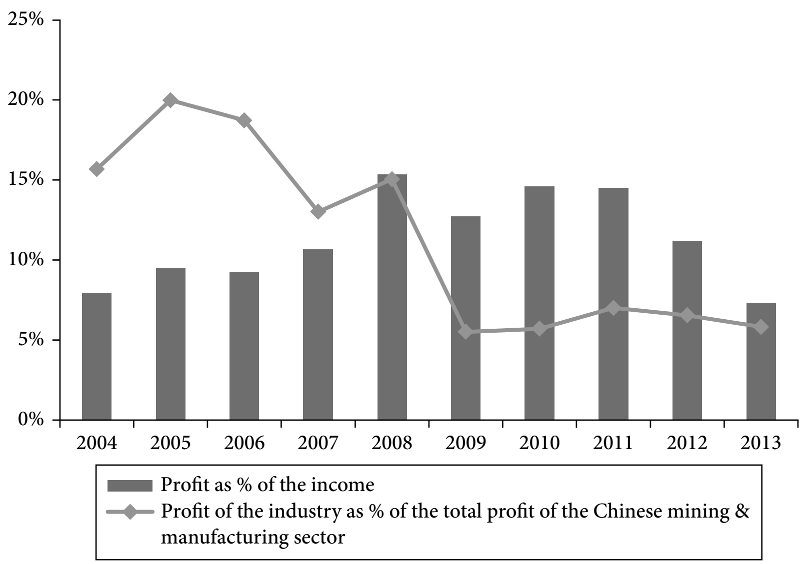

FIGURE 3.5 *Financial performance of China's coal mining industry*
Source: Authors. Based on data available from the National Statistics Bureau, China.

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Yancoal. There are also many smaller SOEs and private firms in the industry, some of which entered after deregulation in the 1980s and many others were lured into the industry because of high profits in the 2000s. There were about 8,000 large-scale coal mining companies by 2013 based on the threshold specified by the National Statistics Bureau of China (i.e. with the annual main business income over RMB 20 million). With the administrative caps on coal consumption (discussed in Chapter 2) starting to bite, the industry faces an uncertain future. Some firms like Shenhua are already looking to diversify into petrochemicals or into renewable energies as a lifeline to the future.

In the winter of 2014/2015 China's coal industry was going through a major slump, exacerbated by weak demand and the impact of government efforts to shift the energy supply system to greener sources. Prices were down by 20 percent on the previous year, according to the National Coal Association. A government ban on production and import of low quality coal (high sulphur coal) was also having a big impact. Coal stockpiles with mining companies stood at around 87 million tonnes, up 2.6 percent over a year ago – an indication of the waning fortunes of the coal sector.[6]

To give a flavour of the depth of the slump hitting the China coal industry, the largest producer, Shenhua Energy, reported a drop in sales and profits in 2014, of 12.4 percent and 20 percent respectively. Shenhua's production of coal was down by 3.6 percent in 2014, to reach 307 million tonnes, while its production target for 2015 has been set at 274 million tonnes, a further drop of 10.8 percent.[7] The company estimates that sales of coal in 2015 will reduce to 404 million tonnes, down 47 million tonnes on its sales in 2014; while capital expenditure in coal and power generation in 2015 is being slashed by 25 percent down to US$3.2 billion.[8] This is as good an indication as any of the slumping fortunes of the China coal industry. But it also needs to be said that China is seeking to phase out coal in a socially responsible manner.[9]

Oil and gas industry

The oil and gas industry is an established industry in China, dating from the discovery of the first large oil field, Daqing Field, in the late 1950s, in the northeast of China. But unlike China's coal mining industry, the oil and gas industry is highly regulated, and there are only a limited number of firms. According to the NBS, there were 138 companies operating in the oil and gas extraction industry with annual income over RMB 20

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million in 2013, compared with 8,000 large coal mining firms. Defined as the aggregate of the activities of exploration and production of oil and gas, the industry in China had total revenues of over US$400 billion in 2014.[10] Revenues declined by 3 percent in 2014 over the level reached in 2013. The industry is dominated by three national oil companies (all SOEs), namely China National Petroleum Corporation (CNPC), China Petroleum & Chemical Corporation (Sinopec) and China National Offshore Oil Corporation (CNOOC). By any standards, these are global giants – in terms of capitalization, revenues and profits.

Owing to high demand and relatively small reserves, China has increasingly sourced oil and gas from overseas. By 2013 China had to import 280 million tonnes of oil (or 1.82 billion barrels) over and above its domestic production. At an average of US$100 per barrel, these imports of oil would have cost China US$182 billion – a sum that even China, with its huge foreign reserves, would wish to avoid. The oil self-sufficiency ratio, an indicator for measuring 'energy security', has now reduced to 41 percent and is falling. Figure 3.6 shows the widening gap between domestic production and consumption, now exceeding 300 million tonnes of oil per year.

While the regulation of the oil and gas industry ensures that the main companies receive substantial profits, the situation is nevertheless critical. Continuing dependence by China on a rising tide of oil imports (the

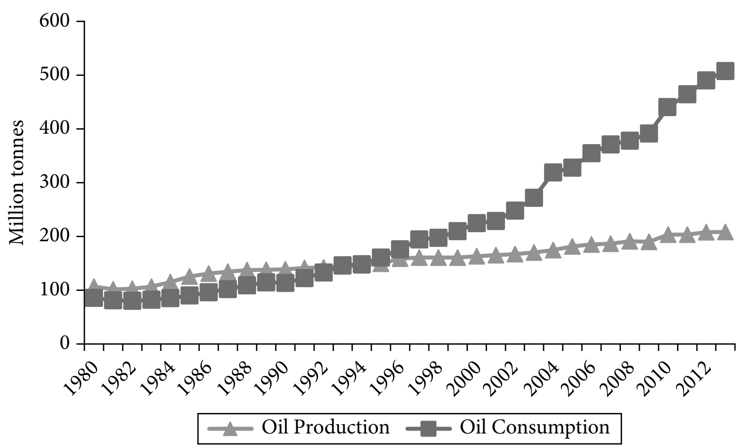

FIGURE 3.6 *China's increasing dependence on oil imports*
Source: Authors. Based on BP 2014 *World Energy Statistics Review.*

'business as usual' pathway) would spell not just rising carbon consumption and carbon emissions, but perhaps even more critically rising dependence on unstable oil regimes around the world – in the Middle East, Africa, Latin America and Central Asia. It is this aspect of energy insecurity associated with continued reliance on fossil fuels that we maintain is partly responsible for China adopting such a firm strategy of expansion of renewable power industries, all of which are based on manufacturing.

Non-fossil fuel energy sector

We focus now on the renewable energy industries themselves, which are the front line in the renewable energy revolution in China. In China the renewable energy industries have been key targets of government support and promotion, while in other countries renewables have sometimes been viewed with hostility because of the grip of established fossil fuel industries. China's energy revolution thus encompasses both nuclear and renewables as non-fossil energy sources, as well as industries dedicated to manufacturing of equipment and devices to harness renewable resources. We focus on the former in this section, examining the resource potentials as well as the latest developments in several energy-producing industries, including hydropower, wind, solar, bioenergy and nuclear power. We conclude the chapter by examining the manufacturing industries, particularly those producing wind turbine and solar PV cells, encompassing end producers and the value chains that feed them.

Hydro power

Hydropower is the oldest renewable energy resource in China, and the one that makes the major contribution today. The damming of rivers to create large reservoirs of water that are then fed by gravity through turbines to generate electricity is one of the most mature of the renewable energy technologies – and utilized in China to a far greater extent than anywhere else (twice the size of the hydroelectric capacity of the next largest country, Canada). The growth of hydroelectricity has followed an exponential trend during the past three decades. The Three Gorges Dam stands as the symbol of this hydroelectric commitment, which in 2009 was already operating at close to its huge 22.5 GW capacity.[11] China has

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already met its 2015 hydropower capacity target of 290 GW a year ahead of schedule.

As a resource hydropower is limited, and so cannot be expected to follow the typical logistic curve uptake in future decades. The Chinese government has plans to expand hydro from 220 GW in 2010 to 330 GW by 2017 and to 350 GW by 2020 – but it can't hope for much more than that. The near-doubling of hydropower in a decade will involve widespread damming of waterways that could provoke civil disturbance (and protest) on a large scale. The results of the 2003 nationwide Hydropower Resource Assessment indicated that China has a potential hydropower capacity of 540 GW that is technically exploitable with an annual power generation potential of 2470 TWh according to the National Development & Reform Commission (ND&RC). Some 400 GW of the capacity is economically feasible, with an annual power generation potential of 1750 TWh, according to the ND&RC. The same planning agency estimates that 350 GW of hydro power will be online in China by 2020.

We are of the view that China will not feel the need to develop any further hydropower beyond this 350 GW capacity as envisaged in the current energy plan (expected to be incorporated into the 13th FYP, covering the years 2016–2020). This will relieve social pressures arising from further major damming projects, and reflects the greater significance of wind and solar power as they are ramped up to take over from hydro as principal renewable sources in the 2020s.

China's hydropower has been developed largely by SOEs such as SinoHydro Corporation, the HydroChina Corporation and the China Three Gorges Power Corporation (CTGPC). The CTGPC was established in 1993 to build and operate the Three Gorges project, the world's largest hydro project, and is now a major energy company in its own right; in 2011 it acquired the 21.3 percent government stake in Energias de Portugal for the reported sum of € 2.7 billion. All the hydro companies are looking actively abroad to extend their hydropower expertise. Using their capability in construction and engineering they are now successfully bidding for Engineering, Procurement and Construction project (EPC) contracts, both to develop hydropower projects as well as wind and solar farms. For example both SinoHydro and HydroChina combined with Yingli Green Energy to win a major solar PV farm project in Algeria in 2013.[12]

One of the most interesting aspects of China's development of hydropower (largely in the remote west of the country, for example along the Jinsha river on the upper reaches of the Yangtze in central China) is that

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a new high-voltage DC transmission (HVDC) system is being built to carry huge new current loads (5 GW) over vast distances (1,000 to 2,000 km) to the coastal cities in the East such as Shanghai. Indeed the HVDC link between Xiangjiaba and Shanghai over 2,000 km is the world's first fully operational HVDC link – and it is seen in China as just the first of a new national 'smart grid' integrated system. In this way, all aspects of grid modernization – from the use of zero-carbon sources to high-capacity transmission systems employing 'smart' IT-enabled monitoring and control – are being brought together in China's leapfrog modernization.

Nuclear power

By the close of 2014, China had 21 nuclear reactors operating, and 28 under construction. China is the world's largest builder and operator of nuclear reactors – although the rate of expansion has slowed considerably since Japan's Fukushima disaster, which triggered a slowdown and a major safety review in China. In 2012 and 2013, China barely added nuclear power capacity. However, investment in nuclear capacity picked up in 2014, enabling the country to add over 5 GW in 2014 resulting in a cumulative capacity of nearly 20 GW by the end of the year. The target in the original Energy 12th FYP was for 40 GW by 2015, and in the new Energy Development Action Plan it is 58 GW by 2020. Many of the nuclear reactors that China is expected to build over the next several years involve 3rd or even 4th generation reactors, such as those in Sanyang and Haiyang nuclear plants, both based on the Westinghouse-designed AP1000 technology, and in the Shidao Bay project in Shandong province which uses 4th generation nuclear energy systems.[13] In fact, according to the Nuclear Electric Power Safety Plan (2011–2020) introduced by the State Council in 2012 after the Fukushima nuclear disaster, all new nuclear reactors built in China must comply with the safety standards of the 3rd generation nuclear technology or above. While this book was being written, the State Council formally approved the first pilot project based on China's own 'third-generation' nuclear power technology, 'Hualong 1', as an important step to commercialize the technology for both domestic and international markets.[14]

In nuclear power, the sector is dominated by the China National Nuclear Corporation (CNNC) and wholly state-owned corporations such as Qingshan Nuclear Power Company or the China Guangdong Nuclear Power Group (CGNPG) (renamed the China General Nuclear Power Group (CGN) in 2013), operator of the Guangdong Daya Bay

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nuclear power station, as well as new entrants from the power sector such as the Three Gorges Dam Corporation.[15] The technology utilized in the nuclear sector is based on existing designs from US Westinghouse as well as pressurized water reactor design from the French company Areva, with China's clear intent being to indigenize the technology and take ownership (with patents) over the course of the next decade.

China's drive for localization of nuclear technology has been intense.[16] For example, some 80 percent of components for the Ningde 3 project were sourced from Chinese suppliers, including for the first time the entire digital control system. Technology for nuclear power has been drawn from France, Canada and Russia, with local development based largely on the French element. The latest technology acquisition has been from the United States (via Westinghouse, owned by Japan's Toshiba) and France. The Westinghouse AP1000 is the main basis of technology development in the immediate future. China has currently budgeted $65 billion for nuclear reactor building, which hinges on replicating the Westinghouse-designed AP1000 reactor (a pressurized water reactor) and the Chinese advanced version of the pressurized water reactor (CPR-1000) – the latter based on technology purchased from France's Areva.

A new nuclear power company was established in 2007 (State Nuclear Power Technology Corporation, or NPTC) to take charge of China's 3rd generation reactor programme. China's State NPTC together with the Shanghai Nuclear Engineering Research and Design Institute have been working on an AP1000-inspired reactor, as well as a more powerful Chinese version CAP-1400 (rated at 1400 MWe), which started construction in 2013. Four of the US-designed reactors were ordered in 2007, with technology transfer to be a major part of the agreement. In May 2015 a merger of SNPTC with China's other major power company, China Power Investment Corporation (CPIC), was announced by the firms involved, with the goal of consolidating China's acquired nuclear power capabilities. The nuclear power companies are also diversifying; CNNC for example has formed a joint venture with wind power company Ming Yang to build a wind farm in China's Henan province.

One of the purposes for the restructuring of the nuclear power industry in China has been to enhance its competiveness in the international market. After importing foreign technologies for the past decades, China has started to sell home-made reactors in foreign markets such as Brazil, Pakistan and Argentina. It was reported in 2014 that China won a major contract to build nuclear reactors in the United Kingdom.[17] While the

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project faces uncertainties because of controversies over the nuclear issue in the United Kingdom, the success in winning such a contract in a highly competitive market of a western country seems to illustrate the rising technological competence of Chinese companies.[18]

Bioenergy

Compared with its huge potential, to date energy production from biomass is at an early stage in China. According to the 12th FYP for Bioenergy Development, China utilized about 24 million tce of bioenergy in total, including electric generation based on biomass and waste, the use of biofuel and biogas, but excluding the traditional use of firewood as a source of direct combustion. The US EIA's data indicates that in 2012 China's biomass and waste-based electricity generation provided 44 TWh of electricity, or about 5.4 million tce of energy.[19] By 2013, China had installed about 8.5 GW of electric generation capacity based on biomass and waste, and was producing about 6 million tonnes of biofuels annually.

However this is only a small part of the potential. According to the assessment by the China National Renewable Energy Centre, the country at present already has biomass resources equivalent to over 500 million tce of energy that can be converted into fuels or electric power, of which about 360 million tce can be from crop straw, about 70 million tce from waste from forestry and forest product processing, and the rest from energy crops and plantations produced from large expanses of marginal lands, and biogas, municipal wastewater and municipal solid waste.[20] The *Medium and Long-Term Development Plan for Renewable Energy* in China released in 2007 indicated that the biomass resource is expected to support energy production of up to 1 Gt of coal equivalent in the future, thanks to the increase of land area allocated for forestry.

Biomass can be used directly as feedstock in a power plant – as bioenergy – or indirectly through biological processes such as fermentation to create liquid biofuels. China is currently a major producer of biomass to be used for food (rice, wheat, millet, corn) and feed – and so there is not a lot of extra land to be used for fuel. Indeed the Chinese government has a 'non-food crops' policy, that is a ban on the use of crops such as corn as feedstock for biofuel in order to avoid any conflicts over food versus fuel. As a result the growth of bioethanol production in China has been relatively slow, from 1 million tonnes in 2005 to 2.1 million tonnes in 2013. The growth is expected to accelerate after the government introduced a

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number of policies to encourage investment in biofuel production based on non-food crops in the year 2013.

Electricity generation from biomass and solid waste has attracted increasing interest from industries and the government. By 2013 China had installed 7.8 GW of electric generation capacity based on biomass, and 3.4 GW based on biowaste. But there has been some public resistance to such projects due to concerns over odours and emissions from the facilities.[21] There were over 100k biogas projects in the country, most of them located in the countryside away from settlements and supported by government funding. These all contribute directly to reduction in rural energy poverty.

Wind power

As discussed in Chapter 2, China was doubling its wind power capacity every 18 months from 2005 onwards, until it became the largest wind power industry in the world. By 2014 the China industry had grown to an installed cumulative capacity of 115 GW, adding capacity of 23.5 GW in that year (a comparative slowdown).[22] Official targets are for the sector to have 150 GW capacity by 2017, and 200 GW by 2020 – both of which would seem to be eminently achievable.

Worldwide, wind power has been growing at an unprecedented rate, reaching a cumulative total of 370 GW by 2014, recovering from a bad year in 2013, and adding 51 GW additional capacity in that year. China's buildup is a large factor in this global recovery; China accounts for 26 percent of global cumulative wind power capacity and for 40 percent of new capacity added in 2014; it is the acknowledged world leader in the sector.

China's present predominance in wind power owes everything to far-sighted industry strategies pursued in the second half of the 2000s. The first grid-connected wind farm came online only in 2006, when the national stated goal for wind energy was 1 GW capacity. In 2005 China's wind power capacity was only 1.26 GW. The industry thus grew 100-fold in terms of installed capacity in the decade from 2005 to 2015.

Of course not all this 'capacity' is actually translated into electric power available through the grid, and media reports consistently indicate that much of the capacity currently remains unconnected or under-utilized (a situation described as 'curtailment').[23] But this is clearly a bottleneck that is being addressed, particularly by the ultra-high-voltage (UHV) transmission lines planned to link the western parts of the country with the eastern industrial areas. In terms of electricity generated by wind power,

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the year 2014 saw 153.4 TWh generated from wind (or 2.8 percent of China's total). Because of curtailment – where some sources are switched off from supplying the grid – China's wind energy capacity factor declined to 1,893 hours in 2014, down from 2,074 in 2013. (Since there are 8760 hours in a year, this translates to a capacity factor of 21 percent.)

Wind power in China is not limited by resource availability, of either wind itself or of land for the wind farms. According to an estimate by the China Meteorology Research Institute in the 1990s, China possesses a potential wind capacity of 1,000 GW, including an onshore wind capacity of 300 GW and offshore capacity of 700 GW (NDRC 2007). However, these estimates are based on the 10-metre hub height turbine and can be expanded using modern wind turbines with hub heights now exceeding 30 metres (Martinot and Li 2007). A study by the United Nations Environment Programme estimates that the total wind energy reserve in China could be as high as 3,000 GW (3 TW), a figure cited by a *Nature* editorial. Using a conservative capacity factor of 25 percent and without considering improvement of the capacity factor in the next decades, the potential wind resources could in theory generate 6570 TWh of electricity annually, or about 807 million tce of energy, which can displace electricity generated from 1170 million tonnes of raw coal in China.

Taking account of economic as well as technical considerations, a study published in *Science* (McElroy et al. 2009) indicates that at a contract price of 0.516 RMB (7.6 US cents) per kilowatt-hour, wind farms in China could economically generate 6960 TWh, or 855 million tce, of electricity. This amount of electricity was more than twice the total consumption of electricity in China in 2007 (3270 TWh) and is in excess of current (2014) electric energy production (5546 TWh), meaning that there is still plenty of room for the wind power sector to grow.

China has promoted the growth of major wind farm developers, the largest of which is Longyuan Power Group, a subsidiary of the SOE China Guodian Corporation (one of the Big Five power generators). The group added 1.6 GW wind power capacity in 2014, bringing its total energy generation to 33.4 TWh in China.[24] It is notable that China has several 10-GW wind farms proposed or under construction, while the world's largest wind farm, the Gansu Wind Farm Project (built largely in western Gansu province where wind resources are plentiful) is due to reach a planned 20 GW capacity by 2020. Other major wind farms that have been built or under plan are listed in Table 3.1.

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TABLE 3.1 *China's plan for large wind farms and their capacities in 2020, 2030 and 2050 (GW)*

Area	2010	2020	2030	2050
Mengxi and surrounding areas	6.5	40	100	300
Mengdong and surrounding areas	3.62	20	40	90
Northeast	7.31	30	38	60
Hebei and surrounding areas	3.78	15	27	60
Gansu	1.44	20	40	120
Xinjiang	1.13	20	40	100
Distributed land wind power farms in east-central area and others	7.43	25	50	70
Near offshore	0.1	30	60	150
Far offshore	0	0	5	50
Total	31	200	400	1000

Source: Wind power development roadmap 2050 (China National Renewable Energy Centre 2014).

There were over 50 companies that had invested in and operated wind farms in China by the end of 2013; but the market is predominantly shared by large SOEs. Four of the five national power companies in China, or 'Big Five' as they are commonly known, owned over 50 percent of China's installed wind power capacity by the end of 2013. The top three windfarm operators, Guodian, Huaneng and Datang, owned respectively 21 percent, 13 percent and 12 percent of the total installed wind power capacity by the end of 2013, followed by Huadian (7 percent). These companies are diversifying into manufacture of wind turbines – such as Guodian United Power Technology company, now a major producer of wind turbines in China, in partnership with the German firm Aerodyn. It is notable that China's nuclear power companies are also diversifying into wind power. China's General Nuclear Power Corporation (CGN) ranked No. 5 in terms of its wind power capacity in 2013. The company was also reported at the end of 2014 to have acquired three onshore wind farms in Britain from the French company EDF Energy Renewables – a deal marking CGN's debut in the European wind power sector. Under the contract of sale, EDF will continue to maintain and operate the sites.[25] All of this testifies to the vitality of the wind power sector in China and its close links with the turbine manufacturing base.

We anticipate that China's wind power sector will continue to expand, both as an industry producing turbines and as a power generation sector (with giant wind farms of 10 GW capacity each becoming the norm). By the end of 2013 China had already installed 63,120 wind turbines, a figure we shall return to below, when discussing the manufacturing challenge of moving to full reliance on renewable power.

Solar power

Solar power is now on the rise in China. By the end of 2014 China had the second largest solar PV capacity in the world (26.5 GW), which was second only to Germany (36 GW). In terms of actual electric energy generation, China produced 25 TWh of electricity from solar sources in 2014, ranking 4th in the world.[26] Since 2012 it began to see serious promotion of the domestic market, such as through rooftop solar and local promotion via Feed-in Tariff schemes that have been tried and proven in other countries, such as Germany. The National Energy Agency (NEA) also set a target for 2015 of 17.8 GW of new added PV capacity.[27]

China added 12 GW of solar PV capacity in 2013 (one-third of the world total addition in the year), and then added another 10.6 GW of solar PV capacity in 2014 (one-fifth of the world total), reaching a cumulative total of 26.5 GW installed capacity. The target for additional capacity in 2015 has been set by the NEA as 17.8 GW – taking the cumulative total by then to 44 GW. The NEA/ND&RC has announced a 2020 cumulative target for solar PV to reach 100 GW and an interim target of 70 GW by 2017 – targets that would appear to be eminently achievable.[28]

In terms of China's domestic installations, where solar PV produces electric power for the Chinese grid, the uptake has been spectacular, starting with less than 1 GW up to 2010 but then expanding to 2 GW in 2011, nearly 4 GW in 2012, and jumping ahead to 16 GW in 2013 and 26 GW in 2014. Official targets for solar generation capacity are for 70 GW by 2017 and 100 GW by 2020 – a projected 100-fold expansion in the course of a decade.

In terms of resource availability, there is no shortage of sunlight as a resource in China or of semi-arid land for solar farms. It is estimated in the *Medium- and Long-Term Development Plan for Renewable Energy* that more than two-thirds of China's territory is suitable for solar energy production, with over 2,200 hours of sunshine annually, and solar radiation per unit area of over 5,000 MJ/m^2 (NDRC 2007). According to the CNREC, the energy received from sun radiation onto the county's land area is equivalent to 17 trillion tce annually in total. China has about 1.4 million square kilometres of desert, which can accommodate 50 TW of solar power capacity. In addition, there are about 20 billion square

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metres of building areas including roofs and wall areas facing south, on which 2 TW of solar capacity could also be installed.

The Chinese government has only recently taken steps to develop the domestic market for solar PV because it judged that with cost reductions so prominent the time had come when solar could compete effectively with thermal coal power. As with the wind power generation market, China's solar power generation industry is also dominated by large SOEs. For example, the top three solar power generation companies in 2013 were large SOEs including China Power Investment Co., China Energy Conservation Group and Guodian, all of which are central government-controlled SOEs. Their installed solar power capacity accounts respectively for 14 percent, 8 percent and 5 percent of China's total capacity.[29] Among the top ten solar power generation companies in 2013 three were private companies – consistent with the view that the Chinese government is using the solar PV sector as one where free market principles can be tried.

There are now several Chinese solar farm builders and operators, such as Powerway, a member of the SinoTech Power group, and a supplier of solar farm construction services around the world as well as in China. It won a contract with the Chinese firm Haier to construct a 10 MW solar farm on the rooftops of Haier's China factories, while it has bid for and won solar farm construction contracts in Burma, Pakistan, Algeria and other developing countries.[30]

Renewable energy manufacturing industries

Wind turbine manufacturing industry

China's renewable energy strategies are distinctive in that they encompass not just the promotion of renewable energy markets (as done in other countries) but the promotion of manufacturing of renewable energy systems, including wind turbines and solar PV cells. These industry promotion strategies have been highly successful. Chinese wind power firms are now strongly represented in the world's Top Ten firms, with Goldwind achieving #3 spot in 2014, and MingYang and Guodian United Power also retaining their spots, while Sinovel dropped out of the top 15. This continuing firm-level success is a triumph for Chinese wind power policy. Some of the firms involved, like Goldwind, are now innovative world leaders. (We shall examine case studies of these firms in the next chapter.) Table 3.2 shows how Chinese wind power firms now figure strongly in the world's top ten.

Unlike China's PV manufacturing industry (discussed in the next sub-section), the growth of the Chinese wind turbine industry has been predominantly driven by expansion of the domestic market (Figure 3.7), which in turn has been strongly affected by government policies.[31]

TABLE 3.2 *Market shares of top 10 wind turbine manufacturers, 2013*

Rank	Wind turbine manufacturer	Country of origin	Global market share (%)
1	Vestas	Denmark	13.1
2	Goldwind	China	11.0
3	Enercon	Germany	9.8
4	Siemens	Germany	7.4
5	GE Wind	USA	6.6
6	Gamesa	Spain	5.5
7	Suzlon Group	India	5.3
8	United Power	China	4.0
9	Ming Yang	China	3.5
10	Nordex	Germany	3.3

Source: REN (2014) *Global Status Report.*

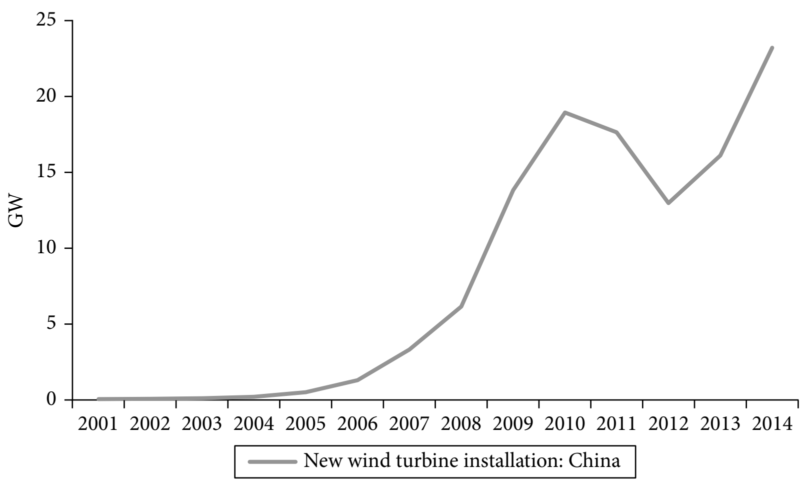

FIGURE 3.7 *Domestic wind power installation*

Source of primary data: China Wind Energy Association (CWEA).

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Before the mid-1990s, there were only small wind farm demonstration projects in China, funded and with equipment supplied by foreign countries such as Denmark, Germany and Spain. The Chinese indigenous wind turbine manufacturers started to engage foreign technologies in the late 1990s, and grew rapidly during the late 2000s. In this decade the sector experienced exponential growth, driven by favourable government policies and the growing global market. However, in the years 2011–2012, the market experienced its first setback. The oversupply of wind turbines prior to 2011 drove down prices, and some installed capacity was not fully utilized because of either the difficulty in getting access to the grid or by curtailment even after being connected with the grid. In addition, the rapid expansion also led to quality issues being experienced in a number of wind farms.[32] Facing severe competition and financial losses, some wind farm developers as well as wind turbine manufacturers exited the market. New installations fell from their first peak in 2010 (19 GW) to 13 GW in 2012. However, the market picked up again after 2013, as the industry was restructured and the curtailment issue was partially addressed. We emphasise that these are difficulties typical of an industry in a stage of rapid growth.

During the development of the Chinese wind power market, a number of indigenous Chinese wind turbine manufacturers have emerged as leaders. In addition to successful technological capability building through various approaches, two external key factors have been behind the emergence of Chinese wind turbine manufacturers in competition with foreign companies in the Chinese market.[33] First, overall cost advantages have provided a temporary advantage to Chinese newcomers in the market. For example, when the price of wind turbines fell, Chinese manufacturers were able to sell their turbines at a price of RMB 3,500 per kW while foreign companies such as Vestas were still selling at RMB 5,000 per kW or more. Second, Chinese companies benefited from the 'local content' policy that required 70 percent of the turbine content in concession wind power projects to be made locally. The top ten wind turbine manufacturers in China in terms of the shipment (MW) in 2014 are listed in Table 3.3; by this time all companies in the list were Chinese-owned firms.

Facing competition from local companies, foreign multinational corporations (MNCs), even with their technological advantages, have largely failed in the Chinese market. The share of foreign companies in the Chinese market dropped drastically from the initial level of 75 percent to

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TABLE 3.3 *Top 10 wind turbine manufacturers in the Chinese market, 2014*

Manufacturer	Number of wind turbines shipped	Wind turbine shipment, 2014 (MW)	Market share (%)
Goldwind	2794	4434	19.1
United Power	1568	2582	11.1
Mingyang	1208	2058	8.9
Envision	1026	1963	8.5
XEMC	889	1781	7.7
Sewind	846	1736	7.5
DEC	755	1298	5.6
CSIC (Chongqing) Hanzhuang	572	1144	4.9
Windey	503	898	3.9
Sinovel	365	729	3.1

Source: CWEA.

less than 10 percent in 2014. The ranking of Vestas in the Chinese market fell, from No. 2 in 2006, to No. 4 in 2008, No. 6 in 2009, No.8 in 2011, No. 10 in 2012 and No. 11 in 2013. The reasons for this decline on the part of foreign wind power firms can be debated, but clearly there has been vigorous promotion of domestic farms by both central and provincial governments as well as increasingly sophisticated strategies towards serving the domestic market on the part of Chinese producers.

While still a relatively small market compared with the domestic demand, the international market has become increasingly attractive to Chinese wind turbine manufacturers. According to the data from Chinese Wind Energy Association (CWEA), exports of Chinese wind turbines have increased from a mere 2.3 MW in 2007 to almost 700 MW in 2013, a 300-fold growth (Figure 3.8). Exports in 2014 dropped, possibly because Chinese manufacturers were more attracted to the booming domestic market in that year. Chinese wind turbine manufacturers are exporting their products not just to expected destinations such as the United States or Australia, but also to developing countries such as Ethiopia or Turkey, as shown in the following Table 3.4.

In recent years the Chinese wind turbine manufacturing industry has undergone major restructuring. Compared with the early years of the industry development, when a large number of small manufacturers rushed into the sector, several firms have now emerged as leaders through consolidation. Earlier scholars have observed that 'output in

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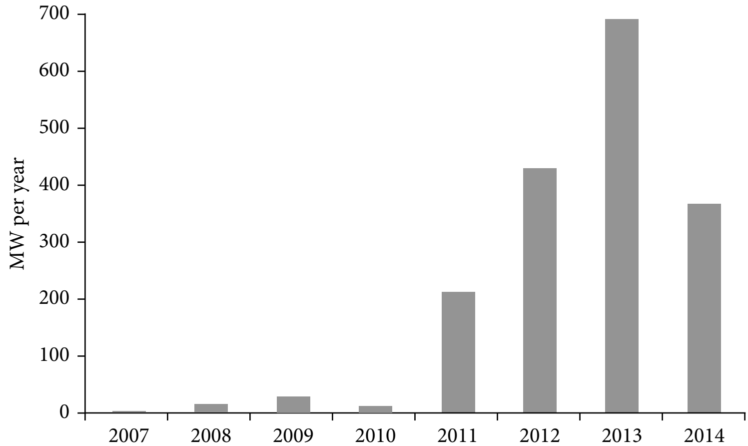

FIGURE 3.8 *Exports of Chinese wind turbines: 2007–2014*
Source: Based on CWEA (2014).

TABLE 3.4 *Top 10 Chinese wind turbine export destinations by the end of 2013*

Rank	Country	Sales (MW)*
1	United States	336
2	Australia	185
3	Ethiopia	135
4	Italy	91
5	Turkey	77
6	Panama	55
7	South Africa	54
8	Bulgaria	51
9	Romania	50
10	Pakistan	49

Note: * Delivered.

Source: Authors, based on CWEA (2014).

developing industries tends to rise over time at a decreasing percentage rate and price tends to fall over time at a decreasing percentage rate', and 'a number of developing industries have experienced a shakeout in the number of producers at some point in their history' (Klepper and Graddy 1990). We can confirm a similar phenomenon in the case of the Chinese wind turbine manufacturing industry; it seems that the industry was experiencing a plateau for the period 2010–2013, consistent with a phase of restructuring, after an initial period of rapid growth. Industry concentration declined largely because the market previously occupied by foreign MNCs was shared by local companies, before the market started to pick up in 2014. Many small companies that rushed into the market when it was booming withdrew during the period of major industry restructuring. Now the market positions of several leading firms, including Goldwind, United Power, Mingyang, Envision and XEMC seem to have stabilized. We shall discuss the strategies and performance of those companies in more detail in the chapter Five.

Thanks to learning effects and economies of scale, the cost of land-based and offshore wind power in China has continuously declined except in the mid-2000s when the soaring demand drove an increase and fluctuations of the cost. According to an estimate in the *China Wind Power Roadmap 2050* issued jointly by the Energy Research Institute of China and the IEA, the cost of large wind power farms in the northern, northeastern and northwestern areas of China (or the 'Sanbei' region) ranged from RMB 7,500 and 8,000 per kW in 2012 and 2013, while in projects in China's eastern and central regions the cost was about 9–10k per kW at that time. The cost of wind turbines accounts for about half of the total cost of wind farms. Offshore wind power is currently about twice as expensive as land-based wind power.[34]

Solar PV manufacturing industry

China's solar PV manufacturing industry has experienced a very different growth path compared with that of the country's wind manufacturing industry. While the domestic market has grown rapidly in recent years, historically the international market played a fundamental role in the rapid expansion of Chinese PV firms. Figure 3.9 shows the changing ratio of exports versus domestic sales by Chinese PV module manufacturers. Prior to 2010, over 95 percent of Chinese PV products were supplied to overseas markets. This ratio has decreased considerably in recent years, especially after anti-dumping investigations and/or measures taken by multiple foreign governments include those of United States, European Union, Canada and other countries against Chinese solar products. The share of exports in the total production of Chinese solar PV manufacturers has been falling (as the domestic market picks up), and reached just over 60 percent in 2013.

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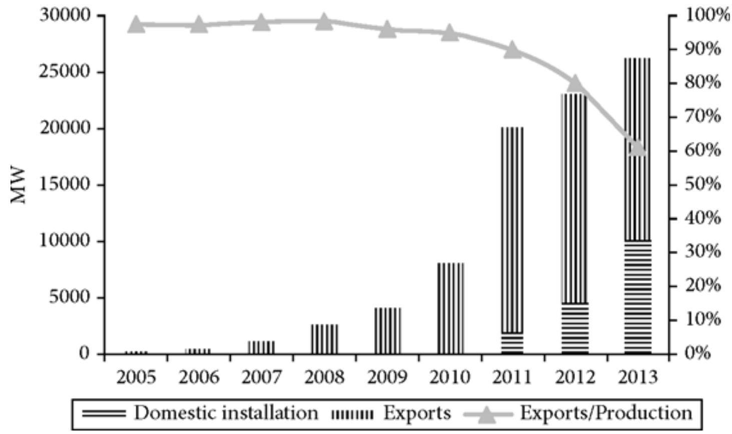

FIGURE 3.9 *Chinese solar PV production and exports*

Source: Authors. The data up to 2011 are available from New and Renewable Energy Yearbook; data of 2012 are from the Ministry of Commerce; data of 2013 are available from China Renewable Energy Industry Development Report 2014.

In this industry too growth has been spectacular. In 2008, Chinese manufacturers produced just 2 GW of solar PV systems, but in 2013 Chinese firms produced approximately 26 GW of solar cells, accounting for 65 percent of the global supply.[35] Among the top ten global PV module manufacturers in 2013, six were Chinese firms.[36] World output of solar cells reached 44 GW by 2014, and is increasing at a rate of 33 percent per year – driven largely by China. The largest Chinese solar module producers in terms of their shipments in 2013 are listed in Figure 3.10.

In 2014, while former Chinese leaders Suntech and LDK Solar have languished, the lead has passed to Trina Solar (now world #1) and Yingli Green Energy, followed by Jinko Solar, Canadian Solar and JA Solar – taking the top six positions in world rankings in 2014, according to the market research firm GlobalData. It is reported that five Chinese PV manufacturers, Trina, Yingli, Jinko Solar, Canadian Solar and JA Solar, produced 3.5 GW, 3.4 GW, 3.1 GW, 2.5 GW and 2.3 GW of solar PV modules respectively in 2014, or about 15 GW in total, accounting for close to 40 percent of the global new PV capacity installed (38.7 GW) in the year.[37]

As firms seek to enter an established industry as latecomers, a typical strategy observed is that they attempt to cover as much of

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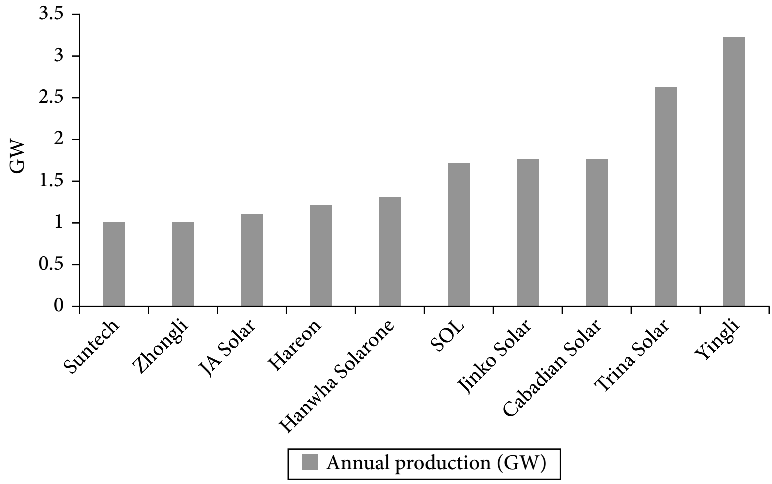

FIGURE 3.10 *Largest Chinese solar module producers, 2013*
Source: Authors. Based on data available from China National Renewable Energy Centre (2014).

the value chain as they can, through forward and backward vertical integration. This is done to minimize risks of supplier and/or customer hold-up. During recent years, Chinese PV firms have actively engaged in vertical integration through both downstream and upstream acquisitions and strategic alliances in systems integration (Table 3.5). This we view as a typical latecomer strategy. As in the wind power sector, China has made enormous efforts to build an entire value chain for solar PV (and now for CSP as well), and has a proliferation of private companies tumbling into every stage of the PV value chain. This has involved reducing China's dependence on imports of upstream purified silicon, and building up local Chinese suppliers such as GCL Poly.

The solar PV value chain created in China has concentrated on polysilicon production, making China less and less dependent on imports of this fundamental starting point from advanced firms in Europe (such as German Wacker Chemie) and Japan and the United States. In 2014 China produced 130,000 tonnes of polysilicon (up 50 percent on 2013), reducing imports down to 90,000 tonnes. This points to crystalline silicon being viewed in China as the dominant solar PV technology up to 2020 at least.

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TABLE 3.5 *Vertical integration model of the major Chinese solar PV firms*

	Polysilicon	Wafers/ingots	PV cells	PV modules	PV systems
JA Solar	√	√	√	√	√
Trina Solar		√	√	√	
Jinko Solar		√	√	√	
Canadian Solar		√	√	√	√
Suntech		√	√	√	√
China Sunergy			√	√	
Yingli	√	√	√	√	
Hanwha SolarOne	√	√	√	√	

Source: Based on Table 3.3. in Bayaliyev et al. (2011)) √: activities in which the company is involved.

The Chinese solar PV manufacturers have been hit hard by the anti-dumping duties and countervailing duties imposed by the European Union and the United States in 2013/2014. Nevertheless China's exports of solar PV modules continued to rise (reported increases of 14 percent in exports in the first half of 2014, to reach US$7.4 billion), and Japan became the largest importer of Chinese solar panels, accounting for $2.4 billion in the first half of the year.[38] The settlement of the United States–China solar PV trade dispute (discussed in Chapter 6) promises to allow Chinese firms to continue to export to the US market.

Energy-intensive industries

The rise of China as an economic powerhouse as well as a major export sourcing country has been built on the rapid expansion of the country's manufacturing sector, which in turn has been supported by its energy system. For example, a recent blog by Bill Gates has once again placed cement production in China under the international media spotlight, where he cited the statistics that China used as much cement in the three years, 2011–2013, as the United States used in the entire 20th century (4.5 Gt for the United States as against 6.6 Gt for China).[39]

Industrial production, particularly in a number of energy-intensive industries, has contributed significantly to the rapid growth of energy consumption registered in China and the high levels of energy intensity. Whereas in more developed countries it is transport and the commercial sector that account for most energy consumption, in China it is the manufacturing sector that accounts for 70 percent of total energy consumption (2.5 Gtce out of 3.6 Gtce in 2012), according to the NBS data. Within the manufacturing sector, there are six extremely energy-intensive industries that account for most of the energy consumption and for the country's still high levels of energy intensity. These six energy-hungry industries are steelmaking, non-ferrous metals, building materials, petrochemical, chemical and power generation; these six were responsible for no less than 77 percent of the energy used by the whole manufacturing sector in 2010.[40]

Soaring energy consumption was first and foremost due to the growth of manufacturing activities in those industries during the past decade, and the resulting scale of production for their products. During the period 2000–2013, China's production of cement and glass quadrupled, that of aluminium increased by 7.4 times, and production of steel increased by eight times, according to the NBS data. In terms of its share in global production, China accounted for about 46 percent of global aluminium production, 60 percent of global cement production, 50 percent of crude steel and about 50 percent of flat glass production in the world (Table 3.6). These proportions give an indication of the scale of China's production system and its energy appetite.

The high levels of energy consumption incurred by those industries is also due to their relatively elevated energy intensity compared with that in the corresponding industries in developed countries. It is estimated that energy intensities in terms of grams of coal equivalent per tonne of product in the Chinese cement, steelmaking and paper industries were 22 percent, 13 percent and 84 percent higher, respectively, than their corresponding industries in Japan in 2008.[41]

These energy- and pollution-intensive industries – commonly referred to in China as the 'two highs and one overcapacity' industries (in Chinese pinyin: *Liang Gao Yi Sheng*), meaning industries with high energy consumption, high pollution and overcapacity – have been the focus of sustained policy attention in China, encompassing energy policies, environmental policies and industrial policies. During the 11th FYP period (2005–2010) China had made some progress in this area, cutting the energy per unit of GDP in the steelmaking, non-nonferrous

TABLE 3.6 *Production from several energy-intensive Chinese industries*

Product	Production of China	Global Production	Share of the Chinese production in the world (%)	Chinese exports
Aluminium	22.1 million tonnes in 2013[a]	47.6 million tonnes in 2013[a]	46	3.5 million tonnes in 2012 (including aluminium, aluminium alloy and aluminium profile)[b]
Cement	2416 million tonnes in 2013[b]	4,000 million tonnes in 2013[c]	60	14.5 million tonnes in 2013[b]
Flat glass	779 million weight cases[b]	Approximately 52 million tonnes in 2009[e]	About 50[e]	195 million square meters in 2013
Crude Steel	822 million tonnes in 2013[d]	1649 million tonnes in 2013[d]	50	62 million tonnes in 2013[b]

Sources of data: [a] Aluminium – US Department of the Interior and US Geological Survey (2015), Mineral Commodity summaries 2015, available at http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf; [b] National Bureau of Statistics, China; [c] estimated by the US Geological Survey, available at http://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2014-cemen.pdf; [d] World Steel Association, available at http://www.worldsteel.org/statistics/statistics-archive/annual-steel-archive.html; [e] http://www.glassforeurope.com/en/industry/global-market-structure.php.

metals, petrochemical and chemical, and building materials (including cement) industries by 23 percent, 15 percent, 36 percent and 38 percent respectively. China had also phased out production capacities with low technology in selected industries, including 120 million tonnes in iron-making, 72 million tonnes in steelmaking, 370 million in cement and 11 million tonnes in papermaking respectively during the period 2005–2010.[42] The 12th FYP on energy efficiencies of China's industrial activities established by the Ministry of Industry and Information Technology (MIIT) sets a target for energy intensity of the manufacturing sector to be reduced by 21 percent in the period 2011–2015, and to reduce total energy consumption in the sector by 670 million tce compared with the 2010 level. The plan has also specified a number of targets and measures for reducing energy consumption in specific industries, as outlined in Table 3.7.

TABLE 3.7 *The energy intensity targets of selected products and key measures in the 12th FYP*

Energy Intensity (energy consumption in tce / tonnes of product, unless specified)	2010	2015 target	Key measures
Steelmaking	605	508	To phase out producing capacity with outdated technologies such as the basic oxygen furnace (BOF) or the electric arc furnace (EAF) with a capacity under 30 tonnes; to increase the adoption of advanced technologies including negative energy converter steelmaking, sintering waste heat power generation etc. and achieve their adoption rates to 65%, 20% and 40% respectively
Aluminium (kwh of electricity per tonne of product)	14013	133,300	To promote new smelter technologies and to achieve an adoption rate of 80% by 2015
Cement	115	112	To promote the power generation technology using waste heat from cement kilns, and achieve an adoption rate of 60% by 2015
Flat glass	17	15	To promote the power generation technology using waste heat from glass kilns, and achieve an adoption rate of 30% by 2015
Paper	1130	900	To phase out production lines with capacity of 34k tonnes or below for the non-wood pulp technology, and 51k tonnes or below for the chemical wood pulp technology.

Source: Ministry of Industry and Information Technology (2012), The 12th Five Year Plan for Energy Efficiency in the Industrial Sector.

Energy production, distribution and utilization have been central to the Chinese manufacturing revolution – not least in the energy-intensive sectors that have grown rapidly to world prominence and are now the subject of sustained policy attention to rein in their levels of energy consumption. But one industry stands out in China as the central driver and shaper of the renewable energy revolution – and that is the electric

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power industry itself. We now turn to examine the processes and policies that are shaping the further electrification of China, and the industrial dynamics in its power sector.

Notes

1 See, for example, Geroski (1995) or Klepper and Graddy (1990).
2 http://www.ce.cn/cysc/ny/gdxw/201501/25/t20150125_4424351.shtml (in Chinese).
3 https://uk.finance.yahoo.com/news/china-april-coal-output-down-065855019.html
4 This chart is to be compared with Figure 1.1, with which it is consistent.
5 The China Coal Price index was 186.2 in June 2012, and 137.3 in January 2015. See http://www.coalchina.org.cn/page/zt/120712/ (in Chinese).
6 See 'China's coal industry freezes over', *China Daily*, 25 January 2015, at: http://usa.chinadaily.com.cn/business/2015-01/25/content_19402093.htm
7 See 'China Shenhua Energy coal sales down 12.4 pct in 2014', Reuters, 10 February 2015, at: http://uk.reuters.com/article/2015/02/10/china-coal-shenhua-idUKL4N0VK4S920150210
8 See 'More signs of peak coal as China's Shenhua forecasts 10% sales decline', *RenewEconomy*, 23 March 2015, at: http://reneweconomy.com.au/2015/more-signs-of-peak-coal-as-chinas-shenhua-forecasts-10-sales-decline-35119
9 Compared with Collier and Venables (2014).
10 Marketline (2014) Industry profile: Oil and gas in China, Datamonitor Group, London.
11 The Three Gorges system operates 32 generators, each rated at 700 MW – or 22 GW at full capacity – plus two smaller generators of 50 MW each to run the hydro plant.
12 See 'Yingli and consortium partners to install 233 MW of PV in Algeria in 2014', *Photon*, 17 December 2013, at: http://www.photon.info/photon_news_detail_en.photon?id=83170
13 http://www.china.org.cn/business/2013-01/06/content_27606925.htm
14 http://af.reuters.com/article/energyOilNews/idAFL4N0XC40G20150415
15 See, for example, the report of the projected merged shareholdings between the Three Gorges Dam Corporation and the China Guangdong Nuclear Power Group, in the online *People's Daily*, at: http://english.peopledaily.com.cn/90001/90778/90860/6968306.html
16 http://export.gov/china/doingbizinchina/leadingsectors/eg_cn_081029.asp
17 http://www.world-nuclear-news.org/NP-UK-government-paves-way-for-Chinese-nuclear-plant-18061401.html
18 http://www.bbc.com/news/uk-politics-30778427

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19 One TWh is equivalent energetically to 0.123 Mtce.
20 China National Renewable Energy Centre (2014) *China Renewable Energy Industry Development Report 2014*, Beijing.
21 See a commentary piece by one of us on the protest over a waste incineration project for electric generation in Hangzhou, China, published in UK *Financial Times China* at http://www.ftchinese.com/story/001056269?full=y
22 See the GWEC world report for 2014, at: http://www.gwec.net/wp-content/uploads/2015/02/GWEC_GlobalWindStats2014_FINAL_10.2.2015.pdf
23 See, for example, Matthew Wald, 'Wind energy bumps into power grid's limits', *New York Times*, 26 August 2008, at: http://www.nytimes.com/2008/08/27/business/27grid.html
24 See: http://www.clypg.com.cn/en/latestnews/latestnews/309534.shtml
25 See 'Chinese nuclear group to buy UK wind farms', *Financial Times*, 16 December 2014, at: http://www.ft.com/intl/cms/s/0/db8c9540-838f-11e4-9a9a-00144feabdc0.html#axzz3V4Txzf7m
26 BP 2014 *World Energy Statistical Review.*
27 http://zfxxgk.nea.gov.cn/auto87/201503/t20150318_1891.htm (in Chinese).
28 Data from the first quarter of 2015 (reported in *RenewEconomy*) indicate that 5 GW of solar PV capacity was added, while senior executives of the leading firms Trina Solar and Yingli Green Energy indicated that the 2020 targets are likely to be exceeded because of wider diffusion of rooftop solar.
29 CNREC (2014) China Renewable Energy Industry Development Report 2014, Beijing (in Chinese).
30 See the company website at: http://www.pvpowerway.com/en/
31 See CEWA (2015), China Wind Power 2014 Statistics, available from www.cwea.org.cn
32 Wang C. et al. 2015. 'The analysis of China wind power industry', *Journal of Chongqing University*, 38(1) 148–154 (in Chinese).
33 Zheng, F. (2014), Vestas failed in the Chinese market. Foreign Investment in China, 9, 62–63.
34 At the same price level, the cost of land-based wind power in China would fall to RMB 7,500 per kw in 2020, RMB 7,200 in 2030 and 7,000 in 2050; and that of offshore wind power would drop from the current level of cost at RMB 14,000–19,000 per kw, to RMB 14,000 per kw in 2020, 12,000 in 2030 and 10,000 in 2050.
35 China National Renewable Energy Centre, 2014. China *Renewable Energy Industry Development Report*, Beijing.
36 REN21 (2014) *Global Status Report*.
37 http://www.pv-magazine.com/news/details/beitrag/iea-pvps--177-gw-of-pv-installed-worldwide_100018832/#axzz3XS9eRPO7
38 See 'China sees robust PV exports to Japan', *China Daily*, 22 November 2014, at: http://europe.chinadaily.com.cn/business/2014-11/22/content_18959213.htm

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39 Bill Gates in his blog, reviewing the book by Vaclav Smil, 'Making the Modern World: Materials and Dematerialization', 25 June 2014, at: http://www.gatesnotes.com/About-Bill-Gates/Concrete-in-China

40 The 12th Five Year Plan for Energy Efficiency in the Industrial Sector, at: http://jns.miit.gov.cn/n11293472/n11295091/n11299485/14480445.html (in Chinese).

41 See an estimate based on data from *China Energy Yearbook 2011* by Guo, G. F. and Wang, Y. P. (2013) Analysis on the Potential and Target of China's Industrial Energy-saving in 12th Five-Year Plan Period (2011–2015), China Industrial Economics, 300(3), 46–58.

42 The 12th Five Year Plan for Energy Efficiency in the Industrial Sector, at http://jns.miit.gov.cn/n11293472/n11295091/n11299485/14480445.html (in Chinese).

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4

Transformation of the Electric Power Sector – Creating a 21st Century Infrastructure

Abstract: *The electric power sector is the industry that is one of the highest energy producers, highest energy consumers and highest carbon emitters in China. So this is where the energy revolution has to start. The transformation of the grid is a national infrastructure project, creating a 'strong and smart' grid as well as complementary projects such as the high-speed rail programme, where China is now the world leader in energy-efficient intercity transport. China's efforts to move to the technological frontier are clear, as can be demonstrated through analysis of patents, standards and public expenditure on the modernizing electric power grid. Efforts to improve energy efficiency, such as in thermal power stations, are also an important part of the process.*

Keywords: electric power; government investment in new industries; high speed rail; high-voltage transmission; local content requirements; power generation industry; smart grid

Mathews, John A. and Hao Tan. China's Renewable Energy Revolution. Basingstoke: Palgrave Macmillan, 2015.
DOI: 10.1057/9781137546258.0011.

As China industrializes and urbanizes, it is becoming a modern society with an electrically powered economy. The electric power sector is the major energy sector, the major producer of energy, a major consumer of energy and the major source of carbon emissions. If there is to be a revolution in China's energy sector, it has to start then in the power generating sector.

We begin this chapter with a description of the trends associated with the changing patterns of power generation and consumption based on the latest data in 2014. We then examine several main groups of stakeholders in the power industry and document their main activities, focusing on the major power generation companies, the national grid companies and their smart-grid and UHV transmission projects, and the power generating equipment companies. We then compare the development of the power industry with that of high-speed rail (HSR), drawing parallels between the capacity-building activities of both sectors through investment in national infrastructure. Finally we discuss the drivers of the transformation of the power industry, focusing on two profound forces, namely the changing technological regimes (encompassing technological improvements and learning curves) and government policies.

Is China's electric power system greening or further blackening?

China's energy system generally, and its electric power system in particular, is still largely based on fossil fuels consumption – just like every rising industrial power in history since the industrial revolution.[1] But China's energy system is also greening – far faster than any other comparable-sized system on the planet. Many commentators continue to insist on the black character of China's electric power system – but ignore the greening tendencies. In a widely reproduced blog posting, Armond Cohen (executive director of the Clean Air Task Force in the United States) claimed that in 2014, 'the amount of new coal energy added to the China grid ... exceeded new solar energy by 17 times, new wind energy by more than 4 times, and even new hydro by more than 3 times'.[2] This assertion is meant to imply that China's electric power system is getting blacker rather than greener. Such an interpretation of what happened in China's power sector is wrong. We use the latest 2014 data to demonstrate why it is wrong.

The data to disprove these assertions are to hand, provided by the China Electricity Council. We use three sources of data to demonstrate that greening tendencies outrank blackening (fossil-fuelled) tendencies. These are data for 2014 electric energy generation (real generation, as compared with the 'putative' generation utilized by Cohen – as discussed in a moment); data for 2014 electric capacity additions; and data for investment in the electric power grid. All three sources demonstrate a greening tendency that outranks a blackening tendency.

Electric energy generation

Data are now available from the China Electricity Council for real electric energy generation added to the system in 2014 from multiple sources. The headline results are that China generated less power from thermal (fossil fuel) sources in 2014 than in 2013, that is thermal power generation actually decreased in 2014. This is an extremely important milestone. By contrast, power generation from non-thermal sources increased by 19 percent – and strictly green sources, encompassing water, wind and solar (WWS), increased by 200 TWh, or 20 percent. This is the greening edge of a huge power generation system.

Here are the data. China's power system generated 5,545 TWh of electricity in 2014, an increase of 173 TWh over the 2013 total, or overall growth of 3.2 percent. So the system as a whole is still growing – but not as fast as the economy as a whole (an important decoupling). Thermal (mainly coal burning) sources generated 4,173 TWh in 2014, down by 48 TWh from the 2013 total (or a decrease of 1.1 percent) – *the first reduction in thermal power generation in recent times*. Non-thermal sources by contrast accounted for 1,372 TWh of electric energy generated in 2014, up 221 TWh on the 2013 total. Strictly green sources (WWS) generated 1,245 TWh in 2014, up 200 TWh on the 2013 total (an increase of 20 percent). Nuclear generated 126 TWh, up 14 TWh on the 2013 total (+13 percent.). So in terms of changes to the system in 2014, thermal was reduced by 1.1 percent while green increased by 20 percent. The most drastic growth was seen in solar power generation, up by 175 percent.

We present these data in Figure 4.1(a and b), the first part of which shows the 2014 additions (positive as well as negative) to the Chinese electric power generation system, in TWh, and the second part the percentage additions.

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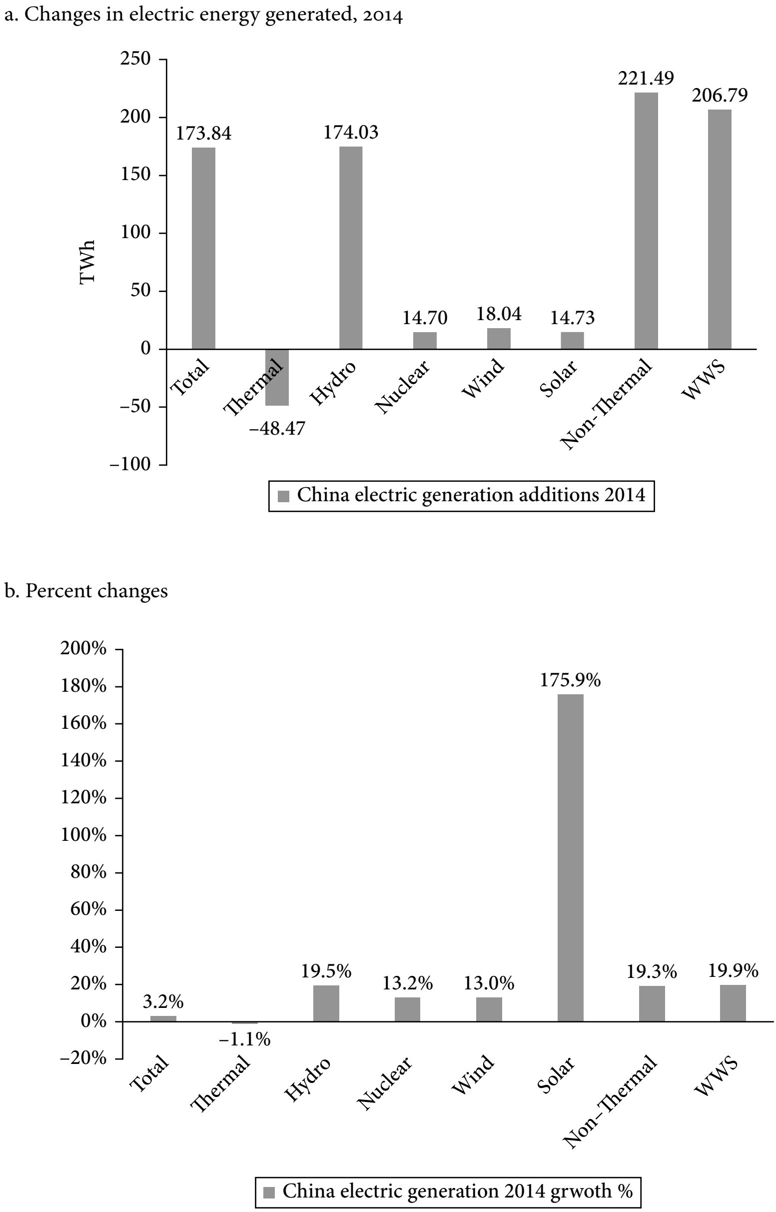

FIGURE 4.1 *China electric generation additions (real) in 2014*
Source of primary data: China Electricity Council.

Our figure differs radically from the chart produced by Armond Cohen, referred to above. His chart shows 'notional' additions to thermal generation of 240 TWh compared with notional additions for water of 65 TWh, wind of 57 TWh and solar of 14 TWh; nuclear, he shows as a notional addition of 42 TWh. He concludes that China added an extra (notional) 240 TWh from coal and only (notional) 136 TWh from WWS (plus 42 TWh from nuclear), so according to Cohen the system is getting increasingly 'black'. But this is a false conclusion based on a misinterpretation of the data. In reality the system is greening at the margin, with actual thermal contribution to electric energy generated reducing by 29 TWh in 2014 and actual WWS sources increasing by 200 TWh – much higher than Cohen allowed for with his notional data.[3]

It is also worth noting that wind generated electricity continued to exceed nuclear (for the third year running). And solar power sources also outranked nuclear at the margin, with additional energy generated from solar (14.73 TWh) marginally exceeding that from nuclear (14.70 TWh). This puts paid to arguments that China will be dependent on nuclear for non-carbon sources of electric power.[4]

We elaborate on these data by showing historic trends in China's thermal (Figure 4.2[5]) and non-thermal (WWS plus nuclear) power generation (Figure 4.3). Note that we showed changes in the total system's

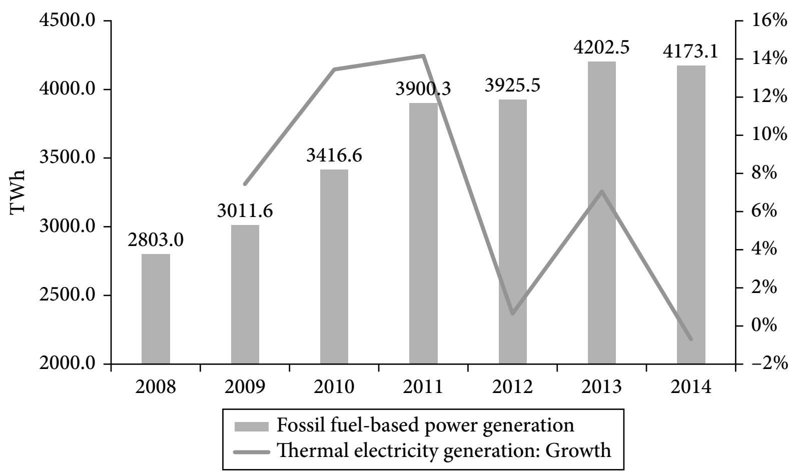

FIGURE 4.2 *China: fossil fuel-based power generation and its growth, 2008–2014*
Source of primary data: China Electricity Council.

DOI: 10.1057/9781137546258.0011

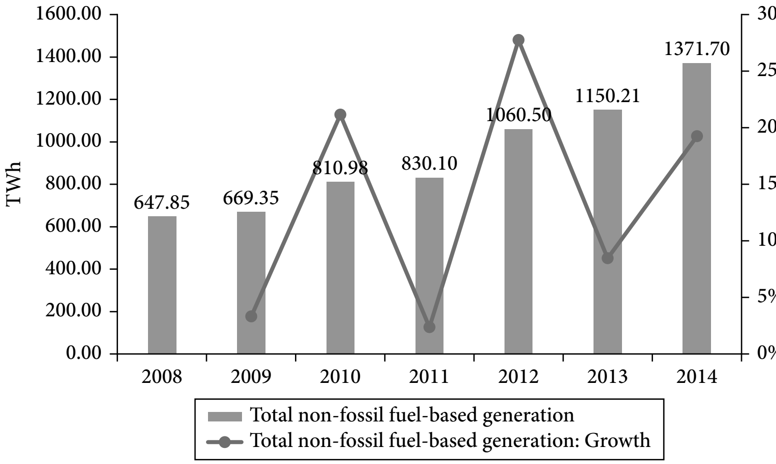

FIGURE 4.3 *China: total non-fossil fuel-based electricity generation and its growth, 2008–2014*

Source of primary data: China Electricity Council.

composition (thermal vs. non-thermal) over the past six years in Figure 2.9 in Chapter 2.

Generating capacity

A second source of evidence on the greening of China's electric power system is provided by data on generating capacity itself. This does not give as accurate a picture of greening or blackening tendencies because of varying capacity factors for wind, solar, nuclear and thermal and their varying utilization hours from time to time – but when compared year by year the data do indeed indicate a trend in the generating capacity of the different sources.

The headline result is that in 2014 China increased the capacity of its electrical generating 'machine' to 1.36 trillion watts (TW) – by far the largest such power generating machine on the planet. (The US generating system stands at just over 1 TW.) In 2014 China increased its non-thermal generating capacity by more than its thermal capacity – for the second year in a row. This is a second indicator of greening. In 2014 China increased its thermal generating capacity by 45 GW, reaching a total of 916 GW; while it increased non-thermal capacity by a larger amount, 56 GW, reaching a total of 444 GW. Strictly green sources (WWS) added

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capacity of 51 GW or 14 percent growth – again, in excess of thermal capacity added.

There is an immediate issue to address in these data. How could China add thermal capacity in 2014 but decrease its actual electric energy generation from thermal sources? There is an entirely plausible reason for this. The reason is reduced utilization of thermal capacity in 2014, as thermal power production was cut back in face of competition from non-fossil fuel-based power, as well as because of central government mandates. By contrast the utilization of WWS capacity was increased, diminishing the curtailment levels that had been keeping wind power under-utilized. (Curtailment refers to non-use of an energy source, by switching off its connection to the grid; thus power can still be generated, but is not utilized by the grid as a whole.) This also provides a plausible explanation for the difference between Cohen's notional results, discussed above, and our results based on actual generation data.

The data for generation capacity can be elaborated as per the following Figures 4.4 (thermal capacity) and 4.5 (non-thermal capacity). We showed changes in proportions of electrical generation capacity in Figure 2.7 in Chapter 2. Note how fossil fuel-based power generating capacity has continued its growth at a modest rate (5.2 percent in 2014). The

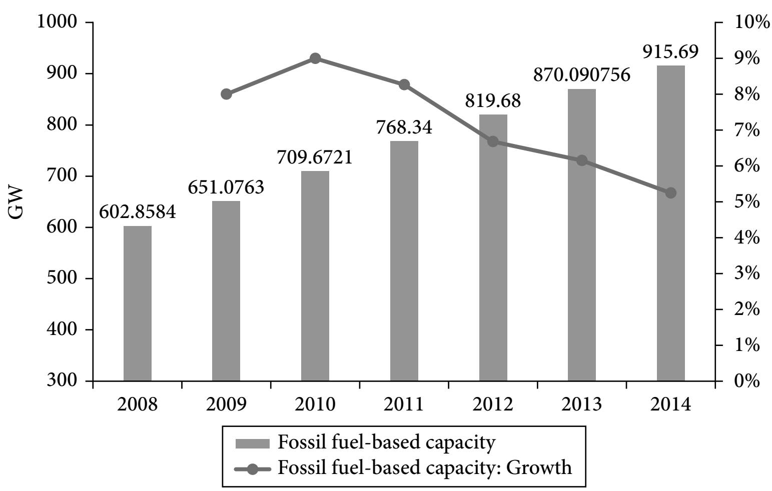

FIGURE 4.4 *China: fossil fuel-based power generating capacity and growth 2006–2014*

Source of primary data: China Electricity Council.

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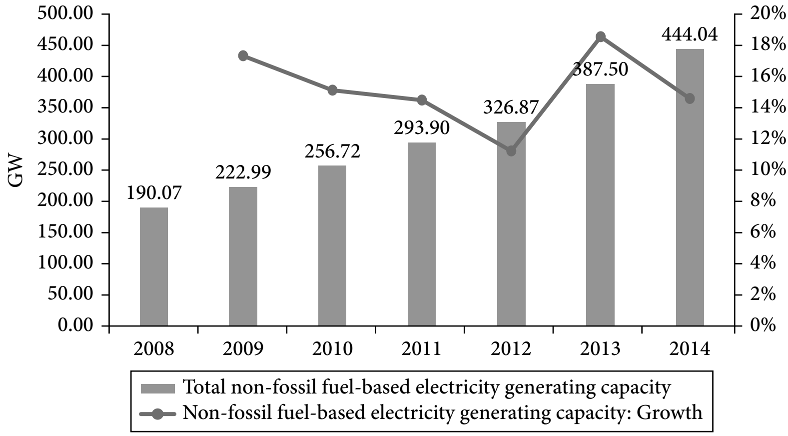

FIGURE 4.5 *China: total non-fossil fuel-based electricity generating capacity and growth 2008–2014*

Source of primary data: China Electricity Council.

decline in fossil fuel-based power generation discussed above, therefore, was presumably due to a fall in the utilization hours in existing thermal power facilities).

Total non-fossil fuel-based electricity generating capacity has grown with a rate ranging from 11 percent to 19 percent during the past six years. China's non-thermal generating capacity, at 444 GW, is far higher than that of any other country. Its strictly green generating capacity (from WWS sources) stands now at 424 GW, with capacity addition in 2014 of 51 GW (meaning that a 1-GW non-thermal power station was added each week, on average). This 424 GW of green generating capacity shows just how much China is investing in the building of this enormous green infrastructure – contradicting the nay-sayers in the US Congress who greeted the US-China Climate Change Accord of 2014 as meaning that China would be 'doing nothing' until 2030. On the contrary, China is building the largest green power source on the planet.

China's official targets for renewable energy capacity additions appear to be fully attainable in light of these 2014 results. The ND&RC issued fresh targets for wind and solar PV in 2014, namely that China would have capacity of 70 GW solar PV and 150 GW wind power by 2017.[6] In capacity terms, it is correct to state that China now has raised its non-thermal capacity to close to one-third of its total power system (and its

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strictly WWS green capacity to 31 percent) – in excess of official targets as outlined in the 12th FYP and subsequent energy policy statements. The Energy 12th FYP issued in 2013 projected that China's non-fossil-fuelled generating capacity would reach 30 percent by 2015 – a target now already exceeded.

Power grid investment

A third source of data regarding the greening versus non-greening of the electric power system is investment. Again the data indicate that China is investing more heavily in green sources of electric power than in non-green (thermal). Indeed China is investing more in its green energy system than any other country. Investment in thermal generation facilities has consistently declined, from RMB 167 billion in 2008 to RMB 95 billion in 2014 (approximately US$ 15.2 billion), while investment on non-thermal sources has increased, from around RMB 118 billion in 2008 to at least RMB 252 billion in 2014 (approximately US$ 40.3 billion). (We cannot be more precise because of a lack of data on investment in wind and solar power for several years during the recent period.) Total investment in the different energy sources in the years up to 2014 are shown in Figure 4.6.

Note that investment in both wind and hydro outranked investment in nuclear sources in 2014. In terms of the investment in electricity

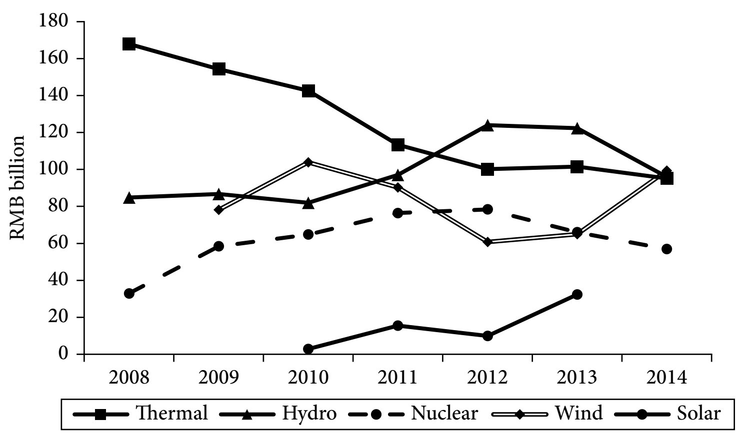

FIGURE 4.6 *China: investments in the electric power grid by sources*
Source: Authors. Based on primary data from CEC.

generation capacity based on different technologies, the share of investment in renewable (WWS) electric generation has increased steadily, from 32 percent of the total in 2007, passing 50 percent in 2011 and reaching 59 percent in 2013. Adding the investment in nuclear power, the proportion of investment in all non-fossil fuel-based electric generation increased from less than 30 percent in 2005, to 37 percent in 2007 to 75 percent in 2013 while investment in thermal power plants declined from 71 percent to 25 percent during the period between 2005 and 2013. The level of investment in non-fossil fuels-based electricity generation declined slightly in 2014, according to data released from the China Electricity Council in February 2015, *but was still staying high at a level of 74 percent*. We depicted these trends in Figure 1.6 in Chapter 1.

The transformation of the Chinese electric power industry that we have documented is in fact a joint result of the activities carried out by many stakeholders in the industry. In the next section, we examine some of those stakeholders and the strategic drivers of their recent activities.

The electric power industry and its principal stakeholders

The electric power industry is defined as the aggregation of the activities of power generation, transmission, energy storage, distribution and retail sales of electricity. Until 2002 electric power generation and distribution in China was controlled through the State Power Corporation (SPC). This central monopoly was disbanded by the State Council in 2002 and competing state-owned entities were established, encompassing grid operators, power generation companies and other investment firms. The power generation industry is now dominated by the 'Big Five' – Huaneng, Huadian, Guodian, Datang and China Power Investment Co (all central-government-owned SOEs). Those five largest power generation groups account for more than half of the electricity generation in China.[7] There are also four smaller but still significant players. The 'Smaller Four' include Guohua Power, which is the power generation arm of the largest coal company, Shenhua; China Resource Power, SDIC Electrical Power, which is a subsidiary of the State Development Investment Corporation, and China General Nuclear Power Group.

Table 4.1[8] reports some of the main performance indicators for the Big Five plus Guohua, in 2014, drawing attention to the extent to which they generate renewable power.

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TABLE 4.1 *Main performance indicators of Big Five plus Guohua*

Power generation company	Huaneng	Huadian	Guodian	Datang	China Power Investment Co.	Guohua
Main business income (RMB billion)	288	215.7	215.4	189	180	69
Profit (RMB billion)	n/a	20.5	19.5	14	10	17.8
Power generation (TWh)	646	501	501	497	380	184
Installed power generation capacity (GW)	151	122	123	120	967	348
Coal consumption in power generation (g coal per kWh)	310	310	313	313	310	309
% of capacity based on clean energy sources	27	>30	24.8	25	38.5	n/a

Source: Authors. Based on a report published in *China Electricity Newspaper*.

Note in particular the proportion of renewable/cleantech sources for the major power generation companies – some of which are switching to clean sources faster than the country overall. All power generation companies in the Big Five increased their share of renewables/clean technology sources compared with 2013 (with the exception of Datang, which slipped to 25 percent from 25.7 percent the year earlier). These large power generation companies are state-owned enterprises operating in heavily regulated markets (where the price of coal and electricity is set by government, not by supply and demand). They are all investing heavily in renewable sources of energy, in line with central government targets.

Grid companies and smart grid implementation 2010–2020

China does not yet have an integrated national power grid. Instead it has six grids that are interconnected, five of which are operated by the State Grid Corporation of China (SGCC) while the southern grid around Guangzhou is operated by China Southern Power Grid Corporation (CSPGC). The two companies were set up in 2002 following the breakup of the previous monopoly, State Power Corporation. We will examine the case of SGCC below.

The most important of China's investments in renewable energy technologies is its building of a new, integrated 'smart grid', over the ten years 2010 to 2020, which will be capable of carrying China's expected 7,000-plus TWh load of electrical current anticipated by 2020 (compared with

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5,000-plus TWh now) – derived from a variety of intermittent sources, with minimal transmission losses. This is the biggest nation-building project that China has underway – comparable in every way (and even more important) than the gargantuan fast-rail network that is also being built over the same decade.

China is leapfrogging the rest of the world in its smart grid implementation in both the scale of the development (far larger and compressed in time than anywhere else) as well as in the choice of carrying technology, namely ultra-high-voltage current. These are fundamental technology choices, implemented with national standards enforced through the state-owned power grid companies SGCC and CSPGC – a clear latecomer advantage insofar as standards battles are avoided (or are confined to the internal processes of the bureaucracy) and once the decisions are taken, implementation can be rapid. The SGCC announced in 2009 that it would be investing RMB 600 billion (US$ 88 billion) over the ten years 2010–2020 in its new HVDC transmission systems and in IT-enabled 'smart grid' upgrading – and then this huge investment was in turn upgraded as part of China's 2009 Stimulus package. The SGCC invested RMB 340 billion in its grid in 2014, and is expected to invest a further RMB 420 billion (US$ 67.7 billion) in 2015. These sums dwarf the levels of investment carried out in other countries.

In 2013 China overtook the United States in spending on smart grid projects proper, ratcheting up US$ 4.3 billion for the year while the United States slipped back to US$ 3.6 billion – according to Bloomberg New Energy Finance. This reflected China's accelerating expenditure on smart meters (installing 60 million for the year) as well as sensors and intelligent management systems (distribution automation) and EV charging infrastructure. McKinsey estimated in 2010 that China's smart grid market itself could total $20 billion annually by 2015.[9]

The ND&RC has plans for a national grid of six corridors by 2015 – three N–S lines and three E–W lines ('3 plus 3') – with more being added by 2020. Figure 4.7 depicts the projected network of UHV power lines that will knit together the integrated, 'smart grid' in China.

Development of ultra-high-voltage transmission technologies

China's plans for a 'strong and smart grid' are based on the vision of a 21st century infrastructure favourable to multiple intermittent sources coordinated via IT – as well as more prosaically the fear of power brownouts

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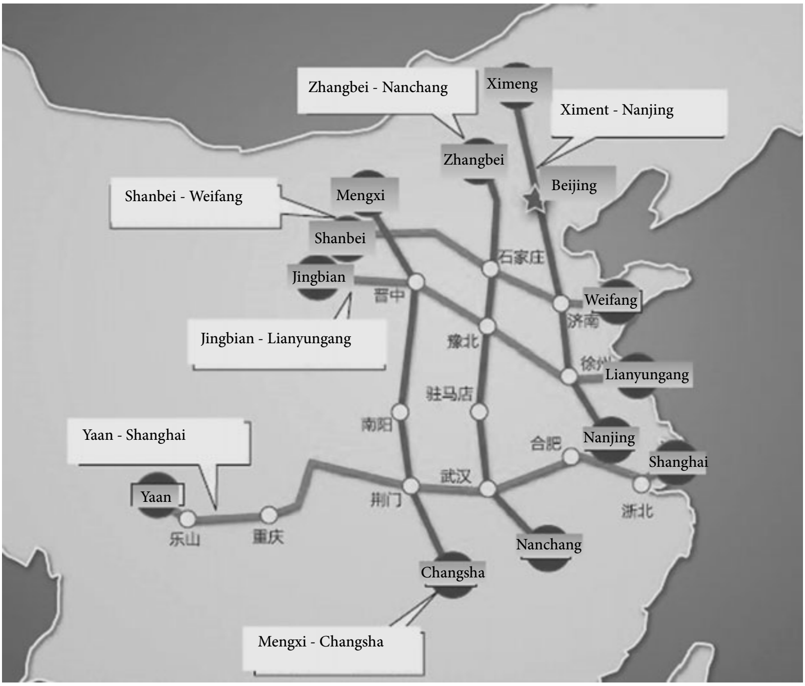

FIGURE 4.7 *China's UHV plan for the strong and smart grid*

Source: Authors. Based on http://www.chinapower.com.cn/newsarticle/1229/new1229778.asp.

and blackouts that have plagued the country during its years of ultra-fast growth. UHV transmission technologies include those in two categories, namely those based on the alternating current technology, that is UHVAC, with the voltage level over 1,000 kV; and those based on the direct current technology (UHVDC), at a voltage of ±800 kV.

There is a consensus in China on the need to upgrade its power transmission system, for two main reasons. First, many of the major power sources in the western regions are distant from the country's main electric load in the coastal areas, and the two need to be connected more efficiently. Second, the ever-growing electric generation based on renewable energy sources needs to be better accommodated and integrated in the electric power system through a smarter grid. The goal of 'developing large-capacity, high-efficiency, long-distance power transmission technologies such as ultra-high-voltage power transmission' is explicitly stated in the country's 12th FYP (2011–2015).[10]

The plan to build a national super-grid based on UHV technologies was first released by SGCC in 2004.[11] In 2006, SGCC started its first demonstration project, with a total investment of just RMB 6 billion. Since the emergence of the plan, the choice between the new UHV technologies and the existing, competing extra-high voltage (EHV) technologies, and that between the two UHV technologies, that is ultra-high-voltage direct current (UHVDC) and Ultra-high-voltage alternating current (UHVAC), as the technology underpinning the 'backbone' of the national power grids, has been a subject of heated debate in China for the last decade.

While UHV transmission projects have already been built in several countries, most of them were of small scale or even experimental in nature. A large-scale UHV transmission system as contemplated by China is unprecedented and requires considerable technological sophistication. For this reason, critics of building a national super-grid based on the to-be-developed UHV technologies, especially the UHVAC technologies, argue that the investment required for developing the new technologies is excessive, and may even put at risk the reliability of the national grid if implemented, which is of huge concern to the national economy and security.[12] Some have questioned the motivation of SGCC in making such a move, and argued that SGCC's large investment is to disguise profits, or to maintain its monopolistic position or even to set the conditions where it will have to become the only national grid company in the future.[13] Our focus by contrast is on the size of the investment and the commitment it indicates to upgrade the grid to make it 'strong and smart'.

SGCC argues that the development of UHVAC as the underlying technology for the backbone project is not only feasible but also necessary, both technologically and economically. In a series of articles, the chairman of SGCC, Liu Zhenya, suggests that UHVAC is a 'resource saving, environmental friendly and advanced technology',[14] which, as he argues, is particularly suitable for the needs of China's energy system as it develops towards 2020. SGCC also makes two additional arguments for development of UHV technologies, based on their being able to support clean energy sources, and provide stimulus for China's electric equipment manufacturing industries.[15] On the latter, thanks to SGCC's efforts, development of UHV technologies has been listed as a priority in several government policy documents, and is recognized as an important national industrial development goal.[16] In 2011, SGCC announced

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that the company will be committed to construct three vertical and three horizontal national transmission corridors as part of the national UHV backbone project, according to its company-level 12th FYP.[17] By the end of 2014, SGCC had in fact built seven UHV projects, two based on the AC technology and three with the DC technology.[18]

In April 2014, after several years of controversy, the State Council finally gave its blessing to the UHV technologies, and SGCC describes this as a start of 'a golden era' for the smart grid in China.[19] The company is accelerating its investment in UHV projects, and is expected to commence a further 14 UHV projects in 2015, including six UHVAC projects and eight UHVDC projects.[20]

As reported in Chinese media, SGCC's 13th FYP which covers the period between 2016 and 2020 has the target to complete the main backbone consisting of three vertical and three horizontal national transmission corridors plus the 'ring', as well as many more DC transmission projects including UHVDC projects. These national corridors demarcate a national power grid that is in every way comparable to the similar national HSR grid being built over the same decade, 2010–2020, and both are comparable to the construction of a national highway system in the United States in the 1950s (thus locking the United States into an oil-based system of transport). China's 21st century counterpart is a post-carbon system that will lay the groundwork for renewable energy technology industries that are likely to be world leaders in the 21st century.

As mentioned above, the SGCC invested RMB 340 billion in its grid in 2014, and is expected to invest a further RMB 420 billion (US$ 67.7 billion) in 2015. China indeed is now investing more in its transmission system than in power generation systems, with the trends revealed in Figure 4.8.

The smart grid investments will not only build a high-capacity national transmission system, but one that is subject to IT-enabled control, and in particular one that is capable of accepting fluctuating input from various renewable energy sources. This is the key to the 10-year national smart grid project 2010–2020 as providing the foundation for building a modern electric power system capable of taking inputs from a vast range of fluctuating sources and integrating them in real time subject to intelligent control.[21]

Large-scale energy storage systems

As well as promoting a variety of leading-edge generation projects (wind and solar farms) and distribution/transmission projects, China is also actively developing large-scale energy storage projects, based on

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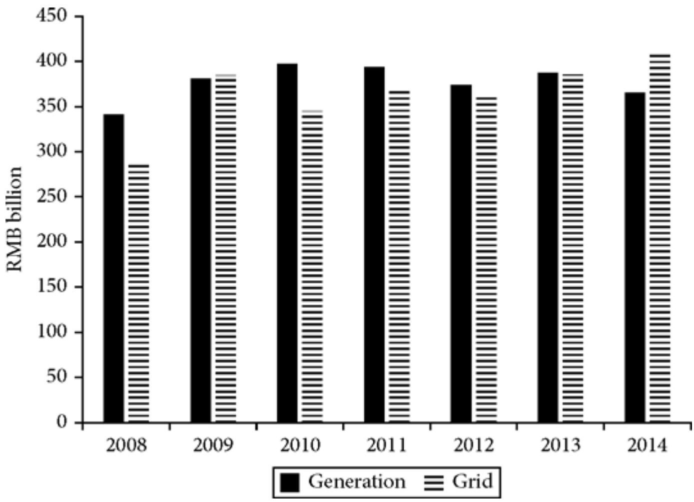

FIGURE 4.8 *Investment in electric power: generation vs. distribution*
Source of primary data: China Electricity Council.

lithium-ion batteries as dominant technology. These projects constitute the third element in a comprehensive transition of the electric power grid to a system based on renewables.

Great excitement greeted the announcement from the US firm Tesla of its commercial and industrial scale energy storage systems in May 2015, at prices that brought energy storage within reach of all. The announcement is backed by Tesla's rapid building of its lithium-ion battery manufacturing plant in Nevada, the 'gigafactory'.[22] But China is already well advanced along this path. The State Grid Corporation of China (SGCC) completed an initial project directed towards large-scale energy storage in 2011, at Zhangbei in Hebei province. Termed the 'National wind and solar energy storage and transmission demonstration project', it operates with an initial energy capacity of 36 MWh (and at 6 MW power output). The SGCC chose Chinese battery company BYD as supplier, utilizing its iron phosphate Li-ion battery technology. The SGCC project is complemented by a similar energy storage project directed by China Southern Power Grid (CSPG) in Shenzhen, also utilizing BYD batteries manufactured in Shenzhen; the 12 MWh (3 MW) project came on line in September 2011. These projects are designed to test a variety of technologies and energy storage providers, and are clearly oriented towards accelerating the emergence of a large Chinese energy storage and battery industry.

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China's electric power generating equipment industry

China is building a power transmission industry, just as the United States built such an industry around General Electric and Westinghouse in the late 19th century. The Chinese are utilizing a well-tested pattern, of allowing foreign companies to make initial investments, and then to demand that they form joint ventures so that knowledge accumulated in the West can be diffused to Chinese firms. In what is by now a typical pattern, the China State Council has allowed some foreign investment in the power sector, by Japanese (Mitsubishi Heavy Industries, Toshiba et al.), United States (GE, Cisco) and European (Alstom, Areva, ABB, Siemens) companies, through joint ventures with Chinese firms.[23] The joint ventures formed work on the principle of 'trading market for technology' and have proved to be very effective means for China to modernize its technologies and industrial sectors.

Chinese companies that are coming to prominence through these efforts include Shanghai Electric, Dongfang Electrical Corporation (DEC) and Harbin Power Equipment, as well as newer companies such as TBEA Co., Baoding Tianwei Group, Xi'an Xidian (unlisted) and XJ Electric Co. These companies are already bidding for international contracts (such as for the building of a new national grid in the Philippines) and will doubtless be significant export earners for China in the coming years.[24] Shanghai Electric in particular is looking to build a global brand (in the manner of a GE or Mitsubishi) and is also diversifying into the building of wind turbines thereby opening up a new market for renewable power generation equipment in parallel with the traditional thermal generator sector.

China's high-speed rail strategy as complement

A counterpoint to China's development of a national integrated high-capacity electric power grid is its parallel development of a national HSR grid. China has emerged as acknowledged world leader in building HSR; it is expected to build more of such a system over the next five years than the rest of the world combined. China had been ramping up the speed and capacity of its inter-city rail network through the 1990s and 2000s, but it was not until the *Mid- to Long-Term Railway Development Plan* (MLT:RDP) was approved by the State Council in 2004 that a separate fast rail grid was envisaged, with new lines and tracks not shared with

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freight rail. (The enormous appetite for coal created by the surge in energy production in the early 2000s contributed to this shift to high-speed passenger dedicated lines to free up the existing rail system for freight transport, largely of coal but also of steel and other raw materials.) By the end of 2014, China had built 16,000 km of HSRs, which forms the largest HSR network in the world.[25] The network is underpinned by '4 vertical + 4 horizontal lines' as its main frame, and details of the main HSR lines are suggested in Figure 4.9.

Total investment envisaged for completion of the plan by 2020 is RMB 2 trillion (US$ 240 billion), or an average of $24 billion per year from 2010 to 2020. Even this high level was exceeded by spending in 2008 and 2009, under the influence of the Stimulus Package, when investment rose to $49.4 billion in 2008 and $88 billion in 2009.

The China HSR upgrading package also incorporates a characteristic latecomer strategy for technology leverage. China's high-speed trains (locomotives) draw on existing technologies, such as:

- China Rail H1 – based on Canadian Bombardier *Regina*;
- CRH2 – based on Japanese E Series 1000 Shinkansen;
- CRH3 – based on German Siemens *Velaro*;
- CRH5 – based on Alstom *Pendolino* ETR600.

Furthermore the tracks are being laid along dedicated lines, separated from existing tracks with their curvatures, bends, gradients and traffic, on a concrete bed designed by a German engineering firm but implemented in China on a scale far larger than anywhere else. This is another example of the latecomer strategy deriving advantages from not having to cope with technological inertia from earlier systems.

Now that China has emerged, within just a single decade, as the largest builder and operator of HSR systems in the world, it is looking to export its production technology as a major export business. For example, Turkey's first HSR line, operating over the 530 km between Istanbul and Ankara, represents China's first major export of its HSR technology. The China Railway Construction Corporation (CRCC) and China National Machinery Import/Export Corporation won the contract in 2005, in a joint venture with Turkish engineering companies. The project was part-financed with $750 million in loans from China.

Chinese rail transport equipment and railway construction companies seem to be accelerating their internationalization in recent years. By 2014 Chinese railway transportation equipment companies had exported

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FIGURE 4.9 *China's Passenger HSR network*

Source: Wikimedia: http://upload.wikimedia.org/wikipedia/commons/9/97/4%2B4_PDL_network_in_China_%28English_version%29.png to over 30 countries, and achieved international sales with a total value of US$ 4.36 billion in 2014 alone.[26] Also in 2014 Chinese companies were involved in many foreign railway construction projects, such as building a key railway line for Nigeria (a contract worth US$ 12 billion was awarded in November 2014). China North Railway (CNR) Corp succeeded in its bid to supply US$ 670 million worth of subway trains to Boston in January 2015, a high-profile deal signalling recognition of its technological capabilities by the US market. The financial performance indicators of several major Chinese railway construction and train equipment companies in 2014 are indicated in Table 4.2.

Thus the HSR package as a whole is distinctively Chinese, like its counterpart in the grid modernization programme. It draws from existing technology models – doubtless with China avoiding Intellectual Property Right (IPR) disputes through holding out the promise of gaining contracts for building trains as part of China's HSR plans. It is useful to note that the China State Council decided to go ahead with conventional technology for HSR in 2006, after discussing the possibility of leapfrogging with German MagLev technology – but abandoned this option when Germany refused to transfer technology nor to enter a JV with a Chinese company. The sole MagLev line in China remains the highly prominent line that takes passengers from the new Shanghai-Pudong airport to the Shanghai city centre.

TABLE 4.2 *Financial performance of major Chinese railway transport equipment and construction companies*

Companies	Income (RMB billion)	Growth of income in % (year-to-year)	Net profit (RMB billion)	Growth of net profit in % (year-to-year)	Foreign sales (US$ billion)
China South Railway Co.	112	20.5	5.3	27.6	3
China North Railway Co.	104	7.3	5.5	33	3.8
China Railway Engineering Co.	612	9.3	10.4	10.5	Not disclosed
China Railway Construction Co.	592	0.9	11.3	9.7	20.4

Note: RMB 1 = US$ 0.16.

Source: Based on a media report at http://www.thepaper.cn/newsDetail_forward_1316193 (in Chinese).

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The changing technological paradigm

Upgrading and technological capability building of the thermal power sector

Policies pursued by the Chinese government in the power sector encourage construction of larger and more efficient generating units, the aim being to upgrade the thermal power sector with a number of advanced power generation technologies such as supercritical (SC) and ultra-supercritical (USC) pulverized coal power generation, integrated gasification combined cycle (IGCC) and natural gas combined cycle. Those technologies have great potential in improving energy conversion efficiency and cutting emissions of CO_2 and other pollutants.

Newly built plants are increasingly adopting SC or USC technology, so that the share of these technologies in the power generation mix has grown from 12 percent in 2007 to 15 percent by 2010 and expected to reach 30 percent by 2020, bringing China abreast of the United States. By 2013, China had over 100 generating units with a total capacity of 80 GW based on the USC technology, which operate at temperatures of 600° Celsius and over.[27] China currently is the largest user and producer of USC technology-based generating units in the world. China is in the process of adopting the 600 MW SC and 1,000 MW USC units as the standard technologies for the newly installed coal-fired power generation capacity in the country – leading to marked carbon emissions reductions.

One of the key strategic objectives of China's power sector is to build its own technological capability. Research and development of key components of the IGCC power generation technology, for example, have been included in the main national science and technology schemes such as the National Basic Research Program of China, or the '973' Program; and the National High-tech R&D Program, or the '863' Program. China is actively engaged in international cooperation in developing the technology. For example, China's Huaneng Group was a key partner in the FutureGen alliance set up for the US government-sponsored US$ 1-billion project – before its dismantlement by the US government. It is anticipated that the US–China Joint Statement on Climate of November 2014 will lead to many more such cooperative R&D projects.

China has almost completely absorbed the SC and USC technologies. Only about six years since the sector started installation of SC and USC units in 2002, the localization rate, namely the ratio of

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domestically manufactured components, had increased from 60 percent to 100 percent. This is a remarkable accomplishment, and gives not only domestic energy security to China but also creates an industrial export platform for the future. The progress achieved is well illustrated in the case of the Shanghai Waigaoqiao No. 3 power station.

BOX 4.1 *Shanghai Waigaoqiao no. 3 power station*

Shanghai Waigaoqiao No.3 Power Station (WGQ3) has now emerged as a world leader in the application of SC and USC thermal generation technology. It is a coal-fired power station located in Pudong, Shanghai, and is invested by Shenergy Group, an SOE owned by the municipal government of Shanghai. With two 1,000 MW USC coal-fired power generating units, the station is responsible for 10 percent of the city's electric power supply. Since the start of operation in 2008, the plant continues to lead the world in energy efficiency in terms of coal consumption per kWh of electricity generated.[a] In 2013, the energy efficiency of the two units reached 276.82 g per kWh, (a lower and more efficient level than that of other advanced coal-fired power plants including 286 g per kWh achieved by the Danish coal-fire station, Nordjylland, and 303.7 g per kWh reported by Isogo power plant in Japan). The Shanghai plant is reported to maintain a world record for energy efficiency (46 percent) for plants using the same generation of USC coal-fired power generating technology.

The success of WGQ3 is due not only to the technology sourced from Siemens,[b] but also to the plant's continuous indigenous innovations over the years, such as the energy-saving quick start-up technology, flexible extraction technology, and steam oxidation solid particle erosion prevention technology.[c] Many innovations involve ways of reducing costs with existing technologies – a typical Chinese strategy. For example, the plant designers were able to position the high-temperature, high-pressure cylinder turbo-generator in direct connection to the outlet of the boiler, so that the length of expensive pipelines linking the two (specifically designed for a high operating temperature at 700° Celsius) can be reduced.[d] This is an example of what business scholars of China call 'cost innovation'.[e]

Notes: [a] See the description of the plant and its history at: http://www.power-technology.com/projects/waigaoqiao-power-station-shanghai/; [b] http://www.energy.siemens.com/ru/pool/hq/energy-topics/publications/living-energy/

pdf/issue-02/Living-Energy-2-Cleaner-Coal-in-China.pdf; [c] http://www.wgq3.com/; [d] http://www.cenews.com.cn/qy/qygc/201411/t20141113_783487.html (in Chinese); [e] See, for example, Zeng and Williamson (2008).

Learning curves and cost reduction in renewable energy-based power generation

A driving feature of the industrial dynamics being exploited by China as it builds its new energy industries is the cost reductions that come with experience – or the learning curve. The link between accumulated experience and falling costs is known as the learning curve, or experience curve; it is of fundamental significance in driving the uptake of renewable energy sources – as practised with great effect by China.

Consider the case of solar PV industry, where the cost reductions have been impressive, leading to expansion of the industry – and as the industry expands, so further cost reductions are discovered, and so on in a virtuous cycle.[28] The Bloomberg/New Energy Finance team in London have analysed the trends (Bazilian et al. 2013). Consider our Figure 4.10 based on IRENA that shows falling costs for solar PV over the past 35 years.

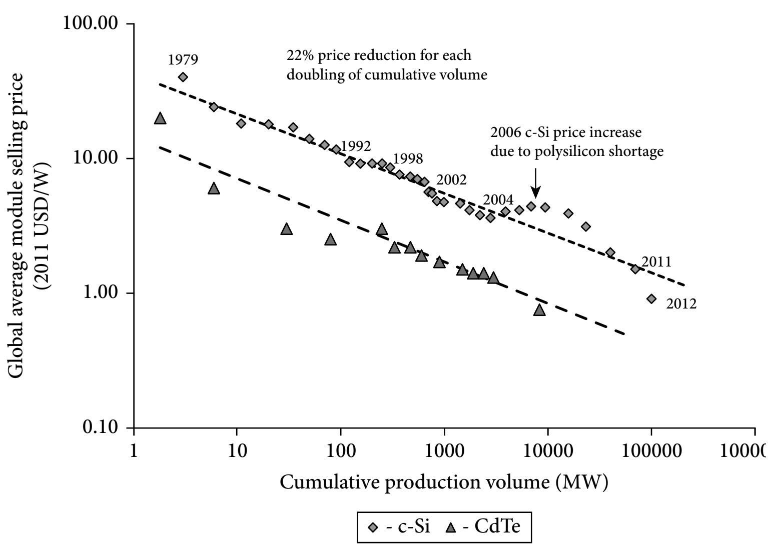

FIGURE 4.10 *PV module experience curve, 1976–2013*
Source : IRENA.

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In this figure the experience curve for first-generation crystalline silicon cells is shown in the upper line, indicating that costs had reduced to the *long anticipated point of $1 per Watt* by the end of 2011 and bringing solar PV power within the range of almost all emerging and developing countries. Costs reduced from around $76 per Watt in 1976 to around 76 cents per Watt in 2011 – a 10,000 percent reduction in less than four decades! This is what is driving the worldwide diffusion of solar PV systems.

The years immediately preceding 2011 show that costs hovered for several years (2004 to 2008) at around four times this level ($4 per Watt) – a phenomenon now understood to be due to tight supplies of silicon. But as silicon supplies became more flexible, so manufacturers reduced their prices, which in turn reduced input costs for solar cell producers, and their prices fell as well. The second, lower line represents the cost curve for thin-film solar cell producers, dominated by the US firm First Solar. Because thin-film PV cells utilize much lower quantities of silicon (or other elements) their costs have been lower – but are not yet enjoying the economies of scale of amorphous silicon cells. Overall, the costs of solar PV cells are falling at around 45 percent per year. Similar learning curves can be constructed for other energy technologies, including wind power (onshore and offshore), energy storage and batteries, thermal power generation systems, electric vehicles and many more.

While the reduction in costs of Chinese renewable energy and producing technologies and devices seem to have been predominantly driven by the expansion in both domestic and international markets, which is clearly supported by Chinese government policies (see the discussion in the next section), there have been some early signs that Chinese manufacturers are catching up with their foreign counterparts in terms of technological capabilities in the process of market competition.[29]

Thanks to the new classification scheme established by the European Patent Office (EPO) for identifying patents related to clean energy technologies (see UNEP 2010 Annex 12), we have been able to extract patents in relevant clean energy technology areas, including PV energy and wind energy, to compare the patent numbers across different countries, including China, United States, Germany and Japan. While the number of granted patents does not fully reflect all innovation activities carried out by a country or an enterprise, this indicator has been widely used as a proxy for their technological capabilities. Figure 4.11 a and b exhibit the numbers of patents filed by inventors in China, the United States, Germany and Japan in two key renewable energy technologies, solar PV and windpower.[30]

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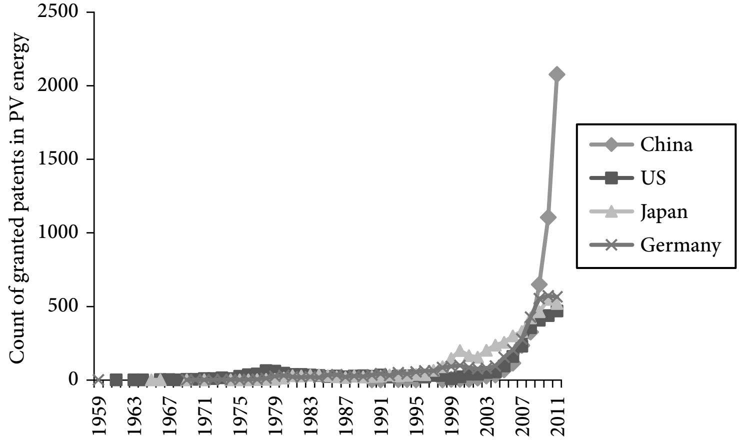
a. Patents granted to inventors in China, US, Japan and Germany: Solar PV technology.



b. Patents granted to inventors in China, US, Japan and Germany: Wind power technology.

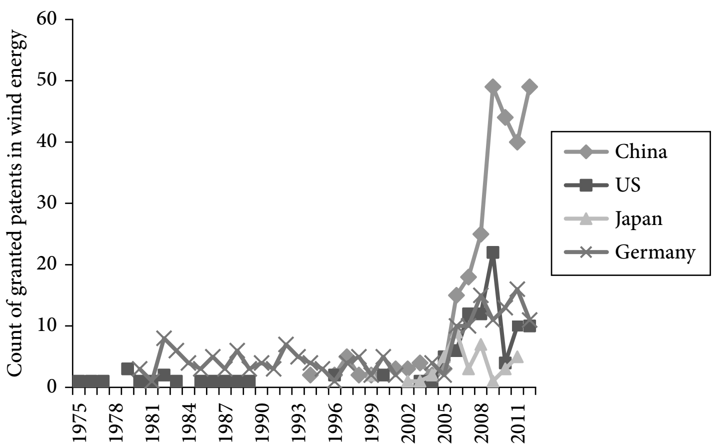


FIGURE 4.11 *Solar PV and windpower patenting*

Source: Authors. Based on data extracted from Thomson Innovation Patent database.

Clearly the number of patents granted to inventors from China concerning the PV and wind power energy has surged since the early 2000s, so that the numbers of patents from China in these renewable energy technologies now exceed those acquired by inventors in advanced industrial economies, namely United States, Japan and Germany. While

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this may be partly attributable to incentives by the Chinese government to encourage patent applications by domestic companies,[31] resulting in the filing of sometimes low-value patents, Chinese companies seem to be actively pursuing technological development as reflected in their patent application activities and the numbers of patents granted to them. For example, the Ministry of Science and Technology established a State Key Laboratory of PV Science and Technology based in Trina Solar in 2010, and by the end of 2013 the Laboratory had been granted 560 patents, including 98 invention patents and 445 utility model patents.[32] This is another area where China seems to be moving rapidly from imitation to innovation.

Government policies and a top-down approach for the energy revolution

Development of the renewable energy sector in China has been strongly driven by government policies, driving both the diffusion of production systems and consumption of green energy. Those range from feed-in tariffs, electricity quota obligation / renewable portfolio standards (RPS), subsidies and other forms of government funding supports, to a carbon trading scheme in parts of the country which is to be extended to the national level by 2016.

Some of the policies were designed to influence the renewable energy sector as a whole, such as the Renewable Energy Law first introduced in 2005 and revised in 2009, and more recently the Energy Development Action Plan, as well as the Air Pollution Control Program, and the US–China Climate Deal. They also include more specific measures for streamlining grid connection for distributed power generation and similar regulations. Some of the recent policies are listed in Table 4.3 a and b respectively.

Strategic Emerging Industry (SEI) Initiatives and prospective 13th five year plan

The 12th FYP, covering the years from 2011 to 2015, sets out the comprehensive goals for China's economic development for the next five years, as approved by the National People's Congress in March 2011. As part

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TABLE 4.3 *Industry-specific policies for renewable energy promotion*

a. Solar PV

Policy	**Issuing body**	**Issuing year**	**Highlights**
Notice on improving PV solar power tariff policy	NDRC	2011	The tariff for the country (except Tibet) is set as RMB 1 per kWh and RMB 1.5 per kWh, depending on the approval date of the project.
12th FYP for development of PV solar industry	MIIT	2012	By 2015, the cost of solar PV modules is to reduce to RMB 7,000 per kW, and that of solar PV system is to reduce to RMB 13,000 per kW. The cost of solar power is to reduce to RMB 0.8 per kWh. The energy efficiency solar PV manufacturing should reach 120 kWh per km for multi-Si PV solar cells. The conversation rate of mono-Si in industrial scale should reach 21%, and that of multi-Si should reach 19%.
12th FYP for development of solar power	NEA	2012	By 2015, China is to install more than 21 GW of solar power capacity (note this target has been revised to 35 GW), and generate 25 TWh of electricity annually.
Several opinions on promotion of healthy development of solar PV industry	State Council	2013	China aims to install over 35 GW of solar power capacity by 2015. New PV panel manufacturing projects should have a conversion rate of 20% or above for monocrystalline-based projects and 18% or above for polycrystalline-based projects.
Notice of utilizing price leverage to promote healthy development of the PV industry	NDRC	2013	The notice sets three levels of tariffs for solar power generation according to the wind resources and construction conditions.
Notice on establishing distributed PV power generation demonstration parks	NEA	2013	The notice establishes the first batch of 18 demonstration PV power generation demonstration parks in China.

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b. Wind power

Policy	Issuing body	Issuing year	Highlights
Interim measures on special funds for developing the wind power equipment manufacturing industry	Ministry of Finance	2008	The government provides funds at a level of RMB 500 per kW to subsidize the first 50 wind turbines manufactured by a company, which is about 10% of the total cost.
Notice on the implementation of the State Council's policy to accelerate the revitalization of the equipment manufacturing industry	Ministry of Finance and other three central government agencies	2007	The government uses a range of measures to support R&D of wind turbine technologies at 1.2 MW and over.
Notice on improving wind power tariff policy	NDRC	2009	The government sets four levels of tariffs for wind power generation according to the wind resources and construction conditions.
12th FYP for the wind energy development	NEA	2012	By 2015 the wind energy capacity is to reach 100 GW, the annual power generation based on wind energy is to reach 190 TWh, and wind power is to account for 3% of the total power generation. China is to produce 3–5 wind turbine manufacturers and 10–15 part suppliers that are internationally competitive.
Notice on improving the grid connection and utilization for wind power in 2013	NEA	2013	The wind energy utilization rate is to be regarded as an important performance measure of the energy sector.

Source: Authors. Based on policy documents.

of the 12th FYP, seven Strategic Emerging Industries (SEIs) were identified and earmarked for special promotion over the next five years. The Plan laid out a target that production value-added from these seven SEIs should reach 8 percent of GDP by 2015. The seven SEIs are:

- Energy-saving and environmental protection – for example recycling;

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- Next-generation IT – next-gen communications, TV/internet networks and so on;
- Bio-industries – biopharmaceuticals, bio-agriculture, bio-manufacturing;
- High-end assembly and manufacturing industries – aerospace, rail and transport, ocean engineering, smart manufacturing;
- New energy sources – nuclear, solar, wind, biomass, smart power grids;
- New materials – advanced structures, high-performance composites, rare earths; and
- New energy-powered cars – electric vehicles, urban charging infrastructure.

In 2012, the State Council released further policy for the development of SEIs, including the objectives, main actions and policies, and roadmaps for each of those SEIs.[33] According to the plan, the added value from those SEIs should reach 15 percent of GDP in 2020.

There could be no clearer demonstration of how China views the link between building energy security, improving environmental protection and creating the export platforms of tomorrow. But it is still difficult to gain a clear perspective on these important targets; the statistics about those SEIs are still rare. The NBS in 2013 established a tentative industry classification for identifying those industries and their associated products.

On the basis of the industry and product classification for SEIs as well as the international patent classification (IPC), the State Intellectual Property Office (SIPO) has published statistics on patenting activities from those SEIs. According to statistics published in 2014,[34] the total invention patents granted in the seven SEIs increased from 26,773 in 2008 to 65,695 in 2012. The growth of patenting in the industries of 'new energy-powered cars' and 'new energy sources' are most notable, achieving average annual growth rates of 90 percent and 55 percent respectively. In 2012, 3,252 invention patents were granted to new energy source-related technologies and 1,941 granted to technologies-related new energy-powered cars. More detailed statistics of SEIs were included in the *Third National Economic Census* carried out in 2013–2014 and are expected to be released in perhaps 2015. According to the first briefing released in December 2014 from the Census office, 166,000 corporates were involved in SEIs activities by the end of 2013 or 2 percent of all corporates in China. Those include 71,000 corporates involved in the

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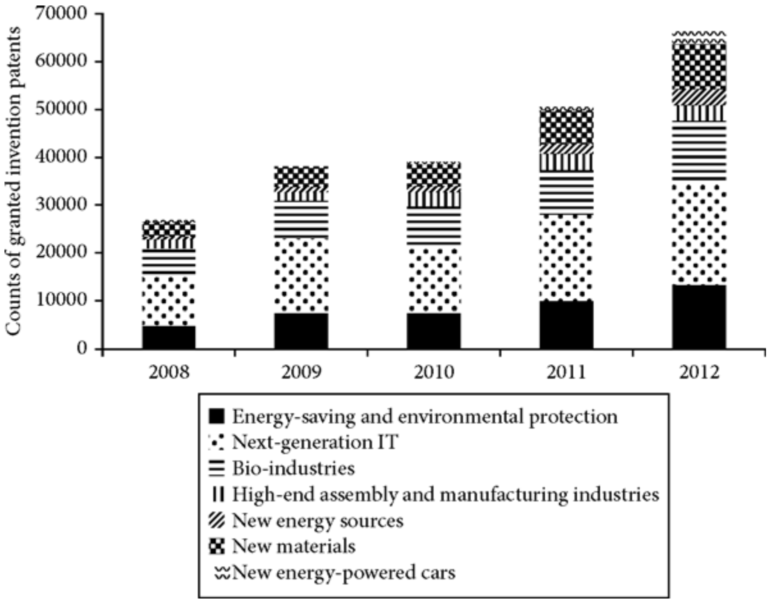

FIGURE 4.12 *Granted invention patents from the seven SEIs: 2008–2012*

Source: Authors. Based on SIPO (2014) Strategic Emerging Industries Patents Statistics Report, State Intellectual Property Office of the PRC, available at http://www.sipo.gov.cn/tjxx/yjcg/.

energy conservation and environmental protection businesses with just over 10 million employees, and 47,000 corporates involved in new materials industry with just over 7 million employees.

Overall we note that China is focused on linking its industrial restructuring policies and export promotion policies with its renewable energy policies, in a way that is criticized by other countries but rarely emulated. And yet it is clear that China's industrial strategies are currently focused very much on these emerging strategic industries, and on the technologies that they embody. China is currently formulating its 13th FYP (2016–2020).[35] In 2014, ND&RC, the central planning body in China responsible for the development of FYPs, invited tenders for carrying out research on 25 key areas, including the research covering SEIs. However, it remains a topic of ongoing debate as to which industries would be identified as the new SEIs in the 13th FYP, or even whether to have any SEIs in the plan at all.[36]

BOX 4.2 *'Good' and 'bad' policies in China's energy revolution*[a]

As we have seen, the Chinese government's industrial policies have played a big role in pushing the green transformation of China. These policies include those specifically designed to support an accelerated development of renewable technologies and industries in China, including direct or indirect investments by the state, tax breaks and price controls.

However, as the designer and implementer of industrial policies, the Chinese government is also being frequently challenged over its judgement, fairness and efficiency. For example, it has come under a lot of scrutiny over its declaration that recent increases in domestic petrol consumption tax were to 'improve the environment and promote energy conservation', while the legal procedure itself has been questioned.[b] In such an environment, the government might consider shifting its focus. One way to off-set ongoing controversies over the introduction of new, 'good' industrial policies, would be a consensus and drive to eliminate existing, 'bad' industrial policies that are currently jeopardizing the energy transition.

Take subsidies for example. There are still explicit and implicit subsidies to the traditional fossil-fuel-based industries (coal, oil, natural gas and thermal power) in China. According to the IEA,[c] the Chinese fossil fuel industries received in the region of US$ 21 billion in subsidies in 2013. Taking into account the external, environmental costs of fossil fuels, the International Monetary Fund (IMF) estimates that the total amount of subsidies awarded to China's fossil fuel industry in 2011 reached nearly US$ 280 billion (but note that these figures include estimates of externalised costs of fossil fuels, such as health costs in caring for those adversely affected by pollution).[d] The scale of these subsidies paid to fossil fuels dwarfs any support provided to renewables.[e] Some of the national oil companies, notably China National Petroleum Corporation (CNPC) and China Petroleum & Chemical Corporation (Sinopec), received huge subsidies from public funds in recent years. CNPC, for example, has been the No.1 recipient of government subsidies among all Chinese publicly listed firms for the past several years. In the ten years leading up to 2014, these two national oil companies received subsidies amounting to RMB 126 billion (or US$ 20.3 billion).[f]

Some companies from energy-intensive industries, such as steel-making, metallurgy and cement production, also receive substantial amounts of subsidies. In order to attract investments and grow the local GDP, it is known that some local governments use public funds to subsidize the use of electricity and coal by local manufacturers.

As a social security measure, China provides fuel subsidies to certain industries and user groups, such as farmers, fishermen, bus companies, taxi drivers and people with disabilities. While fuel subsidies to people with disabilities for their transport needs may be justified, those provided to taxi drivers are not. The issue is, should such subsidies be targeted at fuel consumption needs or should they be included as a general social security payment. To compound the issue, there have been numerous cases where the granting of fuel subsidies has been subject to corruption.[g]

At the G20 Pittsburgh summit in 2009, China together with other countries made a joint commitment to 'phase out and rationalize over the medium term inefficient fossil fuel subsidies [...]'. It should be noted that China's policy reform in this area is necessary not only to fulfil the commitment it has made to the international community, but more importantly, to help accelerate its own energy transition.

Notes: [a] This Box is based on an opinion piece that one of the authors (Hao Tan) published in the website of Institute of Development Studies (IDS) of University of Sussex, UK, available at: http://www.ids.ac.uk/opinion/greening-china-tackling-bad-industrial-policies-should-be-a-priority; [b] See, for example, http://www.ftchinese.com/story/001060207?full=y (in Chinese); [c] IEA (2014) 'Fossil-fuel subsidies', in World Energy Outlook 2014, IEA. http://dx.doi.org/10.1787/weo-2014-11-en; [d] IMF (International Monetary Fund) (2013), Energy subsidy reform: Lessons and implications, IMF, Washington, DC; [e] Our analysis here coincides with that of Lin and Xu (2014), p. 558; [f] http://finance.ce.cn/rolling/201409/01/t20140901_3457560.shtml (in Chinese); [g] See, for example, http://www.chinanews.com/fz/2014/08-28/6537853.shtml (in Chinese).

Notes

1 This section is based on the authors' posting to the *Asia Pacific Journal: Japan Focus*, 'The greening of China's black electric power system? Insights from 2014 data', 16 March 2015, at: http://www.japanfocus.org/-John_A_-Mathews/4297

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2 See Armond Cohen, 18 February 2015, 'No China coal peak in sight: carbon capture will be necessary to tame emissions in this century', Clean Energy Task Force, at: http://www.catf.us/blogs/ahead/2015/02/18/no-china-coal-peak-in-sight-carbon-capture-will-be-necessary-to-tame-emissions-in-this-century/

3 Cohen responded to our points, conceding that China's greening is an important feature of its energy system changes, in *The Energy Collective*, 'China's power system: The green and the black', 24 March 2015, at: http://theenergycollective.com/armondcohen/2209091/china-s-power-system-green-and-black

4 This is an argument used frequently by US climate scientist James Hansen, in Congressional testimony. See, for example, his testimony on 13 March 2014 before the Senate Foreign Relations Committee, at: http://www.foreign.senate.gov/imo/media/doc/Hansen_Testimony.pdf

5 See the briefing released by the China Electricity Council on 2 February 2015 at: http://www.cec.org.cn/guihuayutongji/gongxufenxi/dianliyunxingjiankuang/2015-02-02/133565.html (in Chinese).

6 For commentary on this ND&RC statement, see China, United States look to boost solar and wind capacity, Giles Parkinson, *RenewEconomy*, 19 May 2014, at: http://reneweconomy.com.au/2014/china-us-look-boost-wind-solar-capacity-30830

7 http://www.cec.org.cn/yaowenkuaidi/2014-02-26/117351.html (in Chinese).

8 Original data at http://hvdc.chinapower.com.cn/news/1037/10371844.asp (in Chinese). Note that the figure for Guodian is updated according to the company's website: http://www.cgdc.com.cn/corporate.jhtml

9 Contrast this figure with the investment in the smart grid of US$ 67.7 billion announced by the SGCC.

10 See the English translation of the plan at: http://www.britishchamber.cn/content/chinas-twelfth-five-year-plan-2011-2015-full-english-version

11 http://www.sgcc.com.cn/ztzl/tgyzl/mtbb/188272.shtml (in Chinese).

12 http://finance.sina.com.cn/roll/20140520/011319157448.shtml (in Chinese).

13 See the critique by a professor from the Department of Electric Machinery, Tsinghua University, at http://finance.sina.com.cn/zl/energy/20140404/092218712978.shtml

14 See, for example, Liu, Z. Y. (2013) 'Innovation of UHVAC Transmission Technology in China', *Power System Technology*, 37(3): T1–T8 (in Chinese); and Liu, Z. Y. and Zhang, Q. P. (2013) 'Study on the Development Mode of National Power Grid of China', *Proceedings of the CSEE*, 33(7): 1–10.

15 http://www.sgcc.com.cn/ztzl/tgyzl/tgyzs/226726.shtml

16 See, for example, the 'National Science and Technology Development Plan 2006–2020'; 'Several Opinions on Accelerating the Development of Equipment Manufacturing Industries by the State Council'; and 'National Innovation Infrastructure Capacity Building 11th Five Year Plan'.

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17 http://news.xinhuanet.com/fortune/2011-01/05/c_12948645.htm (in Chinese).
18 The three UHVAC projects include the Jindongnan–Jingmen Demonstration Project and its expansion, the Huainan–Shanghai UHV AC Demonstration Project, and the Zhebei–Fuzhou UHV AC Project. The four UHVDC projects include the Xiangjiaba–Shanghai UHV DC Transmission Pilot Project (greatly extending the sources for Shanghai's electric power supply), the Jinping-Sunan UHV DC Transmission Project, Southern Hami-Zhengzhou UHV DC Transmission Project and Xiluodu–Jinhua project.
19 http://www.sgcc.com.cn/ywlm/mediacenter/corporatenews/05/306406.shtml
20 http://paper.people.com.cn/zgnyb/html/2015-02/02/content_1530301.htm (in Chinese).
21 The theoretical implications are probed in Mathews (2010).
22 See the article by one of us (JM) on this project, at *The Conversation*, 5 May 2015, "The Tesla battery heralds the beginning of the end for fossil fuels", at: http://theconversation.com/the-tesla-battery-heralds-the-beginning-of-the-end-for-fossil-fuels-41197.
23 These JVs include: Changzhou Toshiba Transformer, ABB Chongqing Transformer, Siemens Transformer and AREVA Shanghai. See the investment report by the UK research firm Trusted Sources, 'China's grids power up' (17 November 2008), at: http://www.fng-net.co.jp/ts/China_power_grid_development.pdf
24 See our paper on China's electric power system transformation in the journal *Energy Policy* (Mathews and Tan 2013).
25 http://news.xinhuanet.com/science/2015-01/30/c_133958067.htm (in Chinese).
26 http://www.chinadaily.com.cn/bizchina/2015-02/05/content_19495862.htm
27 http://www.nea.gov.cn/2014-01/29/c_133082942.htm (in Chinese).
28 This section is based on pp. 105–108 in JM's book, *Greening of Capitalism*.
29 See Ru, P. et al. (2012) for an analysis.
30 This patent analysis is based on the concepts of 'patent families' and the 'earliest priority year'. For more details see OECD (2009) *OECD Patent Statistics Manual*, Paris.
31 See the study of Chinese patenting reported by Li (2012).
32 http://www.sklpvst.com/english/
33 http://www.gov.cn/zwgk/2012-07/20/content_2187770.htm (in Chinese).
34 See http://www.sipo.gov.cn/tjxx/yjcg/
35 See an interactive timeline developed by Yale University in regards to key milestones in the development of 13th FYP at: http://epi.yale.edu/visuals/china-five-year-plan/
36 See the speech by a Chinese economist, Fan Gang, who is involved in the planning process of 13th FYP process at: http://finance.sina.com.cn/hy/20150214/152821555156.shtml (in Chinese).

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5

China's Energy Firms: New Dragon Multinationals

Abstract: *This chapter takes the analysis to the meso- and micro-level, where the role of firms in driving the China energy revolution is assessed. Typical latecomer strategies are appealed to in describing and analysing the approaches of the firms involved in the various energy sectors. Insofar as the firms succeed in becoming global players they are assessed as 'Dragon Multinationals' with distinctive approaches to implementing and accelerating their internationalization. Case studies of wind power firms such as Goldwind and MingYang; solar PV firms such as Trina Solar and Hanergy; and grid companies such as China State Grid Corporation reveal the rapid evolution of the latecomer strategies that have propelled companies to world leadership.*

Keywords: accelerated internationalization; Dragon Multinationals; global expansion; Goldwind; latecomer strategies; Suntech

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In this chapter we take the level of analysis from the macro trends to the strategies of the firms involved, both private firms and state-owned enterprises. In some sectors, China has made a deliberate policy choice to let the private sector have the dominant influence (as in solar PV) and learn from the experience. The firms are actively pursuing varieties of fast-follower imitation strategies, learnt from prior East Asian catch-up developmental experiences, but are also becoming strong drivers of innovation, as China's rapid build-up of patents in renewable energies testifies. Specific technology and resource leverage strategies are now discernible, such as Goldwind's leveraging of gearless wind turbine technology and its move to be first in the world to offer products based on this technology to the world offshore wind power market. The complementary strategies of 'going global' pursued by other Chinese energy companies, especially those large SOEs such as SGCC will be examined. The result is a complex impact on global affairs and patterns of Foreign Direct Investment as these firms emerge as Dragon Multinationals (referring to an earlier book by one of the authors). Again it is the scale of these firm-level activities that provides a strong sense that this is a revolution destined to be continued. We provide several case studies that examine the processes of technological leverage and international expansion of these new Dragon Multinationals.

China as energy latecomer and the building of renewable energy industries

It is well known that the latecomers to industrialization are able to offset the obvious disadvantages of arriving late as an industrial player with some clear advantages as well – such as the enjoyment of a lower cost advantage (at least for a short period) and a capacity to 'leapfrog' existing technological arrangements by adopting the very latest versions of technologies.[1] This is an important aspect of latecomer industrial dynamics.

In the case of renewable energy this process is placed in stark relief. China has been able to build new industries without having to dismantle 'old' fossil-fuel-based industries. And it is able to draw on the best available technologies to build a new, 'strong and smart' grid for its future electric power system. China thus stands a good chance of avoiding what is known as 'carbon lock-in' that afflicts earlier industrial powers.[2]

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It is clear that an essential part of China's energy strategy is to view the development of nuclear power and 'new' renewable energy sources as well as hydro as the nucleus of new, export-oriented industries, which promise to grow to be as large as the fossil-fuel-based energy industries of the 20th century. This is a very different development strategy from that pursued earlier by the industrial powers, with their reliance on fossil fuels, or by Russia today, with its reliance on oil and gas resources. China is building its energy system and its industrial base in complementary and synergistic fashion, each one interacting with and serving the other. The difference is that China's plans call for energy to be produced and distributed in the most efficient ways, rather than dug out of the ground and wasted – and this implies a very different approach to energy promotion and regulation.[3]

China's strategy to build renewable energy systems is linked fundamentally to its strategy for building domestic industries to supply the equipment needed – both for domestic consumption as the new energy systems come online in China, and for export (of both products and equipment) to other parts of the developed and developing world. For example, China's example may well spark major investments in renewable energy industries in India and other Asian and Southeast Asian countries; China will be ready to supply them with both products (wind turbines, solar PV systems) as well as with the equipment needed to build them. This is the goal of the 'local sourcing' or 'Local content requirements' (LCR) rules that have guided development of these industries over the past decade and more, and which are now seen to be bearing fruit. China's onshore wind power projects have, since 2005, placed requirements that at least 70 percent of the wind turbine equipment must be produced in China; these were then discontinued in 2009 – *after they had effectively achieved their goal, and elevated local Chinese turbine producers Goldwind, Sinovel and DEC together with joint ventures to achieve more than 50 percent of the domestic market by the year 2008.* Now the same process is underway in offshore wind power, where the ND&RC has imposed local sourcing rules taking effect in 2009.[4] We examine the international trade issues and trade conflicts sparked by these initiatives in the next chapter.

China's renewable energy companies are now globalizing – and as they do so they are replicating latecomer strategies and becoming what one of us called Dragon Multinationals in 2002. Several firms have rapidly internationalized during the past several years, notably Goldwind and

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Sinovel, as indicated by the companies' foreign sales as a proportion of their total sales. Although both companies and their predecessor companies have been founded for years, they had little presence in the international market until recently, and have emerged as Emerging Market Multinational Enterprises (EM-MNEs) in the global wind turbine market within very few years. This is what we call 'accelerated internationalization' – a characteristic of latecomers.

We examined the phenomenon of accelerated internationalization in the Chinese wind turbine manufacturing industry in an article published in *Journal of World Business* in 2014.[5] In the article our measure focuses on an increase in the speed of internationalization – in keeping with the notion of acceleration as a category used in physics. On the basis of this measure, the average acceleration of internationalization of Goldwind in the six years between 2007 and 2013, for example, is calculated as an increase of 15 percent in speed of internationalization over a period of six years, or 0.5 percent increase per year, per year. (Recall that acceleration is an increase in speed of internationalization, where the latter is expressed as a percentage increase per year.) Similarly, that of Sinovel during the same period is calculated as (42 percent–0) as divided by a span of 3.3 years, or 3.4 percent expansion per year, per year – an acceleration rate which is higher even than that of Goldwind for the same period of time.

There are certain common features present in the cases to be discussed below. The primary features lie in the fact that, first, as latecomers they sought to establish capacity by tapping into sources of technological knowledge. They utilize global sources such as technologies accessed either through licensing or through corporate acquisitions; they access knowledge from around the world through establishing R&D Centres in key locations; they deploy novel and well-adapted global expansion techniques such as 'exploration sales'; they utilize local suppliers while operating comfortably through global value chains; and they recognize other global firms as their primary competitors rather than small domestic rivals. They launch aggressive marketing and sales in the international market once they have achieved a certain capacity to compete with the global leaders in the industry. In this way, our case study firms demonstrate accelerated internationalization in their repeated exercise of sequences of linkage and leverage, experienced as enhanced levels of learning.

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BOX 5.1 *Chinese wind turbine manufacturers*[a]

Goldwind was a first mover in the context of China's efforts to build a windpower industry. It was established in the late 1980s in the far-western province of Xinjiang as a small wind farm operator based on imported wind turbines. The company entered into the wind turbines manufacturing industry in 1997; and soon started its own R&D on the 600 kW wind turbines based on foreign technologies, an effort that was supported in the Ninth Five-Year Plan by the Ministry of Science and Technology as one of the State-funded key projects. Goldwind is now China's largest wind power company in terms of annual sales, spanning all aspects of the business, and second largest in the world. By the end of 2012 Goldwind's cumulative windpower installations had a capacity of more than 15 GW.

In 2004 it took a big step by winning a government contract to supply 60 turbines to the 100-MW Yuedian wind farm. It went on to establish a financing subsidiary which also developed wind farms of its own, while improving its capabilities in turbine construction. For this purpose, Goldwind has been a successful practitioner of technology licensing, utilizing German sources. Initial forays were a license to the 600-kW turbine from Jacobs, a small German firm, and the 750-kW turbine from German firm REPower (subsequently acquired by Indian firm Suzlon) – allowing Goldwind to produce 600-kW and 750-kW turbines in 1999 and 2001. Goldwind went on to absorb this technology and move to collaborative R&D ventures, such as joint design of a 1.2-MW turbine with the German firm Vensys, which it subsequently came to control, acquiring a 70 percent stake for € 41 million. Through these means it was able to indigenously innovate to produce its own turbines, particularly those with Permanent Magnet Direct Drive (PMDD) technology, which eliminates the need for gearing. This could well become the dominant technology in the industry, and Goldwind as its key practitioner.

Goldwind was relatively slow (by Chinese standards) to internationalize in terms of foreign sales, winning its first international order from Cuba in 2008 and opening its first overseas sales office in Australia in 2009. The company then secured a foothold in the United States by winning a contract to supply three 1.5-MW turbines

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to the Uilk wind farm in Pipestone, Minnesota. Goldwind partnered with local firms to develop the wind farm, importing its own turbines, and used this experience to build a fully comprehensive US subsidiary, Goldwind USA. Goldwind now promotes itself in the United States as a Chinese firm mastering German PMDD technology which is cost-effective, now being sold for less than $1 per watt. Goldwind USA has its headquarters in Chicago, and by 2012 it had sold around 300 MW of PMDD turbines, the largest order being the Shady Oaks project in Illinois rated at more than 100 MW. By 2014, Goldwind had sold over 1000 MW of wind power turbines to over 16 foreign countries; and the foreign sales accounted for 13 percent of the company's total sales.[b]

Sinovel was a later entrant in China. Founded in 2003 by one of the largest State-owned enterprises in the heavy machinery industry, it had risen to become one of the largest wind power companies in China, and second largest in the world in terms of cumulative delivered wind power capacity. The company was the first to introduce and localize the mainstream 1.5-MW wind turbine technologies in China based on foreign technologies, and later successfully developed its own 3-MW land and offshore wind turbine technologies. Sinovel leapt to prominence in China in 2007 when it won the contract to supply turbines to Shanghai's offshore wind power project, the Donghai Bridge Offshore 100-MW wind farm. Sinovel worked with Windtec, a subsidiary of American Superconductor (AMSC), to develop leading-edge 3- and 5-MW turbines (bypassing the kilowatt stage), and by 2010 it had supplied all 34 offshore turbines to the Donghai Bridge project with its own MW-power machines. Since then Sinovel has internationalized rapidly, opening sales and production points in several countries including the United States, Brazil, Sweden, Turkey, India and South Africa. In the United States Sinovel won a contract to supply a 1.5-MW turbine for a pumping station in Charleston, Boston. Sinovel worked closely with the US firm AMSC and its Austrian subsidiary Windtec, but in 2012 the two companies fell out; Sinovel has subsequently been embroiled in an IPR-infringement suit with Windtec involving criminal charges. This has certainly depressed its international standing.[c]

Ming Yang is a private-sector firm that launched into the wind turbine manufacturing industry relatively late in 2006, based in

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Zhongshan in the southern Guangdong province (Pearl River Delta). Previously a relatively small manufacturer of electrical transmission and distribution equipment, the company became the first Chinese wind turbine exporter to the US market in just two years. Since 2010 it has been listed on the New York Stock Exchange – the first Chinese wind power company to do so. It has collaborated with the German firm Aerodyn Energiesysteme to jointly develop turbines which have won German technical quality certification. Ming Yang has leapfrogged to the lead technologically, through its alliance with Aerodyn, and now offers 1.5-MW three-blade turbines and 2.5-MW as well as 3.0-MW Super Compact Drive (SCD) advanced two-blade turbines. In 2014, the company successfully built and installed a 6.5-MW offshore wind turbine, which was the largest in the world. Ming Yang has established a strong manufacturing base and associated supply chain cluster at Zhongshan. The company taps into global knowledge networks through establishing R&D Centres in both Denmark (near Vestas) and in the United States. In 2012 MingYang announced a strategic partnership with India's Reliance group to develop wind turbines for the Indian market and beyond into Southeast Asia. This South–South pattern of joint development is surely one of the characteristics of the 'emerging' MNEs from emerging markets.

Notes: [a]This case is adapted and updated from the section in a paper we published in *Journal of World Business*, see Tan and Mathews (2015); [b]Further details on Goldwind and its development may be found in Lewis (2011; 2013); [c]See, for example, 'AMSC/Sinovel industrial espionage thriller takes a procedural turn' at: http://www.lexology.com/library/detail.aspx?g=c06d91c6-1d63-4fb0-a1a7-d803bf90ef60

BOX 5.2 *Chinese PV manufacturers*

In the solar PV sector, China produced a world-class industry leader in Suntech, that took solar PV technologies developed in the West into mass production at a scale never before envisaged. Suntech became caught in the financial haemorrhaging that accompanied excess capacity in 2010–2012, and has been forced to declare partial bankruptcy. But other firms with a similar business model, such as Canadian Solar (despite the name, a Chinese firm)

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have prospered. Leaders such as Yingli Green Energy in solar cells and LDK Solar in silicon wafers, have grown to their present size largely through supplying overseas markets, benefiting as they do so from economies of scale to drive down their costs. Now that China is also starting to provide incentives to grow the domestic market for solar-powered electricity, these companies will have the chance to expand further on the strength of domestic sales. State-owned corporations from established sectors such as aerospace are also becoming active; an example is Shanghai Aerospace Automobile Electromechanical Corporation (SAAE), a spin-off from China Aerospace, which has now entered every phase of the solar PV value chain.

Trina Solar is now world #1 solar PV company by scale of production. It began its solar-power products business a decade ago, in 2004, and listed on the New York Stock Exchange in 2006; it has become a vertically integrated company involving manufacturing of silicon ingots, wafers, solar cells and PV module production. In 2013 the company shipped solar PV modules with a capacity of 2.8 GW, reaching cumulative installations of 8 GW. In similar fashion to the case of Suntech, Trina sold its products mainly to the European market. However, the share of the European market in the total sales has declined during recent years, from over 93 percent in 2009 to 68 percent in 2011. Meanwhile the share of the Chinese market has increased from 2.9 percent to 7.1 percent over the same period. This is a characteristic pattern of these latecomer MNEs in that they build their strength abroad before raising their share of the local market.

The company has initiated a number of internationalization moves during recent years. For example, Trina established regional headquarters for the Americas in San Jose (California), for Europe in Zurich, and for the Asia-Pacific in Singapore. It has opened sales offices in Japan, South Korea, United Arab Emirates and Australia; and set up warehouse operations in The Netherlands and in California. Trina became the No.1 provider of PV products in the Australian market in 2012; and has completed a number of significant projects in Italy, Belgium, California and France. In other words, it is becoming completely globalized.

Suntech seemed to have every feature of the so-called born global firms as discussed in Oviatt et al. (1995). Founded by a Chinese

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Australian citizen in 2001, the management team had significant previous international experience; and international capital was involved at very early stage of the firm when the company was listed in the New York Stock Exchange in 2005. It took Suntech only 12 years from its founding to grow to an MNE with 15,000 employees, with 2.4 GW production capacity of PV cells and 1.6 GW in wafer and ingot capacity; and $3 billion in sales revenues – before being forced into bankruptcy proceedings in 2013. Through the years, the company aggressively expanded its panel-production capacity backed by government loans, and became the number 1 PV manufacturer in the world by the end of 2011. Rapid global growth has not only been a key driver in Suntech's previous success story, but also brought bitter consequences for the company. In 2013, the company filed for bankruptcy after defaulting on its convertible bonds, and was subsequently delisted from the New York Stock Exchange in early 2014. Since then the key assets of Suntech were acquired by another PV business tycoon, Zheng Jianming, and it has been reported that the company has risen again as a significant player in the global PV market.[a]

Rapid global growth has also been recorded by Chinese solar PV firms focused on the dominant technology (in this case, crystalline silicon) for firms such as Canadian Solar, Jinko Solar and JA Solar – a technology not developed by themselves but where they were able to develop advantages based on standardization, mass production and cost reduction, utilizing the largest possible market for their product, namely the global market. In this, Chinese solar PV firms such as Suntech and LDK Solar achieved early successes but became over-stretched financially, which is currently a major source of concern for them.

By contrast, other Chinese firms are looking to the next generation thin-film solar PV cells, which promise lower costs (because of their drastically lower material requirements) while improving efficiency. *Hanergy* is a relatively mature renewable energies company that approached the business as one involving a portfolio of activities, and is now China's largest privately held player in this expanding green sector. Founded in Beijing in 1994, it specialized early in acquiring hydropower assets, and then expanded into wind power, solar PV and energy services. Hanergy entered the solar PV sector in 2009 through a share transfer arrangement, and has since become a player targeting thin-film solar PVs (made for example from copper, indium, galenide and selenium CIGS) where US firms such as Solyndra went bankrupt in 2012. It has built China's largest CIGS production facility (a 100-MW production plant) followed by domestic and international expansion. In 2012 the firm acquired the assets of Solibro from Germany's distressed Q-Cells; Miasolé from the United States; and in China Apollo (China's largest thin-film equipment and turnkey CIGS technology provider). Hanergy is involved in global competition in CIGS-based solar cells with US-based First Solar; and with Japan's Solar Frontier and Sharp. Hanergy has plans to develop more than 2 GW of solar power plants around the world equipped with its own panels, with costs at the competitive margin, approaching grid parity at $500 per kW.

Notes: [a]http://www.smh.com.au/business/carbon-economy/former-solar-giant-suntech-rises-from-the-ashes-20140720-zuwke.html

Electric power grid

In the development of electric power production and transmission, and the evolution towards a 'smart grid' China is clearly intent on building a new industry capable of strong export performance. As noted above, Chinese companies include state-owned operators like the SGCC and power equipment companies such as TBEA Co., Baoding Tianwei Group, Xi'an Xidian (unlisted) and XJ Electric Co. These companies are already bidding for international contracts (such as for the building of a new national grid in the Philippines) and will doubtless be significant export earners for China in coming years.

BOX 5.3 *State grid corporation of China*

State Grid Corporation of China (SGCC) is the seventh largest company in the world, and the third largest company from China, according to the 2014 *Fortune Global 500* rankings.[a] The company was formed as a result of the reform that the Chinese government undertook of the country's electric sector in 2002, which created two dominant grid companies in China, that is SGCC and its smaller 'rival', China Southern Power Grid Corporation.[b] The reform was part of

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the ongoing changes in China's domestic energy governance.[c] SGCC is currently one of the largest SOEs that are directly controlled by the central government. Two undertakings of SGCC during the recent years are most significant, namely its investment in UHV technologies, and its foreign mergers and acquisitions. While appearing to be independent, these two undertakings, domestic and foreign, are in fact mutually supportive. Both have been underpinned by its state ownership, where it is able to use its position as the key player in a strategic pillar industry in China. Further, SGCC seems to aim at creating synergies from the two, by building competitive advantage for its international expansion based on the advanced technologies derived from its large-scale investment in the UHV technologies.

Currently a new wave of reform focused on China's electricity sector is underway as signalled by the formulation the document 'A Number of Opinions on Further Deepening the Reform in the Electric Power System' by the CPC Central Committee and State Council (or commonly known as Document #9 in China),[d] which may have significant implications for the future of SGCC. While details of implementing the proposals are yet to be finalized, a key element in the reform agenda would be to rely more on market mechanisms to determine electricity price, and to introduce more competition in the areas of electricity distribution and sales (currently both undertaken by national grid companies), by allocating the functions to separate entities.

SGCC's international expansion

Since 2007, SGCC has been engaged in a number of high-profile merger and acquisition deals internationally. The state ownership of SGCC is a credit in some cases and a liability in others. Recently SGCC has sought to promote its UHV technologies overseas, as a key competitive advantage to support its internationalization strategy. On the other hand, success in securing UHV projects in foreign markets also help enhance the legitimacy of the investment on the technology domestically.

The international moves by SGCC started in 2007, when the company formed a joint venture in the Philippines with 40 percent of the equity; this joint venture won a bid to operate the country's national grid for 25 years. For example, in 2010 and 2012, SGCC acquired 12 Brazilian transmission concession companies in a two-stage deal, which saw SGCC significantly increase its profile in the South American market. Also in 2012, the company acquired a 25 percent share in Portugal's national energy network, Redes Energeticas Nacionais; and acquired a 41 percent stake in ElectraNet, the only power transmission network in South Australia. SGCC went on in 2013 to acquire the assets of Singapore Power (SP) in Australia, enabling the company to gain access to SP's assets in three states (Victoria, Queensland and New South Wales). In 2014, SGCC also engaged in other deals to acquire power transmission assets in Hong Kong, Brazil and Italy.

As a significant SOE from China, SGCC has enjoyed government support for sealing international deals. However, its international operations have sometimes been politicized and subject to political risks. For example, in 2015, it was reported that employees sent from SGCC responsible for the operation of the company's Philippines project would have to leave the country, a development that many commentators attributed to the territory disputes between the two countries.[e]

Notes: [a]http://fortune.com/global500/state-grid-7/; [b]There is a third grid company in China, Mengxi Grid, which is the only province-level grid company independent from SGCC and CSPG; [c]The evolution of governance in China's energy sector is more broadly discussed in Cunningham, E. A. (2015) The State and the firm: China's energy governance in context. GEGI Working Paper, available at http://www.bu.edu/pardeeschool/files/2014/12/Chinas-Energy-Working-Paper.pdf; [d]See the full document at http://hvdc.chinapower.com.cn/news/1037/10374392.asp; [e]https://ph.news.yahoo.com/ngcp-told-downsize-chinese-team-181040831.html (in Chinese).

China's policy settings and regulatory framework for energy

Shaping the industrial dynamics that we foresee unfolding in China over the next several decades are the legislative and regulatory frameworks that are being set in place during the first decade of the 21st century. China has been expending enormous efforts to coordinate and rationalize its energy policies since energy became the top priority industrial sector in the early 2000s. For example, all energy-promoting activities were brought under the umbrella of the NDRC in 2003, at first under the

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NDRC's Energy Bureau, then under the auspices of a NEA, and then in 2010, under a full-fledged National Energy Commission (NEC), which will ensure full ranking for energy matters in the State Council.

In the electric power sector, there have likewise been determined efforts at rationalization. In 2002 the former monopoly, the SPC was broken up, and in its place two electric power transmission entities were created (SGCC and the China Southern Power Grid Company) and five independent power producers – which have subsequently been playing a major role in renewable energy development. A State Electricity Regulatory Commission was established in 2003, to provide an independent regulatory source. All this lays the foundations for a determined effort to integrate and 'smarten' the power grid in China. Under the Renewable Energy Law 2006, regulations have been issued that require the electricity grid operators to accept power generated from renewable sources – paving the way to a smart, decentralized grid.

Indeed it is the Renewable Energy Law of 2006 that has proven to be a powerful instrument driving the uptake of renewable sources in China. It has served as umbrella for numerous regulations, not least on various kinds of promotional measures for renewables. The goal of enhancing renewables was spelt out in the 11th FYP issued by the State Council covering the years 2005–2010; under this plan, the *Medium- to Long-Term Development Plan for Renewable Energy* was issued by the NDRC in 2007, with its various widely cited targets for 2010 and 2020 (since revised upwards in many instances, as in the case of wind power targets). Under the Renewable Energy Law there has been an extensive debate over such measures as feed-in tariffs and industry promotion measures, including local sourcing provisions. Finally, in the 2009 Stimulus Package, China unleashed a wave of very large investments in infrastructure, including in the upgrading of the national power grid and associated activities such as the acceleration of plans for a national high-speed rail network.

Specific measures deployed by China's State Council to drive the development of national self-sufficiency in renewable energy supplies (mainly for energy security but also for environmental and climate change reasons) include:

- Accreditation of national 'indigenous' innovation products – ensuring that renewable energy products made with 'indigenous' (Chinese) intellectual property protection would qualify for government procurement and tax relief priority.

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- Government procurement to act as a means of fostering domestic demand, for example in purchasing decisions made by state-owned wind farms;
- Local content requirements, under which up to 70 percent of equipment used for wind farm concessions has had to be purchased from Chinese suppliers, thereby building up local supply chains.
- Government mandated market share, requiring power generators with installed capacity of more than 5 GW to produce at least 3 percent of their electricity from non-hydro renewable sources by 2010, rising to 8 percent by 2020 (a powerful factor in driving wind power investments).
- The 2009 Golden Sun Programme, under which investment subsidies are to be provided for up to 50 percent of the costs of grid-connected solar power systems.

We interpret China's strategy in introducing what Howell et al. (2010) called a 'vast panoply' of protectionist measures to be aimed at rapidly building the capabilities of China's renewable power sectors, particularly firms along the entire value chain, before reducing the protections and subsidies and allowing the full force of international competition to prevail. This is classic latecomer strategy, deploying all the resources of the 'developmental state' in this critical area of renewable energy.[6]

Indeed, China's overall strategy of promoting growth of renewables through focusing on building an industrial base for them, rather than through various kinds of market incentives (e.g. market mandates, renewable portfolio standards, feed-in tariffs) which have been tried in the West, has proven to be remarkably effective. It is consistent with what is sometimes called a 'technology-led' approach to mitigating the impact of climate change. Through a combination of tax incentives, time-limited subsidies and other time-limited measures such as imposing local content requirements on foreign investors, the Chinese authorities have unleashed a wave of entrepreneurial investment in renewables, led by wind power and now solar. This is a smart strategy because it knits together the interests of the new industries themselves and those of consumers, without directly penalizing the existing coal-based economic interests (as would happen through a carbon tax or cap-and-trade scheme).

China is consolidating this emphasis on the new energy-related industries by announcing at the end of 2009 the establishment of no

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fewer than 16 major national R&D centres to specialize in sectors such as wind power, nuclear power, electric power generation and transmission. These new centres will complement those being established (with Chinese government support) by major multinationals, such as Applied Materials (world's major supplier of solar PV fabrication equipment), DuPont and IBM, all of whom are opening new R&D facilities in China.

Another aspect of China's regulation of its energy revolution is found in the new law governing the shift to a circular economy, under which efforts are being made to economize on the resource and energy intensity of the Chinese economy. The driving concept of the 'Circular Economy', based on industrial ecology and biomimesis ideas, is that the economy needs to move away from a linear model where resources are mined at one end, processed, and then wastes thrown away at the other end, into a sink called 'nature'; rather the outputs of one process need to be linked as inputs into other processes, on the biological model of the great natural cycles of carbon, nitrogen and other resources.[7] In all these ways, China is on track to successfully implement its energy revolution. However the immediate problem of dealing with pollution remains.

BOX 5.4 *'Under the Dome' and 'Silent Spring'*[a]

Under the Dome, the documentary on China's smog issue that has been an Internet phenomenon, invites comparison with *Silent Spring*, Rachel Carson's 1962 exposé of the effects of pesticides. There are indeed striking similarities between the two. Both focus on environmental issues of huge concern to their respective societies; both were made by women with national reputations for their previous work; and both spurred unprecedented national discussions. For all their similarities, there are still many hurdles facing the documentary that Carson's book did not experience.

China is undergoing significant social change, with a growing middle class who are more concerned with quality of life than basic needs, and who are willing to raise their voice over issues that affect their health. This is a similar context to the post-war America in which *Silent Spring* was published. Yet today's world is also more globalized than that of 1962, a fact that could have opposite effects on China's environmental movement. On one hand, the potential solutions to global issues such as climate change, and local issues such as air pollution, may mutually interact and feed off each other.

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On the other hand, globalization has made people more mobile, both within and between countries. Migration has become an option for some Chinese to escape the smog, which might reduce their motivation to engage in the local environmental issues.

In many ways, the reception given to *Under the Dome* is broadly similar to that received by *Silent Spring*. Both were challenged by economic interests, such as the chemical industry in the case of pesticides, and fossil fuel firms in the case of smog. Both were also criticized for a perceived lack of 'balance' or author expertise, and were even accused of being political conspiracies. Both have received plaudits from the scientific community. The legacy of *Silent Spring* was honoured by the American Chemical Society in 2012, while a Chinese professor blogged about *Under the Dome* that '... [compared with Chai Jing] we experts in the field of environmental protection and scientists on the smog research should feel ashamed for our incompetence to communicate with the public and our lack of courage to expose the problem'.

Perhaps the most important difference lies in how the two respective governments reacted, especially given that both the book and the documentary broadly chimed with what authorities were trying to do at the time. *Silent Spring* was published when the then US president John F. Kennedy was implementing his New Frontier programme, while *Under the Dome* has coincided with the Chinese leadership is committing to an 'energy revolution'.

Several key ideas advocated in *Under the Dome* to fight smog are aligned with the government's agenda, such as reducing the share of fossil fuels in the country's energy supply, and increasing the share of renewable energy sources. This may partly explain why the documentary was first released on the website of *People's Daily*, the official newspaper of the Communist Party, and why the resulting media and online criticisms of the government's handling of the smog issue were initially tolerated despite such comments usually being closely monitored and censored by the state. However, after a week of explosive discussion in the public sphere, the documentary was taken down from all Chinese websites. Contrast that with the policy response triggered by Silent Spring, including the appointment of the President's Science Advisory Committee, hearings on the issue in the Senate, and the establishment of the US Environmental Protection Agency. The Chinese government seems

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to fear that grassroots movements may undermine its legitimacy in ruling the country, and very much prefers a top-down approach for the country's energy revolution.

Note: [a]This Box is adapted from an opinion piece by one of the authors (HT) published in Australia's *TheConversation.com*, available at https://theconversation.com/chinas-silent-spring-has-many-more-political-hurdles-to-jump-38604.

Financing China's energy revolution

The sums involved for investment in China's energy future are as vast as the levels of power to be generated. Research by McKinsey indicates that investments in China's renewable energy economy could require as much as 30 to 40 trillion yuan (up to US$ 5.8 trillion) by 2030 – in incremental amounts in each five-year period, rising from Euro 35 billion up to 2015, 145 billion up to 2020, 240 billion up to 2025 and 300 billion Euro by 2030.[8] Comparable sums needed for global investment are voiced by agencies such as the EIA. Chinese financial authorities themselves estimate the sums involved for the immediate future would be of the order of RMB 2.9 trillion per year (US$ 460 billion) over the period 2015–2020 – or approximately 14 trillion yuan (US$ 2.3 trillion) over the five-year period.[9] Where are such vast sums to come from?

McKinsey has no answers on this score, apart from going through the usual range of sources such as the International Finance Group (a branch of the World Bank), the UN's Clean Development Mechanism and multilateral institutions such as the Asian Development Bank. But clearly far greater sums that could be raised by these institutions are going to be needed. Of course China has its own very considerable resources that can be mobilized for the financing of investment in infrastructure and renewable energies. There are the 'Big Four' state-owned commercial banks, which play the role of development financial institutions, and can offer low-cost loans to targeted projects in targeted sectors. The newly created Asia Infrastructure Investment Bank (AIIB) will also undoubtedly play an important role in financing this transformation, particularly for projects involving Chinese firms operating abroad. And corporates such as the China Rail Corporation (CRC) already offer extensive bonds for the financing of the high-speed rail network. Indeed China Railways

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is the largest single issuer of green bonds in the global rail sector, accounting for $140.6 billion of the total bonds issued.[10]

China's financial system is clearly gearing up for a major push in green finance, based on a clear understanding of the need for finance to complement initiatives in energy and resource efficiency. In March 2015 the Finance Research Institute of the Development Research Center (DRC) of the State Council (China's highest official policy body) joined with the International Institute for Sustainable Development to produce a series of recommendations on the greening of the financial system, including the issuing of green credit guidelines to all state-owned banks; green insurance guidelines; green bank lending; and green bonds as means of raising extensive and low-cost capital, from both the Chinese and foreign bond markets.

Apart from China's own considerable resources, such as those held in its foreign currency reserves, one can anticipate that new means of financing will be developed along with the renewable energy technologies themselves. One such source that is currently being discussed is 'Climate bonds/green bonds' or securities issued by banks on the world's bond markets.[11] These financial instruments are targeted at institutional investors, who are estimated by the OECD to have upwards of US$ 70 trillion under management.[12] Some of China's leading banks would no doubt be candidates as issuers of such debt instruments if they are backed by firm guarantees from the Chinese government and by credible commitments to invest the proceeds in designated renewable energy projects and low-carbon technologies.

The People's Bank of China (PBC) (China's central bank) has a comprehensive programme of driving China's energy revolution with green financing, with an emphasis on expanding the role of debt markets (e.g. green bonds) and carbon markets. The PBC's chief economist, Ma Jun, is a prominent exponent of the need to rapidly green China's financial system through such measures.[13]

There are specifically green financing measures now being undertaken, such as the newly established Green Ecological Silk Road Investment Fund, launched in March 2015 to provide financing for projects such as solar PV farms and ecological remediation along the proposed China–Central Asia 'Green Silk Road' corridor. The first round of capitalization of the fund is set at 30 billion yuan (US$ 4.8 billion).

So China's impressive national infrastructure projects involving the building of a national strong and smart electric power grid, and a

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national high-speed rail system, is matched and complemented by a national programme for the greening of finance. Green bonds, green bank loans and green insurance are all seen as playing their role, overseen and reviewed by the People's Bank of China. One would have to go back in Chinese history to the building of the Grand Canal which was finalized during the Sui dynasty in the 7th century AD to find a comparable national infrastructure project.[14]

Notes

1 See the papers on this theme by one of us (Mathews 2007; 2008); and for the original latecomer formulation, Gerschenkron (1962).

2 See Unruh (2000; 2002; Unruh and Carrillo-Hermosilla 2006) for exposition of carbon lock-in.

3 On the centrality of energy issues to industrial development, see Mathews (2008). China's approach to building new energy industries while making itself energy-independent is missed by some commentators. An example is the otherwise comprehensive study of China's energy programs published by the World Bank in 2007 (Berrah 2007). This report is conspicuous by its passing over renewable energies mostly in silence, and its silence on the role that such industries could play in industrial development.

4 See Howell et al. (2010).

5 See Tan, H. and Mathews, J. A. Accelerated internationalization and resource leverage strategizing: The case of Chinese wind turbine manufacturers. *Journal of World Business*. 50(3), 417-427.

6 The 'developmental state' tradition emanates from the experiences of East Asia in successfully catching-up with the advanced countries; see Weiss (1998), Mathews (2006) or Lee and Mathews (2010) for recent expositions. For an application of the concept to energy matters, see Mathews (2007; 2008).

7 The Chinese Law on the Circular Economy was passed in 2008 and came into effect in 2009; it guides the eco-industrial initiatives found in several newly designated Eco-Industrial Parks, such as in the Tianjin Economic Development Area (TEDA). For a description and analysis of these developments, see Mathews, Tang and Tan (2010) as well as Mathews and Tan (2011).

8 See McKinsey and Co., Greater China Office, March 2009, 'China's Green Revolution', at: http://www.mckinsey.com/locations/greaterchina/mckonchina/reports/china_green_revolution.aspx

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9 See *Greening China's Financial System*, Synthesis Report, by Zhang Chenghui, Simon Zadek, Chen Ning and Mark Halle (March 2015), Development Research Center of the State Council, PRC; and International Institute for Sustainable development, at: http://www.iisd.org/pdf/2014/greening_china_financial_system_en.pdf

10 See the report *Bonds and Climate Change: State of the Market 2014*, issued by Climate Bonds Initiative in London, at: http://www.climatebonds.net/files/post/files/cb-hsbc-15july2014-a3-final.pdf (Disclosure: JM is a member of the CBI Advisory Group.)

11 See Mathews et al. (2010) for a brief introduction to climate bonds and their rationale. The 'Climate Bonds Initiative' was launched at the Copenhagen COP 15 conference in December 2009; see the website at: http://climatebonds.net/

12 For discussion, see the OECD reports by Della Croce et al. (2011) and Kaminker and Stewart (2012).

13 For discussion of the proposed measures, see 'Report from Beijing: PBoC chief economist Ma Jun's green finance workgroups close to the finish line – ambitious proposals on the table', Climate Bonds Initiative, Sean Kidney, 19 November 2014, at: http://www.climatebonds.net/2014/11/report-beijing-pboc-chief-economist-ma-jun%E2%80%99s-green-finance-workgroups-close-finish-line

14 The Grand Canal was one of the greatest infrastructure projects undertaken in the pre-industrial world, built largely in the Sui Dynasty (581–618 AD). It stretches from Beijing to Hangzhou, and links the Yellow River to the Yangtze River. Its length is 1,776 km. It is still widely used today by Chinese shipping, 1,400 years after its construction.

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6
Global Impact of China's Energy Revolution

Abstract: *China's energy revolution has an impact not just in China but around the world. The most immediate impact is in drastically reducing costs for producing renewable power; these cost reductions, following technology-specific learning curves, drive uptake of renewables in China as well as in other countries. Renewables are coming to be an energy choice for developing countries everywhere, enhancing energy security and reducing carbon emissions. China's energy consumption is also generating the world's highest aggregate levels of carbon emissions, which are increasingly viewed as a global issue to whose solution China will also have to make its contribution. At the same time China's approach to ensuring its energy security through manufacturing is likely to become a model for other industrializing countries.*

Keywords: carbon emissions; global cost reduction; grid parity; learning curves; logistic uptake of renewables; resource availability

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The effects of China's energy revolution are felt first, of course, in China itself – as explored in the previous chapters. But the impacts more broadly, on aspects as diverse as declining costs of renewable energy production and changing carbon emissions, are also important. We review these wider impacts in this chapter, focusing on six areas: the diffusion of cost reduction; China's addition of carbon emissions to those already created by the West; resource implications of China's renewable energy revolution; the trade conflicts created by China's active promotion of renewable energy industries; the greening of China's urbanization and the impact this is having globally; and finally the likely emulation of China's energy strategies by other large developing countries, such as India or Brazil.

China's energy revolution has profound implications for developing countries everywhere, for whom an energy future based on renewables becomes ever more feasible – with positive implications for the industrialization efforts of the countries themselves (particularly India and Brazil), and for global concerns over carbon emissions and climate change.

Falling costs and their global impact

We covered the technical aspects of falling costs of renewable energies, captured in the learning curve, in previous chapters. Here we wish to highlight the global significance of these falling costs. Most commentators on renewable energy issues recognize that the dramatically falling costs are the single most important feature driving the diffusion of renewables globally. But fewer commentators recognize that it is China that has been driving down these costs – as the scale of its production has increased.

Indeed there is still a pervasive view that renewable energy is costlier than its fossil fuel counterparts – a view that is now being exploded as costs come down, largely through China's efforts.[1] In many parts of the world the cost of generating electric power from wind or solar PV is now less than or comparable with the cost of producing power from fossil fuels.[2]

In many places with good sunshine (including parts of China) producing electric power from solar PVs is now cheaper than producing power from conventional sources, for example, stand-alone diesel generators. Global investment banks such as UBS now talk of the 'unsubsidized solar revolution'.[3] For developing countries, these cost reductions mean that building power systems that utilize solar input received within the country (rather than fossil fuel imports with all their energy insecurity implications) become more attractive as underpinning development strategy, based on reliable and cost-effective power. This is a powerful implication of the falling solar PV costs.

Wind energy as well exhibits learning curve advantages, with costs declining for onshore wind at the rate of approximately 7 percent per annum. Wind power is well on the way to having a global generating capacity of 1 TW – the size of the current entire United States or Chinese generating capacity. As it does so, the 7 percent cost reduction curve will make wind power more and more attractive for countries endowed with the resource, such as China.[4]

Other green technologies such as batteries display comparable experience curves and dramatic cost reductions – as demonstrated in numerous studies and most recently by the Intergovernmental Panel on Climate Change (IPCC) itself in its study of *Renewable Energies* (IPCC 2012) where it states that with adequate government support, renewable energies should be accounting for just on 80 percent of primary energy inputs by 2050. In the case of batteries the earlier generation Nickel Metal Hydride batteries have now largely exhausted their learning curve advantages, while the newer Lithium-ion batteries have substantial learning curve cost reductions already achieved and anticipated for the future. These cost reductions for batteries will in turn mean cost reductions for electric vehicles, and thus the cost-driven capitalist processes of substitution will diffuse, from manufacturing and power generation to transport and beyond. One of the surprising industries to benefit from these falling costs, and changing its business strategies as a result, is the Chilean minerals mining industry.

BOX 6.1 *Impact of falling costs and prices for renewables: The case of Chilean minerals*

Mining companies in Chile are building independent solar, solar thermal, wind and geothermal power plants that produce power at costs competitive with or lower than conventional fuel supplies or grid-connected electric power.[a] Chile is emerging as the southern hemisphere's renewable energy giant.

Here are some examples. The Cerro Dominador concentrated solar power (CSP) plant, rated at 110 MW and utilizing Abengoa technology, now supplies regular uninterrupted power to the

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Antofagasta Minerals complex in the dry north of Chile, in the Atacama desert. This is one of the largest CSP plants in the world, utilizing an array of mirrors and lenses to concentrate the sun's rays onto a power tower, and utilizing thermal storage in the form of molten salts – as perfected by Abengoa in Spain's CSP industry. It supplies steady, dispatchable power, day and night.

The El Arrayán wind power project, rated at 115 MW, now supplies power to the Los Pelambres mine of Antofagasta Minerals, using Pattern Energy (US) as technology partner. Antofagasta Minerals has also contracted with the US PV company SunEdison to build solar PV arrays at the Los Pelambres mine, with a power plant rated at 70 MW; while the related plant operated by Amenecer Solar CAP is rated at 100 MW, the largest such array in Latin America when it came online in 2014. There are many more such projects under review or in the pipeline. The Chilean Renewable Energy Center reported in 2014 that the pipeline of renewable power projects in Chile added up to 18,000 MW (or 18 GW), which is more than the country's entire current electric power grid.

Why are the costs of generating renewable power in remote mining sites coming down, to becoming competitive with conventional fossil fuelled generation? The answer, in a word, is China. As we have argued in this text, as the scale of China's renewable power expands, so the unit costs decline. This is the iron law of the learning curve. It is advantageous for China, of course, but it also means that the same lower costs can be enjoyed by other countries – in this case, Chilean power producers supplying renewable power to the minerals sector. The underlying technology is diffused around the world, and competition ensures that the lower costs are shared by all.

Note: [a]This section is based on JM's article in *The Conversation*, Chile's mines set hot pace on renewables, 17 December 2014, at: http://theconversation.com/chiles-mines-set-hot-pace-on-renewables-australia-take-note-35533.

China's carbon burning and emissions

The other big question concerns China's carbon emissions. Just how much carbon is likely be emitted from burning fossil fuel – including coal, oil and gas – in China during this Renewable Energy Revolution? We revisit this question that was raised in Chapter 1. As discussed earlier, we formulate our estimate based on two parameters, that is: (1), the peaking time of China's carbon emissions which is according to the recent China-US Climate Change announcement (i.e. 2030 or earlier), and (2) the peaking emissions, where we take the estimate by the MIT-Tsinghua research project in its 'middle' scenario (i.e. 12.1 Gt of carbon dioxide (CO_2)). We estimate that in contrast to those of renewable energies, the trends of energy consumption from fossil fuels will largely display as convex curves. Based on those two key parameters, we can model the trajectories of emissions of CO_2 from burning fossil fuels in China up to 2050 as quadratic functions. The data generated by the model suggest that, between the periods 2014 and 2020, 2021 and 2030, 2031–2040, and 2041–2050, China would emit 72.5, 118.8, 118.1 and 96.7 Gt of CO_2 respectively. Over the whole period between 2014 and 2050, China would be expected to emit 406 Gt of CO_2 in total, or 110 Gt of carbon (Figure 6.1, reproducing Figure 1.10 in Chapter 1). Going back to the year 2000, we would estimate China's carbon emissions as being around 494 Gt CO_2, or 135 Gt carbon. This may be counted as the total carbon 'cost' of China's industrialization.

We may ask what will be the impact on CO_2 levels of these extra gigatonnes of carbon emitted as a by-product of China's industrialization? We know (e.g. from the Carbon Mitigation Initiative at Princeton) that addition of each billion tonne of carbon to the atmosphere each year drives up the volume-based measure of CO_2 concentration by around

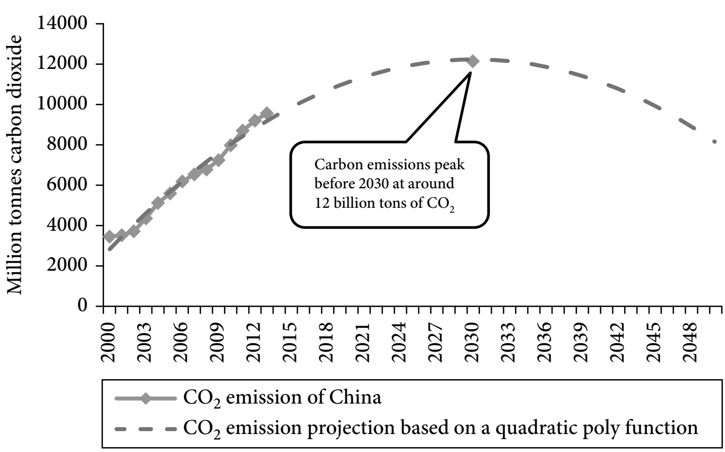

FIGURE 6.1 *China: projection of carbon emissions to atmosphere, 2000–2050*
Source: Authors.

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0.22 ppm for each Gt carbon emitted.[5] Thus addition of 110 Gt of carbon emitted by China cumulatively from now (2015) to the middle 2050 would force CO_2 concentrations to rise by 24 ppm.

So we seem to have an estimate of the 'carbon emissions' cost if China does follow the trajectory of the renewable energy revolution and associated industrialization, based on burning coal and other fossil fuels in its whole energy system. The 110 Gt carbon added to the atmosphere by China's industrialization and energy revolution up to the year 2050 is likely to drive up CO_2 concentrations by 24 ppm. Since the CO_2 concentration stands at about 400 ppm (in 2015),[6] China's net forcing is likely to drive this up to 424 ppm – taking the world close to the 'prudent level' of 450 ppm established by the IPCC. Of course other countries' carbon emissions have to be added to this to gain a global perspective.

We do not wish to be misunderstood on this point. We are certainly not advocating that China cease its industrialization because of the expected carbon emissions. This contribution from China needs to be compared with the cumulative contribution from the countries of the West as they industrialized; these countries emitted more than 440 Gt carbon over the 250 years from the Industrial Revolution to the year 2000, and drove up CO_2 concentrations from the pre-industrial level of 280 ppm to around 380 ppm by the year 2000 and 400 ppm by 2014.[7]

So China's industrialization from now up to the year 2050 is likely to 'cost' (in terms of carbon emissions) around just 25 percent of the carbon 'cost' of the Western industrialization experience. We are not surprised that China's cost should be lower because more efficient energy technologies are available now, and will become so, and are being used by China. The difference is that we can be confident that China will pass through and then beyond a fossil fuel phase – whereas we can have no such confidence that the West will break out of its 'carbon lock-in' and move on to new non-fossil fuel sources (Unruh 2000; 2002). Indeed the prospects for the West moving safely into a post-peak oil phase look grim; they look (to us) to be better in China.

Resource implications of China's energy revolution

A major source of concern is whether China's renewable energy revolution will run into resource constraints, directly in the form of available renewable resources (water, wind, sun) and in terms of land allocated to renewable energy projects, and through the materials required for manufacture of renewable power devices.

We have published on this topic, looking at the global transition underway to renewables and the resources challenge it represents, particularly the land resources required. In our paper published in the *Journal of Sustainable Energy Engineering* (Mathews and Tan 2014) we demonstrated that a 10-TW 'Big Push' to transform the world's fossil fuelled power system to one powered entirely by renewables, over the course of 20 years (2015 to 2035), would call for resources that are large but entirely feasible. In particular, we discussed a 'Big Push' of 10 TW of delivered power, calling for 30 TW of installed capacity based on renewable energy sources, and involving 3 million wind turbines (delivering 19.5 TW), 12,500 solar PV farms (delivering 5 TW), 14,000 CSP installations (delivering 5.6 TW) and 1000 hydro plants each rated at 1300 GW (delivering 1.3 TW). This huge transformation effort would call for land resources (on a worst case basis) of just over 5 million km^2 – noting that multiple uses are available for the land. Such a land area is equivalent to twice that of a country like Kazakhstan – clearly a substantial area, but one that could easily be accommodated in the world's desert and semi-desert areas; it constitutes just one thirtieth of the world's total land area of approx. 150 million km^2.

Now of course China's resource requirements would be much more modest. Let us again adopt a 'worst case' scenario and assume that China's build-up of renewables systems to be larger than in reality it is likely to be, and assess the resource requirements involved. In Figure 2.9 we take a likely scenario for China's adoption/take-up of renewable energy systems based on a projection by the National Centre of Electric Power Planning and Research, where it is anticipated that it would reach a target of 1.2 TW of renewable electric power by 2030 and possibly 1.7 TW by 2050 or before. So let us assess the resource and manufacturing requirements of meeting the target of a 2-TW 'Big Push' over the next three decades (bearing in mind that this is probably in excess of what the country will really have to achieve).

Scaling the results we reported in our *JSEE* paper, we would see China's challenge as meeting a target of installed renewable power of 2 TW. Using the same combination of renewable sources as we discussed in our *JSEE* paper, this would translate into the following manufacturing challenges (Table 6.1).

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TABLE 6.1 *Manufacturing challenges for China to meet 2 TW delivered power from renewable sources*

Energy technology	No. of plants or devices needed	Rated power of one plant or device (MW)	Installed capacity needed (TW)
Wind power	200,000	6.5	1.3
Solar PV	900	400	0.4
CSP	600	400	0.2
Hydropower	50	1300	0.1
Total			2.0

Source: Authors.

These targets are all manufacturing challenges: 200,000 wind turbines generating at a capacity of 1.3 TW (or 130 wind farms of 10 GW each)[8]; 900 solar PV farms at 400 MW each, delivering over 400 GW of capacity (or four times the current target for 2020); and 600 CSP installations, delivering a capacity of 200 GW. For hydro a simple scaling based on our *JSEE* paper would indicate 50 hydro installations generating at 100 GW of capacity – which is actually only another 50 GW on top of the 50 GW to be added from now to 2020 as planned by the National Development & Reform Commission (China) (ND&RC).

Applying the same ratios that we used for the global energy transition, the land requirements for such a scale-up of China's renewable energy capacity would amount to 330,000 km^2 – a land area that is just over 3 percent of China's total of 9.3 million km^2. In other words such an area could be easily accommodated in China's desert and arid/semi-arid areas, where there would be no interference with existing agricultural or pastoral activities.[9]The materials requirements can likewise be specified – and be shown to be very much within the scale of current industrial activities, in China and worldwide. Scaling down our estimates in the article on the 10 TW push (or about 30 TW of actual installation) for a global renewable energy system, the renewable energy revolution in China would require 37 million tonnes of iron, 120 million tons of steel, and 0.5 Gt concrete to build 1.3 TW of new wind power capacity needed over the next 30 years, or 1.3 million tonnes iron, 4 million tonnes steel and 15 million tonnes concrete annually. To build the required 200 GW of CSP would require between 25 and 29 million tonnes of glass, between 50 and 90 million tonnes of steel and about 5 million tonnes of aluminium over the period 2014–2050.[10] We make these calculations in

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order to demonstrate that the technical challenges involved in meeting renewable energy targets are large, yet feasible – thereby refuting claims that renewables impose impossible resource burdens.[11]

China's urbanization challenge

China is urbanizing and industrializing at the same time – at a pace unprecedented in history.[12] From a basically rural country at the time of the Revolution, it achieved 20 percent urbanization by 1980, then 30 percent by 1996, 40 percent by 2002 and 50 percent (or majority city-based) by 2011 – as shown in Figure 6.2. Over the decade from 2001 to 2010, China's urban population increased from 500 million to 680 million, or 180 million over the decade – meaning on average 18 million people moving to the cities each year. This is equivalent to building six new cities each year, each of three million inhabitants. This rate of urbanization is expected to continue. According to the 12th Five Year Plan (FYP), China's urbanization is anticipated to be 54 percent by 2015.[13]

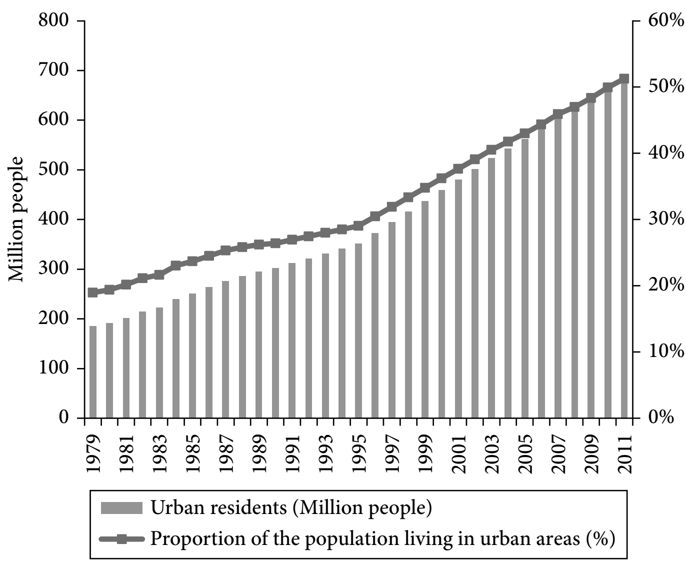

FIGURE 6.2 *Urban residents and their proportion in the total population in China: 1979–2011*

Source: Authors. Based on data from the NBS (2011).

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Rapid urbanization in the 21st century raises critical challenges for China to combat pollution and climate change. Compared to its rural counterpart, the modern urban life style tends to lead to higher energy consumption and carbon emissions per capita. On the one hand, current levels of per capita energy consumption in Chinese cities reflects higher income levels and better quality of life. On the other hand, at the same level of expenditure city residents consume less energy than their rural peers because of improved efficiencies enabled by cities. Against this background, it is not surprising that increasing efforts have been made in China to reduce pollution and energy consumption in cities; a number of initiatives at the city level have been implemented.[14] However, it was not until 2008 that the concept and term 'low carbon city' was introduced in China by the World Wildlife Fund (WWF), a non-government organization. In that year the WWF in collaboration with two municipal governments in China introduced a 'Low Carbon City Initiative' which was specifically designed for the context of cities. Among the two participating cities in the initiative, Shanghai was expected to focus on promotion of new eco-buildings and improvement of energy efficiency of existing buildings, and engagement of the public to raise their awareness in energy saving. Another participating city, Baoding, was to facilitate local renewable energy industries as a means toward establishment of low carbon cities.

In 2010, the notion of low carbon cities was picked up at the national level. In 2010, the National Development and Reform Commission (NDRC), the country's premier policy maker, chose five provinces (Guangdong, Liaoning, Hubei, Shaanxi and Yunnan) and eight cities (Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang and Baoding) as pioneering cities and provinces for pilots of low carbon initiatives.[15] In 2012, the second batch of participating provinces and cities for low carbon pilot projects was announced, including two municipalities (Beijing and Shanghai) and 26 other cities.[16] These now represent the front line in China's green urbanization challenge.

In keeping with its greening strategies overall, as China tackles the huge task of urbanizing in a green fashion it utilizes models developed around the world.[17] Under the NDRC's 'low carbon cities' guideline, some of the models proposed by local or provincial governments are in line with international experience (Table 6.2). We note that by 2015 China was able to specify in its submission on climate goals to the United Nations that it would seek to raise the share of green buildings in new construction projects to reach 50 percent by 2020.

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TABLE 6.2 *Patterns of development of Chinese low carbon cities*

Type	Features	Chinese cities	International model
1	Zero emission as an overall objective	Chongming Island, Shanghai	Copenhagen
2	Development of low carbon local communities	None	London
3	Focus on a change of industrial structure	Suzhou	Birmingham in UK
4	Comprehensive measures towards low carbon society	Hangzhou	Tokyo
5	Focus on industrial development in renewable energy production	Baoding, Dezhou	Barcelona
6	Focus on key low-carbon projects	Shanghai	n/a

Source: Based on Song and Zhang (2012).

We highlight the cases of Wuxi and Baoding to show how local initiative is what drives these urban greening processes.

Wuxi

The town of Wuxi, famous as the headquarters of Suntech solar PV panels production (as well as others such as Canadian Solar and Trina Solar), is also a leading proponent of greening strategies involving Circular Economy initiatives. Wuxi achieved unsought notoriety in 2007 with an outbreak of blue-green algae in the heavily polluted Taihu Lake – severely contaminating the city's water supplies. Since then determined efforts have been made to turn the problem into a solution. Much of the industrial water that was formerly a waste product at Wuxi (from companies like Suntech and Hynix Semiconductor) is now treated by the company Wuxi Deppel Water Investment Co, capable of reclaiming 10,000 tonnes of wastewater each day. Using advanced membranes, the company takes waste water as input and turns it into a useful output, thereby closing the water loop in the semiconductor and solar PV manufacturing industries.[18]

Baoding

The city of Baoding, just 100 km from Beijing, provides another graphic illustration of China's urban greening strategies and the global impact these are having. After experiencing a major pollution crisis in the 1990s, the city of Baoding embarked on a serious course to reinvent itself as a renewable energy cluster, succeeding in attracting multiple firms in the solar and wind turbine manufacturing business (such as Guodian

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United Power in production of wind turbines), as well as energy efficiency equipment. This cluster is based on the Baoding New and High Technology Industrial Zone, which by 2014 boasted the presence of numerous firms all engaged in the manufacture of renewable energy and energy efficiency systems and their associated value chains.[19]

Trade conflicts engendered by China's promotion of renewable energy industries

We have noted repeatedly that China has been promoting not just the utilization of renewable energy systems to green its electric power generation, but has been actively promoting its renewable energy industries as well. This has resulted in trade conflicts, as countries hit back at China's export successes.[20] Washington think tanks have been arguing that no one can stand up to Chinese mercantilist policies which promote standardized products at the expense of innovative new ventures competing in market niches. But is China really the ogre that is destroying 'the global energy innovation ecosystem'?[21]

There would appear to be some prima facie support for such an argument when we look at United States and European companies that have been developing innovative new solar PV cells. They have had to succumb to Chinese competitive pressures in recent years. Solyndra in the United States had to declare bankruptcy, after first generation crystalline silicon PV cells reached costs lower than its second generation CIGS cells. German Q-Cells had to sell off its CIGS subsidiary, Solibro (CIGS stands for Copper, Indium, Gallium, Selenide – alternative materials to silicon). Chinese power producer Hanergy snapped up the firm. These were two cases where the firms were developing new CIGS 'thin film' solar cells that would operate at slightly lower efficiencies, but much lower material costs, thereby promising decisive cost advantages. But they were never able to capture these potential cost advantages as costs of first generation cells continued to plummet – the China effect.

Chinese support for renewable energy is determined, serious and relentless. China targets well-established and standardized technologies for rapid scaling-up and diffusion (such as first generation crystalline solar PV cells), and does so very effectively. The strategy is being pursued not primarily for reasons to do with climate change, but as a national energy security policy, to allow China to build its energy system without

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impinging on other countries' fossil fuel entitlements and thereby threatening war. It is a smart strategy that suits China. So how then should other countries respond?

One way is through trade retaliation. The US government has provided one way forward, by seeking to curb Chinese activities overseas and imposing trade sanctions (countervailing duties and antidumping duties (CV&ADs)) on Chinese-made imports of solar cells into the United States. The European Union (EU), for its part, has imposed even broader sanctions, not just on PV cells but on modules and whole systems as well. Such tariffs are designed to curb sales of China-made products abroad.

Either instrument is rather blunt – and already circumvented by smart Chinese companies. They have been building their manufacturing base in the United States and are globalizing their production activities and importing solar cells into the United States from non-mainland Chinese sources (e.g. Taiwan). Moreover, the Chinese are perfectly able to impose counter-tariffs on US exports of high-value PV components and materials, including pure-grade silicon (where the United States currently runs a trade surplus with China). These unanticipated consequences are likely to make the US trade sanctions relatively ineffective – while incurring severe displeasure from China, for which there will be a political price to pay.

The EU has also opted for a different competitive strategy. The European market for solar PV systems was expanded through consumer subsidies, notably feed-in tariffs – in the expectation that German manufacturing industries would expand to supply the market. As a market expansion strategy, this worked extremely well, allowing firms to benefit from cost reductions via the learning curve. But, of course, it turned out that Chinese firms were the main beneficiaries – in the absence of specific German industrial policies designed to grow the market in Germany for German-owned and designed PV technologies. Since Germany's swing against nuclear power in 2011/2012, there has in fact been a revival of German industrial policies designed to boost what is left of the solar PV cell manufacturing sector – with (so far) positive results.

The US-China dispute reached something close to a settlement in January 2015 when the US Commerce Department announced lower punitive tariffs following its review for the period 2012–2013.[22] The EU was likewise forced by internal divisions to relax its initial strong imposition of punitive tariffs. Ultimately, however, there is only one effective response to the serious competitive threat posed by China's strong support for renewables – and that is equally strong support for innovation and market expansion by Western countries.

Our suggestion is that advanced countries apply industrial strategies for the building of their own industries to counter China. Other countries can place reasonable curbs on China's imports (regulating that they remain below a certain threshold, in line with World Trade Organization [WTO] stipulations), while actively supporting and building innovative alternatives to China's standardized products. It was open (and still is open) to the United States, EU and Japanese governments to opt for policies to rapidly build the market for new, thin-film CIGS solar cells (through producer subsidies and government procurement, both allowable under WTO rules). That would ensure that they achieve cost reductions that would keep them ahead of their first generation crystalline silicon alternatives.

If the market for CIGS cells is grown fast enough, then CIGS technology will become the new dominant technology, with German, United States and Japanese firms already occupying a strong position, and able to tweak the technology to drive further improvements. Of course, Chinese firms would then switch to this new, dominant CIGS technology, driving costs and prices down as they do so – and so weaker German, United States and Japanese firms would be driven from the market. But stronger ones would maintain their position, particularly in supplying their domestic market, while they ramp up further innovative variations. And so the process would continue, from one technology generation to another.

Why don't the United States, German (EU) or Japanese governments pursue such an obvious counter to the Chinese competitive onslaught? In a word – because they are afraid of anything smacking of 'industry policy'. So powerful has the neoclassical objection to anything to do with promotion of some specific technology become (called 'picking winners') and promotion of market expansion through government procurement (called 'market interference') that policy makers are now afraid to propose anything along these lines. The net effect of these ideological blinders is that they leave the field wide open to the Chinese.

Think tanks like the Information Technology and Innovation Foundation valiantly struggle to portray 'innovation' as the only way forward, and provide support for trade sanctions – under the guise that Chinese policies are 'mercantilist' (and yet are no more so than those

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pursued by individual US states like California). What they should really be supporting (in our view) is a full-blooded counter to Chinese targeted industry promotion, through counter-targeting of new, innovative technologies and deliberate and determined market expansion via instruments such as public procurement.

China's energy strategy and world development

As China's scaling-up of its renewable energy capacities and its enhancement of resource efficiencies through the Circular Economy improves, so it becomes increasingly attractive as a model for other developing countries. Take the case of Africa, which has languished for the past half century while other countries in East Asia have raced ahead. Now China is the major investor in infrastructure in Africa, building new energy systems, transport infrastructure and other projects. Several projects in Africa have been mentioned already. There are solar PV farms involving Chinese solar cell producers such as Yingli and JA Solar; solar farm construction companies such as Powerway; and established hydropower SOEs like SinoHydro, HydroChina and Three Gorges Corporation all diversifying into new infrastructure projects with a strong focus on Africa. China's investments are an exercise in 'soft power' that would appear to be paying handsome dividends.[23]

China's strategies are likely to prove attractive to many developing countries, demonstrating as they do that countries can build their industrialization efforts around renewables and the manufacturing activities that they entail – rather than through playing geopolitics with fossil fuels and incurring the crushing import costs that have wrecked economies in the past. China's model also offers a clear alternative to countries like India and Indonesia, even as they ramp up their coal and fossil fuel supplies. China has exploded the myth that countries have to go through a fossil fuel apprenticeship before they can play a role on the world stage.

Notes

1 This section is based on pp.105–108 in JM's book, *Greening of Capitalism: How Asia is Driving the Next Great Transformation* (Stanford University Press, 2014).

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2 The Deutsche Bank has lent its name to such a prediction; see Becky Beetz, Deutsche Bank – Sustainable solar market expected in 2014, *pv-magazine*, 28 February 2013, at: http://www.pv-magazine.com/news/details/beitrag/deutsche-bank--sustainable-solar-market-expected-in-2014_100010338/#axzz2NJVDi3wr

3 See UBS Investment Research, 'The unsubsidised solar revolution' (15 January 2013) which explains the reasoning; widely reproduced at: http://qualenergia.it/sites/default/files/articolo-doc/UBS.pdf

4 Technological innovations such as Permanent Magnet Direct Drive (PMDD), being taken up and propagated by Chinese and German giants such as Goldwind and Enercon, eliminate the need for gearing and drastically reduce maintenance costs, especially for offshore wind power farms. In this way technological innovation works with the experience curve to drive down costs.

5 See the Carbon Mitigation Initiative website, and the presentation on Stabilization wedges at: http://cmi.princeton.edu/wedges/slides.php

6 http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html

7 See the webpage of the Carbon Dioxide Information and Analysis Center at: http://cdiac.ornl.gov/pns/current_ghg.html. For the estimate of the cumulative carbon emissions over the 250 years, 1750–2000, see Allen et al. (2009).

8 Note that China had already installed over 66,000 wind turbines by 2013 – so the 600,000 target is not insurmountable.

9 According to a report in *China Daily*, China currently has about 2.6 million km^2 of desertified land, and 170 million km^2 of land eroded by sand. http://www.chinadaily.com.cn/cndy/2011-01/05/content_11795228.htm

10 Those estimates are based on specifications in Pihl et al. (2012).

11 See, for example, Ausubel (2007) whose claims are refuted by the Chinese experience.

12 This section is based on Mathews, Hu and Tan (2013).

13 McKinseys expect the addition of a further 300 million people to cities in China over the 20 years from 2010 to 2030 – or on average a growth of the urban population of 15 million per year.

14 See 'China must take care of its city-dwellers', by Tom Miller, *Financial Times*, 14 April 2013, at: http://www.ft.com/intl/cms/s/0/ab9a6376-a358-11e2-ac00-00144feabdc0.html#axzz2mRQqJo1l

15 See the 'Notice from the NDRC about carrying out the work of low-carbon provinces, autonomous regions, and cities pilot projects', at: http://www.sdpc.gov.cn/zcfb/zcfbtz/2010tz/t20100810_365264.htm (in Chinese).

16 See http://www.ndrc.gov.cn/gzdt/t20121205_517506.htm (in Chinese).

17 See Song and Zhang (2012) for a categorization of Chinese urban greening projects into several types.

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18 See 'Fueling the Circular Economy', *China Daily*, 13 May 2011, at: http://europe.chinadaily.com.cn/epaper/2011-05/13/content_12504548.htm

19 For a discussion of the strategy of cluster formation as driver of renewable energy industries promotion, with a focus on Baoding, see Dong et al. (2014).

20 The following section is based on the posting by one of us (JM) to *The Globalist*, How to compete with China in renewables, 26 April 2013, at: http://www.theglobalist.com/the-globalist-debate-how-to-compete-with-china-in-renewables/

21 See Matthew Stepp, The dangerous appeal of China's green mercantilism, *The Globalist*, 6 February 2013, at: http://www.theglobalist.com/the-globalist-debate-the-dangerous-appeal-of-chinas-green-mercantilism/

22 See 'US agency confirms final duties on Chinese, Taiwan solar products'. 29 January 2015, ICTSD at: http://www.ictsd.org/bridges-news/bridges/news/us-agency-confirms-final-duties-on-china-taiwan-solar-products

23 See 'China's investment in infrastructure key to Africa's development: experts', *People's Daily*, 24 February 2015, at: http://en.people.cn/n/2015/0224/c90883-8853073.html

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7
Concluding Remarks

Abstract: *China is building a 21st century infrastructure based on electric power (industrial power, high speed rail) that is increasingly sourced from renewables, and is likely therefore to emerge as world leader in all the associated products and technologies involved – just as the United States emerged as world leader of oil-based industries and technologies in the 20th century, and Britain and Germany had emerged as world leaders of coal-based technologies in the 19th century. There are clear implications for international political economy in such an analysis. China may be viewed as the world's first country to be liberated from the constraints of fossil fuel dependence, and as such the creator of a new energy paradigm with epochal implications.*

Keywords: breaking free of carbon lock-in; coal-based national strategy; new technoeconomic paradigm; oil-based national strategy; renewables-based national strategy

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China's energy revolution is a world-historic event with global ramifications. It is having a profound impact in China itself as the country pioneers a national energy strategy based on the domestic manufacture of renewable devices and their utilization to capture renewable sources of energy at home. It is also having a profound impact on the rest of the world as China drives through a green industrial revolution that others had contemplated but none had dared to accomplish at the scale now being pursued. China is building a 21st century infrastructure based on electric power (industrial power, high speed rail) that is increasingly sourced from renewables, and is likely therefore to emerge as world leader in all the associated products and technologies involved – just as the United States emerged as world leader of oil-based industries and technologies in the 20th century, and Britain and Germany had emerged as world leaders of coal-based technologies in the 19th century. There are clear implications for international political economy in such an analysis. And China's recent emergence as an industrial power is a phenomenon with long historical roots.[1]

Our broader argument is that China has taken renewables from the margins, where they were seen as a decorative addition to a country's 'real' energy policy which had to involve combinations of fossil fuels and nuclear, to a position where they play a central role not just in solving problems of energy security but are seen as central pillars of the future economy. This liberates renewables from being burdened as the principal source of decarbonization – an important role, but not necessarily their most important feature.

We argue that the key to success in the renewables transition is to view them from a different perspective, not so much as sources of lower carbon emissions (decarbonization) but as sources of energy security – what may be called 'energy security through manufacturing'. This was the key point in the paper we published in *Nature* last September 'Build energy security through manufacturing'. This is what China is doing (though never stating it as such) and what Germany is now doing and what one can predict Japan will soon be doing.

Following on from this we argue that the usual emphasis on the United States (and to some extent the European Union and Japan) as purported pioneers of renewables technology is misconceived. These are in fact the places where carbon lock-in is most intense, and they are likely to be the slowest to make the transition. Instead China with a less developed form of carbon lock-in is likely to borrow technology from around the world

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and move fastest to the lead in the new energy regime. It has both motive and means (in the form of a strong state). It is already doing this in key renewables, and in high-speed rail and arguably in smart grid build-out.

It has taken a long time for a major country to break out of the grip of fossil fuels during the 'long 20th century' where oil, gas and coal held sway. There is now growing recognition that many of the wars of the past century, from small disturbances to major conflagrations, owe their origin to disputes over access to and ownership of oil and other fossil fuels. China too has been drawn into such disputes, as in its claims to oil from West Africa (Sudan, Chad and Darfur). But the difference is that China is also building its manufacturing systems for renewable energy devices that are making the country progressively less dependent on fossil fuel imports. We argue that these points are reinforced by learning curves, which drive down the costs of new energy systems as the scale of uptake increases. The fact that all renewables are the products of manufacturing means that they benefit most from cost reductions as the scale of production increases – which has been amply demonstrated by China. This means that government intervention to drive uptake, and government procurement, are as important as R&D in driving the transition.

China as a model for the developing world

Increasingly China is seeing itself not just as a successful case of development of a vast country, raising millions out of poverty, but increasingly as a model for other developing countries. China has always stayed aloof from the neoliberal economic policies favoured by the World Bank, the International Monetary Fund and the US Commerce Department, known as the 'Washington Consensus', and has instead pursued policies where the state acts as ultimate pilot, coordinator and agent of change, modelled pragmatically on the prior successful development experiences of Japan, Korea, Taiwan and Singapore.[2]

But China is going beyond any of these countries in the extent to which it places a change of energy paradigm at the very core of its development strategy – in the full knowledge that in breaking the 'carbon lock-in' that afflicts other economies, China is achieving several goals: it is promoting its own alternative energy industries and creating new export industries for the future, promoting rural development, building national infrastructure, reducing energy dependence on other countries (particularly

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oil suppliers) and, last but not least, playing its role in reducing the risks of global warming. This is an attractive model for the rest of the world.

The main features of China's energy pathway we have identified as being encapsulated in the following nine steps:

1. From 2001 onwards, when China opened up to the world trade and investment system, energy became of fundamental importance, and the foundations of a reliable and expandable energy system were laid.
2. Coal was viewed as the fossil fuel of choice, while at the same time drastic efforts to improve efficiency in the coal sector were implemented.
3. Oil and gas were seen as interim fossil fuels that could be secured through geopolitical initiatives around the world, opening up fuel pipelines to China (in some cases, literally) to stave of looming fuel shortages.
4. Coal substitutes including nuclear power and a range of renewable energy alternatives, led by hydro, wind and solar, were ramped up in drastic fashion, through investment, policy initiatives and relaxation of controls over entrepreneurship.
5. The building of supply chains (value chains) for these renewable energy and low-carbon industries was given the highest strategic planning priority, as well as the opening of export markets for products and equipment created by these industries.
6. The electric power system was viewed as the primary facilitating means for accommodating a variety of fluctuating power sources and its modernization and upgrading, using the world's most advanced high voltage power lines, was made a strategic priority.
7. The Chinese domestic market for electric power consumption was grown alongside the supply-side initiatives, in keeping with the comparable costs of generating power ('grid parity').
8. The carbon emissions from this 'big push' in energy-based industrial development would be contained as much as possible, through major efficiency initiatives and 'carbon intensity' targets, which would be highlighted by China in international climate change mitigation negotiations.
9. China's path would be held out as a model for other industrializing countries as a feasible way forward in an energy-constrained world.

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These nine steps constitute the foundations of what may be described as a 'Beijing model' of linking energy security with industrial development along economic and environmentally acceptable lines.

The energy revolution is now well underway, and it will doubtless have a huge impact everywhere. But we see China as *the* country to study in this regard, because we see it as the country that is going to set the pace in renewable energy adoption in one sector after another. It is already world leader in solar PV cell production; world leader in solar thermal installations; world leader in hydroelectricity; world leader in addition of new wind generation capacity; world leader in building and installing nuclear reactors – and it is likely to be soon world leader in PV cell installation, and no doubt in other renewable energy systems as well such as geothermal and bioenergy.

What we find so interesting about China's case is that for this country, renewable energy and low-carbon technologies are synonymous with its own industrial revolution. It is industrializing, in the sense of raising its energy levels to the point where they will be comparable with those in the West (e.g. in Europe), by breaking the 'carbon lock-in' that has delayed the energy revolution in other developed countries, particularly in the United States but also in Europe and Japan. While the United States has been changing tack under the Obama Administration, and investing heavily in R&D in renewable energies, this is perhaps too little too late as far as competing with China is concerned – the lead role has already been ceded to America's rival across the Pacific.

In a broader politico-economic context we see China's renewable energy revolution as being driven by the immediate need to control disastrous levels of pollution and in the medium-term to ensure energy and resource security. We have emphasized the point that energy security through renewables is based on the fact that they are products of manufacturing – a 'discovery' by China that goes back 400 years to the treatise by Antonio Serra of 1613 on the sources of wealth in cities. Serra contrasted the wealth of Venice based on manufacturing and trade with the poverty of Naples based on extraction (mining) of precious metals. The contrast between renewables based on manufacturing and fossil fuels based on extraction is immediate and telling and a powerful argument as to why countries should prefer an energy strategy based on renewables.[3] Now China sees renewables as a source of business success, of exports and global business influence – a source of wealth and power, as Orville Schell and John Delury put it, in China's long march to the 21st century.[4]

Notes

1 See Selden (2012) for a review of China's role in the international political economy and the country's continuing importance right through the 19th century.

2 There is a vast literature on the Washington Consensus and its critique. For a recent summary, and contribution to the development of a new BeST Consensus (Beijing-Seoul-Tokyo Consensus), see Lee and Mathews (2010).

3 This contrast, and the treatise by Serra published in 1613, is discussed in Mathews and Reinert (2014).

4 See Schell and Delury 2014.

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Appendix: Energy and Power Units and Measures

A perpetual obstacle to clear discussion of energy strategy is the multiplicity of units utilized and the confusions involved in creating equivalences between them. In the case of China this difficulty is compounded because the primary fuel utilized is coal, and so primary energy inputs in terms of coal equivalent are most appropriate – both to capture what is happening now and to depict the coal-displacing potential of renewable energy sources.

For example, 1 tonne of coal does not equal 1 tonne coal equivalent (tce). We are using a conversion factor of 1 tonne coal = 0.68 tonne coal equivalent, or conversely 1 tonne coal equivalent = 1.45 tonne coal. The reason for the discrepancy is that tce is a unit presenting energy theoretically generated by burning one metric tonne of coal, which has been defined to be equal to 29.27 GJ in China. However, the actual consumption of coal in its various types and grades would need to be higher to generate the same amount of energy.

The unit of watt hour is used for electrical energy. 1 GW source generates 8760 GWh at 100 percent efficiency in 1 year. In practice, different power sources deliver less than 100 percent efficiency. The annual utilization hours of different power generating facilities vary for technological, economic and institutional reasons. According to the historical data from the National Energy Administration (China) (NEA), the numbers of average annual utilization

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hours during the period 2005–2013 for hydropower, wind, solar, nuclear and thermal power facilities in China are 3425, 1958, 1190, 7806 and 5210 respectively.

For other unit conversations, readers can consult the website http://www.conversion-website.com/energy/energy.html.

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