In the struggle to mitigate the worst impacts of global climate change, China’s energy transformation will be a critical example for the rest of the world. As the world’s largest emitter of greenhouse gases and the world’s second-largest economy, China’s strategies for blending economic growth with decarbonization will be watched carefully, particularly by rapidly-growing countries at earlier stages of development. China has made it clear to the world that it takes climate change seriously, and it is investing in multiple decarbonization strategies, from widespread deployment of wind and solar, to a growing nuclear program, to electrification of transportation. Indeed, China now leads the world in all three major forms of nonfossil energy deployment: wind, solar, and nuclear. China’s bilateral agreement with the United States in 2014 was critical to energizing the Paris Agreement. China agreed to stabilize current emissions by 2030, and to increase its share of nonfossil primary energy (i.e., hydro, nuclear, wind, and solar) to 20 percent of total primary energy. But beyond 2030, China will need to start reducing emissions, joining most other developed countries in a steady march toward zero emissions, if it is to make good on its pledge to reach carbon neutrality by 2060.

The zero-emissions target seems distant, particularly for a country responsible for more than 25 percent of global fossil fuel–related CO₂ emissions. But zero emissions must remain the ultimate goal. Climate-modeling studies have demonstrated that the climate system responds above all to cumulative emissions of CO₂, the longest-lived major greenhouse gas, and is remarkably insensitive to the specific emissions trajectory [1]. This means that the long-term objective of reducing global carbon dioxide emissions to near zero as quickly as possible should be the primary focus of climate policy. And yet until recently, nearly all international climate negotiations – including the Paris treaty and the bilateral US–China agreement – have focused on near-term emissions targets.

Near-term targets can be important, particularly for the largest economies, because progress can be more easily monitored and verified. Moreover, such
targets encourage the growth of low-carbon technologies, particularly those that are already competitively priced, such as low-penetration wind and solar. But the development of critical technologies needed to achieve deeper reductions in the long run – such as next-generation nuclear power, advanced biofuels, or economical strategies for managing high penetration of intermittent energy sources such as solar and wind – is crucial. Such technologies must receive attention now to allow them to become options for the future. A balance is needed between investments that will lower emissions in the near term and investments that may have only a small effect on emissions over the next few years but will be critical to achieving success in the long run. The latter can be neglected if the sole focus is on near-term emissions targets.

In China, most energy policy analysis has focused on how to achieve the 2030 targets, although attention to longer-term emissions reductions is beginning. One of the biggest challenges for Chinese decarbonization efforts is to find a substitute for the more than 1,000 GW of coal-fired power plants that currently dominate the electricity sector and the additional 200 GW under construction as of the end of 2020. Currently, there is no plan for how to achieve this transition, and very little discussion about what might happen beyond 2030. Rapidly-growing wind and solar deployments in China are leading the world, with nearly half of global wind and nearly a third of global solar photovoltaic (PV) capacity. Renewable electricity is now nearly 40 percent of the total generation capacity with wind and solar each representing more than 10 percent of electricity generation. Will expanding wind and solar capacity be able to displace coal in the electricity sector? The answer may depend on critical decisions made today related to siting of generating capacity and transmission. Most importantly, it is likely to depend heavily on smart energy policy, which will set the stage for decarbonization in China beyond 2030. Carbon pricing, electricity market reform, and infrastructure policy, for example, will all play important roles in constraining various technological pathways for decarbonization, and may affect how easy it will be to achieve high levels of penetration of wind and solar capacity.

Another example of near-term policies likely to affect future energy systems is the strategic deployment of electric vehicles. Policies that encourage electric vehicles in China are primarily motivated by concerns about air pollution and energy security, as China is now the world’s largest importer of oil. Electric vehicles in China are likely to have limited impact on CO\textsubscript{2} emissions over the next two decades due to the electricity sector’s heavy dependence on coal. So, if one were concerned only with near-term emissions targets, electric vehicles would not be a major priority. If one considers decarbonization beyond 2030, however, investment in electric vehicles today may be the only way to lower greenhouse gas emissions from vehicles in the future, as decarbonization of the electricity sector proceeds.
In this book, we consider how a long-term perspective on decarbonization can affect current energy and climate policy choices. It would be naïve to think that decisions about energy policy in China today will be dominated by long-term concerns several decades into the future. Moreover, the advance of multiple energy technologies, from batteries to nuclear power plants, makes it difficult to predict what technologies are likely to be deployed in the future. If one evaluates energy policies and electricity market reforms in China today purely based on the near-term emissions targets over the next decade, some important opportunities for long-term technology development may be lost. Through detailed discussions of electricity pricing, electric vehicle policies, nuclear energy policies, and renewable energy policies, this book considers how near-term climate and energy policies can affect long-term decarbonization pathways beyond 2030, building the foundations for decarbonization in advance of its realization. The book focuses primarily on the electricity sector, simply because electricity will be the main battleground for decarbonization over the next century. There are certainly important efforts to decarbonize other parts of the energy system beyond electricity, such as biofuels or low-carbon fuels for heavy freight transport and air travel. But such technological changes are likely to occur later in the sequence of decarbonization steps, as their current costs are much higher than those discussed in this book.

China shows no sign of shrinking from its new position as a global leader in addressing climate change, as indicated by the EU–China climate discussions. As China continues down the path of decarbonization, the reforms discussed in this book will be important to allowing long-term decarbonization goals to be achieved more smoothly and with reduced long-term costs.

1.1 Background
1.1.1 China’s Climate Progress Prior to the Paris Agreement

China’s carbon emissions experienced rapid growth due to its fast-growing economy. In 1990, energy-related carbon emissions from China were 2.2 billion tons of CO₂, accounting for roughly one-tenth of the world’s total, while US emissions were more than 5 billion tons, close to a quarter of the world’s total. By 2019, China’s energy-related emissions had increased to almost 10 billion tons, nearly 4 times its 1990 level, while the United States had added only 5 percent. In 2008, China surpassed the United States, becoming the largest carbon emitter in the world. In 1990, China’s per capita carbon emissions were less than half the world average; in 2007, China’s per capita carbon emissions exceeded the world average and are now quickly approaching the level of the 28 EU Member States.
In 2009, China set its 2020 carbon management target under the Copenhagen Accord, reducing its carbon intensity—measured as carbon emissions per unit of GDP—by 40–45 percent, as compared to the 2005 level. By the end of 2014, China’s carbon intensity was 33 percent lower than it had been in 2005, well on track to deliver its Copenhagen pledge. Meanwhile, China’s energy-related carbon emissions continued to grow, from 5.5 billion tons in 2005 to nearly 10 billion tons in 2014.

Despite the continued increase in total carbon emissions, the growth rate of Chinese emissions has decreased since 2005. Several different government policies have played key roles in bringing down the carbon growth rate. First, energy efficiency in all major sectors has been improving. Coal-fired power plants now use less than 290 grams of coal per kWh of electricity. The best coal-fired power plants in China are now the global leader in energy efficiency, and the national average efficiency of all Chinese power plants is rising to be among the best in the world.

A second factor in slowing the growth rate in emissions is the development of renewable energy. China is now leading the world in investing in renewable energy, contributing to more than a quarter of the world total. Nearly 50 percent of installed wind generation capacity is now in China. The installed capacity of solar power generation in 2005 was 700 MW and grew to more than 280 GW by the end of 2020, a 400-fold increase in 15 years.

A third factor in reducing the growth in emissions has been a concern for air pollution, which has helped to set a cap for coal consumption in key regions, which will eventually extend to the whole country. However, it is unclear whether air quality will remain a major pressure on decarbonization as improvements in scrubbing of conventional air pollutants threatens to sever the relationship between CO$_2$ and air quality.

Fourth, some provincial and municipal governments have taken on leadership roles in exploring low-carbon development paths. From 2009 to 2012, 42 provinces or cities entered into a national pilot program for low-carbon development. These pilots seem to be making an impact on other subnational and local governments on choosing an alternative pathway for addressing economic growth and climate change.

Finally, China has made a deliberate decision to launch a nationwide carbon market for the electricity sector. When fully deployed, this market will be the largest carbon market in the world, more than twice the size of the EU cap-and-trade program.

In the context of this progress, on November 12, 2014, China and the United States signed a bilateral agreement on climate change and clean energy cooperation. Under the joint agreement, “China intends to achieve the peaking of CO$_2$ emissions around 2030 and to make best efforts to peak early, and intends
to increase the share of nonfossil fuels in primary energy consumption to around 20% by 2030” [2]. This was the first time that China committed itself to a target for total carbon emissions. Assuming that these goals are achieved, China’s carbon emissions will continue to increase by roughly one-third to one-half of the current level before it stabilizes or declines, reaching per capita carbon emissions of approximately 10 tons. Much of this progress will come from reductions in coal use in the industrial sector, outside of electricity generation. But perhaps the most important component of the joint China–US agreement is China’s commitment to increase the share of nonfossil fuels in primary energy consumption to 20 percent. Reaching this target will not be easy, as it requires the addition of 800–1,000 GW of new electricity generation capacity based on wind, water, solar, and nuclear sources. If these goals are achieved, it opens the possibility that these nonfossil technologies will be used in the rest of the developing world as rapidly-developing countries make their own energy choices in the decades ahead.

1.1.2 How Will China Actually Reduce Emissions beyond 2030, Given Their Current Dependence on Coal for Electricity Generation?

The challenge of deep decarbonization in China is more difficult than in the United States because of China’s enormous dependence on coal-fired power plants for electricity generation, as well as rapidly growing demand for oil in the transportation sector. In addition, based on current estimates of its natural gas resource base, China cannot follow the path of the United States and much of Europe in reducing emissions by substituting natural gas for coal. The capacity of coal-fired plants in China is currently more than 1,000 GW and growing, which makes longer-term progress on reducing carbon emissions especially challenging. Emissions from the transportation sector are roughly 15 percent of China’s total emissions, in contrast to 32 percent in the United States. But as the largest automobile market in the world since 2009, emissions from the transportation sector are likely to grow without a major shift in technology. Hence, efforts to drive decarbonization will have to tackle emissions from both the electricity and transportation sectors. This will prove more difficult with a lower rate of economic growth than that experienced over the past two decades. Investments in infrastructure, including new electricity generation capacity and new transmission, will be more difficult to finance for a post-2030 China that may be growing at less than 5 percent per year.

1.1.3 Three Pathways

There are three main technological strategies for decarbonization beyond 2030, and China is likely to require a combination of all of them. One pathway is deeper
penetration of renewable electricity, in particular wind and solar, as hydroelectric power has already expanded closer to its maximum. This is a large part of China’s current energy strategy, as China led the world in 2018 in new solar (45 percent) and wind (44 percent) generation and has more than 32 percent of global wind and solar cumulative installed capacity. But China has not yet faced the daunting challenge of managing high penetration of intermittent renewable energy sources. Much of China’s current wind capacity is in the north, and solar capacity is mostly in the northwest, but adequate transmission to bring power to the large demand centers does not yet exist. As deployment of wind and solar continues beyond 2030, China will need to explore storage and demand management among strategies to stabilize their grid. There is also a strong provincial component of this problem, as current electricity policy in China is heavily influenced by provincial decision-making, which can create obstacles for managing the intermittency of renewables by restricting interprovincial energy trade. In particular, current electricity pricing and electricity markets are not optimized to encourage the best investments, especially not in consideration of the system operation as a whole, rather than the needs of individual provinces.

A second pathway for decarbonization is the Chinese nuclear effort, with plans to add 150 GW of new nuclear capacity by 2030. Expanding this effort to the scale required to make a significant substitution for coal-fired power plants (currently more than 1,000 GW) seems daunting. Moreover, the current nuclear program is facing various challenges, including cost and local acceptance. Investments in nuclear engineering, both in research and development of new reactor designs and in institutional knowledge and experience in building reactors more cheaply, are best understood in terms of creating an option for a decarbonization pathway, if it becomes difficult to incorporate greater levels of intermittent wind and solar resources.

A third pathway is the electrification of the transportation and industrial sectors. Due to the rising standards of living and large-scale infrastructure development over the past two decades, passenger cars are gaining penetration in China at an unprecedented rate. Emissions from transportation, previously a fraction of those from manufacturing and electricity, will see the fastest growth among all sectors. A long-term plan to fundamentally transform the transportation sector should be an integral part of China’s odyssey down the path of decarbonization. But such efforts can only be viewed in the long term, as rapid substitution of electric cars for petroleum-fueled vehicles raises overall carbon emissions in the short term, due to the high carbon footprint of the electricity sector.

All of these decarbonization pathways depend on China’s ability to reduce, and eventually eliminate, the inflexibilities and inefficiencies that characterize its current electricity system. These rigidities extend the life of the most inefficient and carbon-intensive generators at the same time that China is actively promoting
their replacement by nonfossil-fuel alternatives. The basic structure of China’s grid system was designed more than 30 years ago to provide low-cost coal-fired baseload power to a rapidly growing industrial sector. The challenge at the time was to construct new baseload generation fast enough to keep up with the rapid growth in heavy industry and manufacturing. Approximately 70 percent of China’s power in 2005 was consumed by industrial facilities, most of which operated 24 hours per day.

In a decarbonized energy system, the challenges will be different. Supplies from renewable generators – such as wind and solar – will be intermittent, while the demand will vary throughout the day. The growth in service industries, transportation, and the commercial sectors will increase daily fluctuations in demand. China will need to simultaneously increase the total capacity of its grid, while improving the flexibility of the system to account for changing supply and demand patterns. Structures that met China’s energy needs 30 years ago will be impediments to its ability to decarbonize.

1.2 Chapters Overview

1.2.1 Electric Utilities

In Chapter 2 of this book, Pu Wang identifies many of these structural rigidities and provides suggestions for actions that China can take to fix them. Wang focuses on three problems: (1) Outdated governance structures lead to responsibilities that are inadequately delineated and often result in internal tensions and conflict; (2) The current dispatch protocol creates perverse investment and operation incentives, resulting in the overuse of the least efficient power plants, the curtailment of renewable capacity, and additional investment in carbon-emitting coal facilities and (3) Pricing policies disincentivize investments in needed ancillary services, such as peaking generators, demand-side management, and solar and wind capacity.

Most of China’s electricity generators are state-owned monopolies, two grid companies transmit all the power, operate all the regional grids, and retail almost all of the country’s electricity. Financing is provided by state-owned banks and almost every aspect of this industry is regulated by either central or provincial government agencies. Hence, governance has a greater impact on the shape of this industry than it would in a system more reliant on markets and private companies.

Multiple agencies and departments oversee various parts of the investment and operation processes at both the central and provincial levels. There is a lack of formal coordinating mechanisms to improve the interface between these agencies, and, as a result, they often embrace different priorities and act inadvertently
counter to each other’s intentions. As regional energy markets emerge, coordination among provinces will become more important, especially if China modernizes its national grid, allowing the country to move power efficiently between regions. To be able to decarbonize successfully, China will have to improve its governance structures at all levels and create institutional structures that will encourage agencies to work together.

Most power systems in North America and Europe have adopted a least-cost dispatch protocol in which generators with the lowest operating costs access the grid before those with higher operating costs, as long as the security of the grid is maintained. Since renewable generators have almost zero marginal operating costs, they are dispatched whenever they are available. Least-cost dispatch protocols maximize the efficiency of the grid and, by favoring renewable generators, advance low-carbon options. Wang points out that China uses an “equal-share” dispatch rule in which generators are guaranteed an equal number of operating hours regardless of operating costs. This system leads to greater inefficiencies, curtailments of renewables, and excess generating capacity. In 2018, for example, although China had a surplus of generating capacity, it still proceeded to build new coal-fired plants. The driver in creating these inefficient incentives was the equal-share dispatch system. Such policies may have made sense in the past when China was attempting to accelerate investment in baseload plants, but in today’s market it is retarding China’s ability to accelerate the development of a less carbonized grid.

As mentioned earlier, an electric grid with substantial renewable generation will need to maximize the flexibility of the system to account for fluctuations in supply and demand. This means that the coal and nuclear assets must be able to supply power in tandem with changes in demand. It also means that the government will need to stimulate investments in facilities that provide generation capacity for only those few hours when the demand is highest. Building flexible systems requires regulators to price power at its actual value, which is constantly changing throughout the day. As the energy system transitions to greater use of electricity and less direct fuel use, pressures on government regulators to amend tariffs to reflect the real-time value of electricity will grow. A decarbonized energy grid is almost certainly one in which electricity pricing reflects the value of power across time.

1.2.2 Coal

The greatest challenge facing any effort by China to decarbonize will be to reduce its use of coal, which is comparatively inexpensive and widely available. In Chapter 6 of this book, Michael Davidson points out that the difficulty of reducing coal use is compounded by two factors. First, China has embarked on an effort to
close coal-fired stations around its eastern cities, build new facilities near coal mines and then transport the power to the eastern population centers through a network of high-voltage transmission lines. Second, many of these new facilities are among the most efficient coal-fired plants in the world, reaching efficiency levels previously thought to be unattainable. As a result, China has a large fleet of very efficient generating plants, and more than half of these have a useful life that extends beyond 2050. Any effort to prematurely close these plants will result in stranding a large asset base and forfeiting billions of dollars.

Hence, China has not only a strong financial disincentive to retire its coal plants, but strong incentives to build more of them as well. Many of the same incentives discussed in Wang’s chapter on electric utilities, such as average cost pricing and equal shares dispatching, encourages investors – both public and private – to develop new coal facilities. Davidson identifies additional incentives, such as an array of tax and fee subsidies, less onerous permitting processes, and lower transmission costs, that favor the construction of new coal plants and protect the operation of older and less-efficient facilities. As a result, it will be difficult and expensive for China to reduce its dependence on coal for electricity prior to 2050.

In most countries, the vast majority of coal consumption is for electricity generation. Even in India, where direct use of coal for heating remains high, 75 percent of coal consumption is in the power sector. China is an exception. In 2017, 54 percent of China’s consumption of coal was for industrial, district heating, and residential uses. Thus, any long-term plan to reduce coal consumption must include strategies to transition industries, such as steel and cement, to electricity, and eliminate coal-fired district heating, either by switching the plants to natural gas or developing other sources for heating, such as direct use of natural gas or more efficient heat pumps. Coal use for home heating remains common in rural communities in northern China. The government is committed to reducing and eventually eliminating such use in order to meet local and national health standards. Direct use in small heating systems is the least efficient use of coal, and eliminating it fits not only with the country’s health goals but also its commitment to improved energy efficiency.

The move away from coal is likely to be fraught with political resistance, and also raises serious social issues. Coal mining employs four million people and hundreds of thousands more work in coal-intensive sectors, such as electricity generation, steel, or cement. Davidson argues that any effort to reduce China’s coal production and consumption must be accompanied by a strategy on how to manage worker displacement and the social issues that go with it. These include environmental inequities in that the localities that bear the environmental costs are not necessarily the same as those that reap the benefits. Income disparities between provinces and cities may grow larger, as some flourish in a decarbonized economy
and others struggle. If there are no programmatic or policy options readily available to manage this transition, governments are likely to slow the progress to a lower-carbon energy system.

1.2.3 Renewables

Deep decarbonization will require China to dramatically increase the rate at which renewable options, such as wind and solar, are deployed. In the period 2012–2018, China has been the largest producer and consumer of renewables. Annual growth rates exceed those of any other country in the world by large margins. Yet to actually reduce emissions, China will have to increase these growth rates much faster while reducing curtailments (wind and solar generators hooked up to the grid, but not dispatched).

In Chapter 3 of this book, Wei Peng, Zhimin Mao, and Michael R. Davidson describe the magnitude of the investments that will be needed in the renewable energy sector. If the challenge could be reduced to the singular task of increasing growth in renewable generation, China would likely meet whatever schedule it sets for itself. But the task is complicated by the same system deficiencies – a grid system that is too rigid, pricing policies that protect existing conventional generators and discriminate against renewables, and the need to replace a transmission and distribution system that was established to support local baseload plants with one that supports distant intermittent sources – discussed in the earlier chapters.

China is building nine major high voltage lines to move power from western provinces that have greater amounts of solar and wind resources to eastern provinces with fewer resources and large populations. More are in the planning stage. However, long-distance transmission lines face three challenges. First, they must be sited and receive approval from multiple agencies in each province they cross. Obtaining approvals from multiple agencies may be less of a problem in China than it would be in countries like the United States, but given the governance problems discussed earlier, the challenges in China are real. Second, moving electricity through multiple provinces is only economical if utilities and consumers in one province are willing to purchase power generated in another. In the past, each province has protected its higher-cost generators, mostly state-owned enterprises, from competition from lower-cost generators in other provinces. As long as provinces receive a portion of their annual revenues from local coal plants, this barrier to trading electricity remains. Third, the economics of transmission depend critically on using power lines at a high capacity. Lines that transmit electricity from baseload facilities that operate 7 days per week and 24 hours per day will cost less per unit of electricity than lines that carry intermittent power that