# Climate Mitigation and Adaptation in China

## Policy, Technology and Market

"*Climate Mitigation and Adaptation in China* is a sophisticated study of China's efforts to decarbonize its economy, which is especially valuable for its sensitivity to global policy discussions and its awareness of the close connections between international commitments and domestic public policy choices."

—Robert O. Keohane, *Princeton University, Member of the US National Academy of Sciences*

"The role of China in tackling climate change will be critical to the success in facing up to the world's greatest challenge. This book explores how policy, technology and markets need to work together to create the conditions to move to a green economy as a model for others to follow."

—Philip Allmendinger, *University of Cambridge, Fellow of the British Academy of Social Sciences*

"This is a deep, up-to-date and rigorous analysis of China's strategic, economic, and technological pathways towards carbon neutrality... An essential reading to understand the new role of China in the global governance of climate change."

—Alberto Quadrio-Curzio, *President, the International Balzan Prize Foundation, and President Emeritus, the National Academy of Lincei, Italy*

"This book provides important insights into Chinese thinking and Chinese policy toward decarbonization. It will be of interest to anyone concerned about Chinese policies toward climate change—and, more broadly, to anyone concerned about the potential for successful action to mitigate climate change globally."

—Jeffry Frieden, *Harvard University, Member of the American Academy of Arts and Sciences*

"As a major and growing economy, China's role in meeting a global climate challenge is simply crucial. As we approach COP 26 in Glasgow in November (2021), the timing of this book could not be better. Professor Fu Jun and his colleagues have done a masterful job of laying out the parameters, policies and prospects of China's path to sustainability. It should be essential reading, domestically and internationally."

—A. Michael Spence, *Stanford University, Nobel Memorial Prize Laureate in Economic Sciences*

Jun Fu · Dongxiao Zhang · Ming Lei
Editors

# Climate Mitigation and Adaptation in China

## Policy, Technology and Market

冶金工业出版社
Metallurgical Industry Press

Springer

*Editors*
Jun Fu
National School of Development
Peking University
Beijing, China

Dongxiao Zhang
College of Engineering
Peking University
Beijing, China

Ming Lei
Guanghua School of Management
Peking University
Beijing, China

ISBN 978-981-16-4309-5 ISBN 978-981-16-4310-1 (eBook)
https://doi.org/10.1007/978-981-16-4310-1

Jointly published with Metallurgical Industry Press, Beijing, China
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Metallurgical Industry Press



This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

# Preface

Climate change is a huge challenge facing humanity in the twenty-first century. The 2015 Paris Agreement represents a global consensus to keep global temperatures well below 2°C above the pre-industrial levels and to pursue further efforts to limit the temperature increase within 1.5°C. In 2018, the UN Intergovernmental Panel on Climate Change (IPCC) has further warned that the impact of above 1.5°C of global warming will spell disasters to the ecosystem on Earth. As a response to the call for renewed efforts at mitigation and adaptation to climate change, in 2020, China has again pledged to the international community that it will peak $CO_2$ (carbon dioxide) emissions prior to 2030 and try to achieve carbon neutrality by 2060—indeed a tall order to fulfill given China's current stage of development.

Fight against climate change calls for concerted efforts by all walks of life, both domestic and international (e.g., if every individual in China were to reduce one ton of $CO_2$ each year, it would amount to a total reduction of 1.4 billion tons of $CO_2$, which is roughly an equivalent of the yearly $CO_2$ emissions by the Chinese steel or cement industry). Similarly, as reflected by the on-going research on climate change at Peking University, cross-disciplinary approach is highly desirable. Presented here is a book-length study organized through what one may call a triple helix of three schools at Peking University—the National School of Development, the College of Engineering, and the Guanghua School of Management. The scholars and experts associated with these three schools cover three domains of knowledge—policy, technology, and markets—that are essential in fight against climate change.

China is a large developing country with 1.4 billion people in the midst of industrialization and urbanization. GDP per capita in China in 1979 is about US$156; it is about US$ 10,000 in 2020; urbanization is 18% in 1979; it is close to 60% in 2020. Topping output of 220 of 500 major industrial products in the world in 2011, China became the world's largest industrial country. As a consequence, currently China is the largest $CO_2$ emitter in the world, and it contributes roughly a quarter of global $CO_2$ emissions, although on per capita basis, China has remained moderate—about 7 $tCO_2$ per year, as compared to 16 $tCO_2$ for the U.S. and 5 $tCO_2$ for the world average.

Take the iron/steel sector in China for instance. The sector has a total of some 500 firms with a total output of crude steel reaching 1.065 billion tons in 2020, accounting for over 57% of the world's total. In terms of $CO_2$ emissions, it accounts for over 60% of total $CO_2$ emissions from global steel production and about 15% of total domestic industrial $CO_2$ emissions, following the power (including heat) sector (about 50%) and above the cement sector (about 12%).

But China has been working hard at mitigation and adaptation to climate change and trying to de-couple economic growth from $CO_2$ emissions at the earliest date possible. And the present study provides a prism through which to see China's efforts and appreciate its magnitude. The study is organized around the three linchpins, i.e., Part I, Policy; Part II, Technology; and Part III, Market. This study ends with a projection to 2060 in Part IV, by which China has pledged to achieve carbon neutrality. China has to be an integral part of the global efforts in fight against climate change—the most consequential threat facing humanity. As the latest UN Intergovernmental Panel on Climate Change suggests, without concerted efforts, the dire situation will only get worse. Everyone must act now—with a sense of urgency—to address the crisis.

What follows is a synopsis of the these principal building blocks—as well as the overall research design—of the study.

## Part I Policy

At a fundamental level, climate change reflects the logic of negative externalities of what scholars have described as "the tragedy of the commons." In order to prevent that tragedy from happening, public policy becomes indispensable. To understand China's evolving policy framework to decarbonize its economy, a principal theme to watch is the dynamic interaction between China's international commitments and domestic agenda setting with respect to climate change. At the risk of oversimplification, three sets of milestone international commitments can be identified for China's efforts of mitigation and adaption to climate change.

Under the principle of "common and differentiated responsibilities" of the UNFCCC (UN Framework Convention for Climate Change), in 2009, China pledged to the international community to reduce carbon intensity per unit of GDP by 40–45% by 2020 from the level of 2015. In 2015, China pledged again to peak carbon emissions around 2030 and reduce carbon intensity by 60–65% by 2030 from the level of 2005. In 2020, building upon previous successes, China again pledged that it would peak carbon emissions prior to 2030 and try to achieve carbon neutrality by 2060. This pledge was particularly significant. Indeed, shifting from carbon *equity* toward carbon *neutrality* indicates a change of political philosophy from particular justice to general justice. (Note that China, about 157 $tCO_2$, was still below the world average, about 209 $tCO_2$, in terms of per capita accumulated $CO_2$ emissions from 1900 to 2019. By comparison, it was about 1218 $tCO_2$ for the U.S., 930 $tCO_2$ for the U.K., and 516 $tCO_2$ for France). These international commitments, in turn, have been successively factored into China's 11th Five-Year Plan (FYP 2006–2010), 12th FYP 2011–2015, 13th FYP 2016–2020, and 14th FYP 2021–2025, and together they have constituted an evolving policy framework, shaping the country's efforts to decarbonize its developmental path.

Initial evidence is compelling that China has taken these commitments seriously. In 2019, for instance, China has fulfilled its 2009 pledge one year ahead of schedule, with carbon intensity reduced by 48.1% from the 2005 level and non-fossil fuels raised to 15.3% as a share of energy structure. In 2016–2019, a total of 1.4 billion tons of $CO_2$ emissions were reduced due to work at energy efficiency nation-wide. As evidenced in the steel sector, with both "sticks" and "carrots," the Chinese government had aggressively pursued a low-carbon strategy, by way of reducing inefficient overcapacity and enhancing energy efficiency in the 13th FYP (2016–2020). And the steel sector has been planning for a super-low-carbon strategy for the 14th FYP (2021–2025). Arguably, the overall current approach seems to be more fiat than market. But the trend is increasingly market-oriented. Indeed, having gained experience from its eight (7+1) regional ETS pilots, China operationally rolled out a national carbon market (or ETS) in 2021, which promised to become the largest in the world.

The Paris Agreement set out a global action plan to keep the world on track by limiting global warming to well below 2°C above pre-industrial levels in the long-term and urged contracting states to undertake rapid carbon emission reductions with best available technologies (BATs). As a contracting state to the Paris Agreement, China has been keen on BATs, as illustrated by its policies to encourage and shape the development of carbon capture, utilization, and storage (CCUS). Indeed, as a global fieldtrip would attest, in the last few years China has been catching up rapidly in this field and has become one of six leading countries (the USA, Canada, UK, Norway, Japan, China) in the world. Thus far, whereas most CCUS pilots and demonstrations in China are in the power sector (accounting for about 50% of total industrial $CO_2$ emissions), its steel sector (accounting for about 15% to total industrial $CO_2$ emissions) seems increasingly posed to set up CCUS pilots as well in the 14th FYP (2021–2025).

## Part II Technology

Generally speaking, there are three board categories of technologies of decarbonization, i.e., low carbon, zero carbon, and negative carbon. To illustrate, hydrogen, hydraulic, wind, and solar power are examples of zero-carbon technologies, but the caveat here is the supply incongruence or instability of wind and solar energy for the grid, unless battery technology has made hitherto unknown breakthroughs. Currently, however, only about 15% of China's grid capacity is VRE (variable renewable energy) compatible for wind and solar power, the sources of which vary across different regions and are unstable by nature, although their cost, excluding storage, has come down dramatically in recent years. The challenge here is for the grid to move up to higher phases of VRE integration. Various techniques or methods of energy conservation and energy efficiency—aggressively pursued in China's iron/steel sector thus far—typically embody low carbon technologies. By contrast, carbon capture, utilization, and storage (CCUS), including both onshore and offshore sequestration, represents negative carbon technology. Looking forward, a strategic pathway for China to move toward carbon neutrality by 2060 is likely to feature a dynamic mix in different proportions of all three categories of technologies.

To cut into the web of green technologies, our research strategy is to address the most complex and still evolving one head on, i.e., CCUS, believing that, having done the most difficult, the rest—e.g., hydraulic, wind, and solar power, etc.— would be relatively easier to piece together. After all, much research has already been done on the latter part of the picture, the basic contour is clear, and we do not have to start from scratch. Accordingly, lending credence to the strategic roadmap based on simulation for the future deployment of CCUS in the Chinese steel sector in the previous chapter, Part II of this study takes an in-depth look at CCUS as an emerging strategic reserve technology on industrial scale for direct abatement of $CO_2$ emissions. Under country-specific engineering conditions, the study begins by methodically going through a typical iron/steel plant in China. In the process, it provides a systematic analysis of the appropriate options as well as potential pitfalls of $CO_2$ capture technologies—physical or chemical or both—in steel-making processes, including options for $CO_2$ transport and storage. In addition, cost estimates, together with tech-performance, of a full-chain CCUS are also provided to assist planners or decision-makers in identifying most cost-effective pathways.

For example, integrated infrastructural outlays involving optimal $CO_2$ source–sink matching can presumably reduce unit cost of a CCUS-retrofitted plant operating in a hub-spoke cluster. In light of the source–sink matching and the maturity of various CCUS technologies for $CO_2$ emission reduction in the near, medium, and long term, there is evidence to suggest that the steel sector should adopt the strategy linking enhanced oil recovery (EOR) and enhanced coal bed methane recovery (ECBM) technologies as the near- and medium-term utilization and storage solution and storage in deep saline aquifers as the long-term storage solution. At present, EOR and ECBM in China, experimentally or otherwise, account for only a few million tons of $CO_2$ used annually–indeed a tiny part of the 10.4 billion tons of $CO_2$ that China emitted in 2020. Beyond the steel sector and for considerations of scale economy and public good, it also makes sense for the government to plan, design, and invest in the basic infrastructure of hub-spoke transport clusters to facilitate or speed up the deployment of integrated full-chain CCUS projects.

Currently, however, while slow progress on CCUS pilots or demonstrations has been under way in China and overseas, huge initial investment and lack of viable business models for cost considerations are seen as the main obstacle to rapid development of CCUS, globally. The International Energy Agency (IEA) has warned that CCUS is not on track for Paris Agreement targets and picking up the pace of CCUS deployment is urgent. In China, currently CCUS pilots are mostly in coal-fired power plant and none has captured $CO_2$ emissions in the steel and the cement sector. But as China revs up efforts to achieve carbon neutrality by 2060, it is expected that the deployment of CCUS would quicken steps in fossil fuels-intensive industries, including in the iron/steel sector. Indeed, if the rapid unfolding of the fast-speed railway network in recent years is any indication, China would also be particularly good at building multiple $CO_2$ source–sink clusters for CCUS to scale up. And one would anticipate that work is likely to start during the 15th FYP (2026–2030), if not earlier. And if it does, it would be better to pilot first rather than big-bang approach, because CCUS has remained complex, costly, and uncertain in the nexus of all green technologies thus far. As such, in strategic sequencing, it makes sense to see CCUS as a reserve technology or “the lender of last resort”, so to speak, to borrow a term from finance.

## Part III Market

Right sequencing is a critical component of a successful strategy—a lesson that China has learned from its own experience of reforms and opening-up in the past 40 years. This logic seems to have applied to the development of carbon market in China as well. That is, "testing it out before scaling it up," so to speak. On the heels of the previous part on technology, lest one forget, markets as humanly-made institutional arrangements are institutional technologies, the design of which has to deal with both politics and economics and as such can either speed up or slow down the rate of production of ideas, products and services. Fundamentally, markets and the rule of law, as is often said, are the two sides of the same coin. In building carbon market, in 2013, after two years of preparations, China rolled out seven regional ETS (emission-trading system) pilots (i.e., in Beijing, Chongqing, Guangdong, Hubei, Shanghai, Shenzhen, and Tianjin) as a first step. The vision was—if these regional ETS pilots were successful—to build a unified national ETS starting in 2017, which eventually would become the largest ETS in the world, covering well over 6 billion tons of $CO_2$ emissions, or more than half of China's total $CO_2$ emissions.

Theoretically speaking, ETS built on the theme of "cap and trade" can reduce $CO_2$ emissions at a lower cost than direct government regulations such as mandated technologies and performance standards. Thus far, the theoretical proposition has been validated by the experience in the USA and the European Union. Are the regional ETS pilots really working in the Chinese context of regional disparities? To assess their validity in terms of behavioral changes on the part of polluting firms toward de-carbonization is thus the focus of Part III. For the sake of analytical rigor, the present study has made efforts to go beyond mere descriptive statistics by deploying the method of synthetic control in evaluating the efficacy of these regional ETS pilots.

Going beyond a prima facie case, the main findings of the investigation are as follows. First, even at this early stage, except Tianjin and Chongqing, there is evidence of varying degrees that these regional ETS pilots have contributed to the reduction of $CO_2$ emissions, with Hubei ETS pilot being the most salient case. Second, the early success is nevertheless uneven across different regions in China, suggesting that caution is needed when considering scaling up regional ETS pilots to a unified national carbon market after 2017. Given the varying industrial structures in different regions across China for historical reasons, strategically a gradual rather than a big bang approach—with different phase-in periods for various sectors—to the construction of the national ETS would seem appropriate. Or, one could run the risk of making rich regions richer and poor regions poorer.

Third, as information and transparency is essential for market operations, a robust MRV system (monitoring, reporting, and verification) is critical, as China moves further ahead with the construction of the unified national carbon market, as well as with green financing. According to the People's Bank of China (PBOC), by 2030 China will need to invest about RMB 2.2 trillion on a yearly basis to decarbonize its economy, and the amount will further increase to about RMB 3.9 trillion from 2030 to 2060. To meet the need, both public and private funds must be mobilized.

By 2020, all of China's regional ETS pilots had covered a total of some 3000 firms and accumulated a $CO_2$ trade volume of some 430 million tons, or about RMB 10 billion. Yet the current carbon price of these regional ETS pilots, averaging about RMB 30/t$CO_2$, seemed too low to spur serious strategic shifts in terms of investment in new technologies such as CCUS. In principle, carbon price must reflect environmental cost, and, here, China still has a long way to go. By international comparison, carbon price in the USA and EU was about US$ 15–16/ton in 2018. Globally, unless carbon price increases dramatically in the years to come, say over US$ 70/t$CO_2$, to galvanize a more robust path to decarbonization, it would be difficult to achieve the goal of the 2015 Paris Agreement, i.e., keeping global temperatures well below 2 °C above the pre-industrial levels.

In this connection, Part III also explores various design options of ETS on how best to incentivize CCUS from the perspective of a business model, for investment decisions with respect to green technologies (not necessarily CCUS) are ultimately made at the firm level, and sensitive to public policy and institutional environment. Take it as a brain teaser to think further ahead, now that China has rolled out a national ETS in 2021, bringing the world's largest ETS online after three years of preparation on the basis of its experience of eight regional ETS pilots. As a first step, the national ETS now regulates some 2,200 firms from the power sector (including combined heat and power, as well as captive power plants of other sectors), and its scope is expected to expand further in the future, to cover refining and petrochemicals, chemicals, building materials, steel, nonferrous metals, paper, and aviation as well. If and when the national ETS expands to cover all eight sectors, it will cover well over 60% of China's total emissions down the road.

## Part IV Projection

Taking stock and looking forward, in 2020, China has pledged to the world that it would peak carbon emissions prior to 2030 and try to achieve carbon neutrality by 2060. The task is daunting. Put in international perspective, China's deadline is very tight. Whereas most advanced economies have planned to spend 50–70 years from carbon peak to carbon neutrality, China has only given itself a 30-year transition period. Thus, in the years ahead, China must move aggressively to decarbonize its economy, and in the process, transitional risks can be enormous, especially for resource-intensive and fossil fuel-intensive industries. In 2020, China emitted about 10.4 billion $tCO_2$—or about 7.4 $tCO_2$/per capita—about 92% of which comes from the burning of coal (about 7.4 billion $tCO_2$), oil (1.5 billion $tCO_2$), and natural gas (0.6 billion $tCO_2$). As can be imagined, the challenge for China to de-carbonize its economy within the next 40 years can be mind-boggling.

Be that as it may, there are basically four general approaches for China trying to meet the challenge lying ahead, i.e., public policy approach (PPA), market-based approach (MBA), carbon capture and storage (CCS), and nature-based solutions (NBS), such as forest sink. Based the conceptual framework of PPA+MBA+CCS+NBS (or PMCN model for short), a big part of Part IV represents efforts to project forward by way of disciplined exercises of simulation of various scenarios, such that one can see more clearly what lies ahead and reckon how best to respond. On the basis of these simulations or projections, the main takeaways are as follows:

First, as was true during the so-called new normal period, when growth rate of Chinese heavy industry (i.e., energy, cement, steel, automobiles, shipbuilding, construction, etc.) dropped dramatically from above 10% in 2008–2011 to 6% in 2015, generally economic slowdowns have lessened the steep upward trend of $CO_2$ emissions, thus helping China peak $CO_2$ emissions by 2030. Conversely, the simulation exercises also show that all the strategies of carbon emission reduction, including ETS, come at the cost of GDP loss, with modest declines in employment, investment, and consumption. That said, a better calibrated mix of policy instruments will take smaller costs of economic loss. In this context, in the various PPA+MBA combinations, high carbon price rather than low energy enhancement is a preferred option. In longer terms, market approach is a preferred choice over administrative fiat.

Second, to peak $CO_2$ emissions before 2030 and achieve carbon neutrality by 2060, along the spectrum of PPA+MBA+CCS+NBS, all the instruments currently available (e.g., improvement in energy efficiency, cost reduction in renewable energy, and carbon pricing) are all necessary, but not enough even in a full combination of all above instruments. New instruments, especially for a more powerful shift from fossil to no-fossil fuels, are needed to achieve the carbon neutral goal in time. Here, carbon tax and green finance, including green loans, green bonds, and green projects, are important areas that need further explorations. Lying between PPA and MBA, carbon tax and green finance could be a potent tool to facilitate technology shifting or even leapfrogging from fossil to non-fossil fuels. And just as in ETS, to develop a robust, sophisticated and standardized MRV system, not just domestically but also internationally, including good metrics or protocols of ESG to avoid "green washing" or reduce moral hazards, is also critical in green finance, if only for the sake of risk assessment, e.g., green assets vis-à-vis brown assets. The issue of moral hazards would arise, where people's interest and risk are not well aligned so they may have incentives to take on greater risk than they would if no one else effectively contributed insurance. Here, we must encourage international cooperation and create the right incentive structures, with respect to risks, rewards, and responsibilities.

Finally, combined rather than separate PPA aiming at de-carbonization will reshape the future structure of energy demand most powerfully. Specifically, renewable energy will be on the rise, whereas fossil fuels, especially coal, will decrease. Yet a caveat is in order. Even in the most comprehensive of all PPA scenarios available today, by 2060, renewable energy will only account for less than 80% of energy structure, whereas fossil fuels still account for more than 20%. In this light, introducing carbon tax and promoting the electric vehicle sector and other forms of electrification are important for further reductions in fossil energy, but the prerequisite is that the sources of electricity have to be clean (Currently, however, fossil-fuels power plants account for roughly 70%, the rest is non-fossil—hydraulic roughly 15%, wind 7%, nuclear 5%, and solar 3%). And hopefully, variables exogenous to the current parameters of the simulation model—e.g., dramatic expansions of green finance, technology breakthroughs, including additional PPA instruments—may come along the way, thus increasing the chance that China achieve carbon neutrality in time.

Admittedly, accurate and trustworthy predictions are difficult, even when people do their best to model everything relevant. The inputs and assumptions that enter any particular model might significantly affect a conclusion. It is therefore critical to be straightforward about uncertainties if a prediction is to have any value. Note as well, there is a difference between simulation and emulation. Whereas the former is basically linear in thinking, the latter is characterized by both deductive and inductive tinkering, constantly searching for order out of complexity and even chaos. Fundamentally humans are good at emulation. Indeed, facing uncertainties and unknowns, one has to stand ready to adjust and adapt as circumstances change. Accordingly, as a research strategy for such a complex issue as climate crisis threatening humanity, one ought to conceptualize like a "philosophy-king", straddling different disciplines of knowledge for a broad and yet logically consistent vision, and act like an academic "foot soldier", who is well armed with the "state-of-the-art" tools or techniques of rigorous analysis and investigation. After all, philosophical views could affect the conceptual framework one deploys to describe predictions, even though not the predictions themselves. And indeed, it is at least in this spirit that the current book is orchestrated and written, leaving ample room for adding details and making corrections down the road, as contingency preparedness by way of both deductive and inductive tinkering increases resilience in transition. Our hope is to provide a rough map rather than the actual driving itself, as we move towards the middle of the 21st century.

To sum up, to peak carbon emissions prior to 2030 and achieve carbon neutrality by 2060 is a very tall order, fraught with uncertainties and unknowns down the road. What is certain is that China has to undergo a veritable green revolution —from what the Chinese would say "*Gongye Wenming*" (industrial civilization) to "*Shengtai Wenming*" (eco-civilization), which, broadly speaking, would also include protecting biodiversity and healing geo-environmental degradation – both are relevant topics but nevertheless beyond the scope of this study. In the process, as the world is intrinsically interconnected, none of us will be spared the harsh realities of ecological crisis, which means we are all in this together—"*Tongzhou Gongji*" (all in the same boat).

Beijing, China Jun Fu

# Acknowledgements

Initial research included in this book was financially supported by BHP through a project-based grant to Peking University which began in 2017 through 2020 with a focus on carbon capture, utilization and storage (CCUS) in the steel sector. Follow-up research and editing of the book in 2021 through its publication was financially supported by the Leo Koguan Foundation and the Deloitte Touche Tohmatsu CPA Ltd. through their educational and CSR programs. On behalf of our colleagues involved in this cross-disciplinary study, the editors of this book—who have led the research teams on climate change from the National School of Development, the College of Engineering, and the Guanghua School of Management at Peking University—gratefully acknowledge the generous support.

For logistic support, we would like to thank Peking University Public Policy Forum International, which has hosted many stimulating workshops and seminars on climate change, among others. We are also grateful to Yin Jianhong, Zhao Ting, and Hu Weiyi for administrative support.

# Contents

# About the Editors

**Jun Fu**, Esq., is Professor of Political Economy and Public Policy at the National School of Development, Peking University. He received his Master's degree and Ph.D. from Harvard University and is the first Chinese to have been elected Foreign Academician of the Bologna Academy of Sciences in its long history. He is the author of *Institutions and Investments* (Studies in International Economics, the University of Michigan Press), and *The Dao of the Wealth of Nations* (Peking University Press). Previously, he held faculty positions at the School of Economics and Management, the School of Public Policy and Management, Tsinghua University, and the School of Government, Peking University. He has served, among others, as Member of the Listing Committee of Shenzhen Stock Exchange, Vice Chair of the World Economic Forum's Global Agenda Council on New Growth Models, and Advisor to Chairman of the Executive Council of UNESCO. As a globally known thought leader, he was twice featured in the *Outlook on the Global Agenda* (World Economic Forum). Appointed by its Governing Board, he has also served on Visiting Committee for International and Area Studies across Harvard University.

**Dongxiao Zhang** is Chair Professor at College of Engineering, Peking University. An internationally well-known expert in unconventional oil and gas production, groundwater hydrology, and geological carbon sequestration, he had held positions as Senior Scientist at Los Alamos National Laboratory, Miller Chair Professor at the Department of Petroleum and Geological Engineering at the University of Oklahoma, Chair Professor at the University of Southern California, and Executive Dean of Graduate School and Dean of College of Engineering at Peking University. He has published over 220 peer-reviewed papers and authored 2 books, *Stochastic Methods for Flow in Porous Media: Coping with Uncertainties*

(Academic Press), and *Theory, Modeling and Field Investigation in Hydrogeology* (Geological Society of America). He earned both his Master's degree and Ph.D. in hydrology and water resources in 1992 and 1993, respectively, from the University of Arizona. He is Member of the U.S. National Academy of Engineering, Honorary Member of Society of Petroleum Engineers, and Fellow of Geological Society of America.

**Ming Lei** is Full Professor at Guanghua School of Management, Peking University. He is the author of *Green Input-output Accounting: Theory and Application, Green Accounting of China* (1992–2002) and *Integrated Analysis of China's Natural Resources-Economy-Environment* (1992–2002) (Peking University Press, 2000/2010/2011). He was Associate Professor of Donated Chair by KENSAI Power of Japan, Graduated School of Energy Science, Kyoto University, Japan in 1998, and has held numerous honorary and academic positions, including President elect of Asia Pacific DSI, Senior Expert of Chinese National Green GDP Accounting Project, Fellow of International Sustainable Energy Association (ISEA), Fellow of Chinese Environmental Science Society, Fellow of Chinese Operation Research Society, Fellow of Chinese Environmental and Culture Society, Fellow of Chinese National Accounting Society, and Fellow of Chinese Energy Society. A Member of the Editorial Broad of *Economic Science*, he is Dean of the Institute on Poverty Research at Peking University and Honorary Professor of the University of Edinburgh.

# Abbreviations

| | |
|---|---|
| AAUs | Assigned Amount Units |
| BATs | Best available technologies |
| BECCS | Bio-Energy CCS |
| BFG | Blast furnace gas |
| BFs | Blast furnaces steelmaking |
| BOF | Basic oxygen furnace |
| CAMU | China Association of Metal Scrap Utilization |
| CCER | China certified emission reduction |
| CCS | Carbon capture and storage |
| CCUS | Carbon capture, utilization, and storage |
| CCX | Chicago Climate Exchange |
| CDM | Clean Development Mechanism |
| CERs | Certified emission reductions |
| CNPC | China National Petroleum Corporation |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| $CO_2$-EOR | Enhanced oil recovery |
| CSLF | Carbon Sequestration Leadership Forum |
| DAC | Direct air capture |
| DICE | Dynamic integrated model of climate and the economy |
| DRI | Direct reduce ion |
| EAF | Electric arc furnace |
| EC | European Commission |
| ECBM | Enhanced coal bed methane |
| EIA | Environmental Impact Assessment |
| EIB | European Investment Bank |

| | |
|---|---|
| EOR | Enhance oil recovery |
| ERUs | Emission reduction units |
| ESA | Electric Swing Adsorption |
| ETG | Emissions Trading Group |
| ETS | Emission trading system |
| EU ETS | EU Emissions Trading System |
| EU | European Union |
| FFCER | Fujian Forestry Certified Emission Reduction |
| FYP | Five-Year Plan |
| GCCSI | Global Carbon Capture and Storage Institute |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| HBFG | Hot blast furnace gas |
| IEA | International Energy Agency |
| IET | International Emission Trading |
| IPCC | Intergovernmental Panel on Climate Change |
| IUCN | The International Union for the Conservation of Nature |
| JI | Joint implementation |
| KPI | Key Performance Indicators |
| LDG | Linz–Donawitz gas |
| LSIPs | Large-scale integrated projects |
| MAF | Electric arc furnace |
| MBA | Market-based approach |
| MEA | Mono Ethanol Amine |
| MEE | Ministry of Ecology and Environment |
| MEP | Ministry of environmental protection |
| MIIT | Ministry of Industry and Information Technology |
| MIRV | Monitoring, Reporting and Verification |
| MNR | Ministry of Natural Resources |
| MOF | Ministry of Finance |
| MOST | Ministry of Science and Technology |
| MOT | Ministry of Transport |
| MSPE | Mean Square Percent Error |
| MTCE | Million tons of coal equivalent |
| NAP | National Allocation Plans |
| NBS | Nature-based solutions |
| NCSC | National Center for Climate Strategy and International Cooperation |
| NDC | Nationally determined contributions |
| NDRC | National Development and Reform Commission |

| | |
|---|---|
| NPC | National People's Congress |
| NRA | National Railway Administration |
| NSW | National Trust of Australia |
| NTCC | National Technical Committee on Carbon Management |
| PHCER | Pu Hui Certified Emission Reduction |
| PPA | Public Policy Approach |
| PSA | Pressure Swing Adsorption |
| RICE | Regional dynamic integrated model of climate and the economy |
| SAC | Standardization Administration of China |
| SACC | Strategy Analysis of Climate in China |
| SFA | State Forestry Administration |
| $SO_2$ | Sulphur dioxide |
| TCE | Ton of coal equivalent |
| TGRBF | Top Gas Recycle of Blast Furnace |
| TRT | Top Gas Pressure Recovery Turbine |
| TSA | Temperature Swing Adsorption |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VPSA | Vacuum Pressure Swing Adsorption |
| WTO | World Trade Organization |

# List of Figures

**Chapter 3**



**Chapter 4**



**Chapter 5**

## Chapter 6



## Chapter 7

# List of Tables

## Chapter 5



## Chapter 6



## Chapter 7